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Criticality and Recyclability Assessment of Car Parts—A Thermodynamic Simulation-Based Approach

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Abstract: Using a thermodynamic approach, this paper identifies the most critical parts of a car, considering their composition. A total of 11 car parts that contain valuable and scarce materials have been selected using thermodynamic rarity, an indicator that helps assess elements and minerals in exergy terms according to their relative scarcity in the crust and the energy required to extract and refine them. A recyclability analysis using a product-centric approach was then undertaken using dedicated software, HSC Chemistry. To that end, the dismantling of these car parts into three main fractions was performed. Each car part was divided into non-ferrous, steel, and aluminum flows. A general metallurgical process was developed and simulated for each flow, including all the required equipment to extract most of the minor but valuable metals. Of the 11 parts, only 7 have a recyclability potential higher than 85%. By treating these selected car parts appropriately, the raw materials' value recovered from the car can increase by 6%. The approach used in this paper can help provide guidelines to improve the eco-design of cars and can also be applied to other sectors. Ultimately, this paper uniquely introduces simulation-based thermodynamic rarity analysis for thermodynamic based product "design for recycling".

Keywords: thermodynamic rarity; critical raw materials; recycling; end-of-life vehicles; product-centric-approach

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1. Introduction

Renewable energies, ICT technologies, efficient lighting, and vehicles all use an increasing number of raw materials in common. As a result, society uses today almost the whole periodic table to satisfy their needs. Many elements essential to connect, make the economy more efficient or "green", are scarce in nature, or their production is located in a few spots in the world. For this reason, many regions such as the European Union (EU) [1], the United States (US) [2], Canada [3], or Australia [4] have established in the recent past lists of critical raw materials, identifying elements whose disruption in supply may put the very development of their respective economies at risk. Such lists include rare earths, indium, cobalt, gallium, and tungsten, among others.

One of the many factors always considered in such studies is the supply risk, as disruptions could compromise the economies [1–4]. The reduction of supply risk, which is vital for many importing regions, entails either betting on the exploration and exploitation of new mines or moving toward a circular economy to keep the materials in the technosphere as long as possible [5]. In some developed countries, there is strong opposition to opening new mines, where the motto "Not in my backyard", also called the Nimby effect, prevails [6]. Due to the increase in the number of mining projects in the EU, protests have also become more visible, as people are concerned with environmental impacts, socio-economic issues, or health, among others [7].

The second option, closing material loops, seems easier to achieve, yet it comes with physical restrictions. That said, it is a fact that achieving higher recycling rates could help decrease raw materials' primary extraction and processing [8]. Specific characteristics of the so-called anthropogenic resources, such as resource or recovery potential, are still far from being known due to significant statistical gaps [9]. According to UNEP [10], almost all scarce and critical raw materials have meager recycling rates, most of them below 1%. These low recycling rates are arguably due to the following reasons. First, technological products are achieving outstanding performance in terms of the size reduction or functionalities, owing to the fact that they are made of an increasing number of chemical elements. These elements are present in the form of compounds mixed in such a way that they are extremely difficult to separate [11]. This is a consequence of the second law of thermodynamics, the greater the mixture, the greater the entropy generated. Therefore, returning to the initial state is technically impossible or requires an enormous amount of energy [12]. Second, current recycling technology is mainly based on the recovery of bulk metals, notably steel, aluminum, and copper. However, it is not prepared to recycle the minor but valuable elements such as tantalum, tellurium, neodymium, etc., which cannot be recovered [13,14]. End of life vehicle legislation in Europe has not favored this issue, as the established vehicle recycling targets are based on weight and not on quality [15].

Moreover, downcycling is another critical point. Downcycling refers to the recycling of waste where the recycled material is of lower quality and functionality than the original material. This is something that occurs very frequently in the recycling of cars [14,16–19]. Many minor metals end up dispersed in low-quality steel or aluminum alloys, into slags as well as flue dust, sludges, etc., making them unsuitable for the same original purpose [20]. Again, this is a consequence of the second law of thermodynamics and solution chemistry which includes excess entropies of solution.

Thermodynamicists know well that one of the most entropic processes that exists is mixing, especially of multi-material mixtures such as particles, solutions, melts, etc. And the entropy increases with the number of species involved in the mixture [21]. The effort required to purify a given element increases exponentially with the grade attained. Achieving copper at 99.9% purity requires exponentially more energy and reactants than staying at a 99% grade. In the same way, recovering an element from a mixture at a concentration of 0.1% is much more complicated than if it were at 1%. Moreover, the concentration and the chemical form in which it is found and the other chemical substances that accompany it in the mixture also affect their final recoverability.

The second law of thermodynamics posits that every process has losses; thus, if applied to recycling, complete recycling is impossible. There are always losses. In other words, the circular economy is a nice myth, but in reality, we can only strive toward a "spiral economy". Loops cannot be entirely closed due to inefficiencies, and the identification and minimization are crucial along the entire life cycle of a product [22]. One can design processes and products to make them long-lasting, efficient, and much more recyclable. In this respect, a deep understanding of thermodynamics is key to moving closer to a spiral economy [23].

Nowadays, a conventional passenger car needs a huge amount of scarce metals [24], making this sector more vulnerable to shortages and disruptions in supply [25]. Car manufacturers face severe semiconductor supply shortages, forcing them to stop production for months [26]. This issue will arguably become even more severe considering that, by 2030, up to 1.85 billion vehicles are expected to be added to the current fleet [27]. With the massive adoption of electric, connected, and autonomous cars, it becomes clear that additional quantities of critical metals (CMs) will be required, given that additional electric and electronic equipment will be present within the car. As shown in a previous study conducted by the authors, an electric car contains 50% more metals than a conventional one (1200 kg versus 800 kg) [28]. Most of them are located in the electric powertrain: the lithium-ion battery, the electric engine, the charger, and the power electronic. Just selecting one example, whereas a conventional car currently demands 4 g of lithium, an electric car requires almost 7 kg.

Car electronics represent 30% of the total car cost and will constitute 50% in the year 2030 [29]. As several studies have pointed out, car electronics are an important source of secondary critical metals, which nowadays are not being recycled [13,14,24,28,30–40]. Current recycling practices are focused on bulk metals recycling, whereas minor strategic metals are mainly lost in landfills [13,24,35,37]. Since the last ten years, the study of critical metal content and their location within the car has gained increasing attention, particularly in the EU, the US, and Japan [13,14,24,28,30–39]. The data gathered in these studies are based on the information located in the automotive database IMDS (International Material Data System) or chemical analysis (input or output driven). Most of the studies show aggregated data for the whole vehicle and vehicle subsystems, being difficult to know in which specific car parts the critical metals are located. As general conclusions, Restrepo and co-authors [40] drew four important insights: (1) Rare earths are the focus of most studies, indicating the importance of these CMs in automotive applications; (2) the mass fraction of gold in cars is similar to the average ore grade in mines; (3) neodymium stock has a great potential as a secondary source in the US and Japan; (4) out of the CMs investigated, only platinum from catalytic converters is functionally recycled, ending the rest of CMs in landfills or as impurities in scrap-metal fractions. From a metal recycling viewpoint, ELV recycling plants are based on shredding processes to obtain two main outputs: ferrous and non-ferrous fractions. The first one is sent for the steelmaking process and the second one is for aluminum production [29,30]. Additionally, separation processes based on density are applied to mainly recover the copper fraction. Therefore, car electronics are shredded together with the car wreck, with the subsequent loss of the contained metals, unintentionally ending up in steel- or aluminum-making processes. Moreover, the presence of these metals as impurities can affect the properties of final alloys, reducing their ductility. This entails diluting different alloying elements or adding more primary resources [41].

In this paper, thermodynamic insights are applied to analyze the criticality and recyclability of different elements present in cars to overcome these issues. Both raw material criticality and recyclability are assessed in this paper using a thermodynamic approach, explained in the next section, which is strictly based on the physical aspects of resources. In addition, recyclability refers to the potential to recover the separate elements contained in the car. The recyclability analysis can be carried out with a product-centric approach (PCA) [42,43]. Contrarily to a material-centric approach (MCA), in a PCA, the complexity of the products in terms of composition and concentration of the substances contained in them can be considered. By doing this, recycling processes can be designed for an effective recovery of valuable metals. As shown in the so-called metal wheel [44], it is imperative to analyze the inputs introduced to the different recycling processes since selecting the wrong recycling process for a given product may induce dramatic material losses. Therefore, it is crucial to understand the metallurgy and thermodynamics (as well as mass and energy transfer processes) behind the processes and also especially the non-ideal solution chemistry, which also includes excess entropies of solution in the evaluations. For the recyclability assessment, we use a specific software, HSC Chemistry 10.0 (Metso Outotec, http://www.hsc-chemistry.com/ (accessed on 15 June 2022), where metallurgical processes can be simulated to analyze the number of metals recovered from the different flows. This software has already been successfully used to assess the recyclability of different end-of-life products, such as mobile phones [45] or LED lamps [46,47] and to simulate aluminum recycling processes [48].

The novelty of our approach is three-fold in comparison with related previous studies [13,24,28,30–39]. First, we are identifying the valuable car parts in terms of thermodynamic rarity (exergy vs. mass approach), thus considering the physical value of minor and scarce metals. Second, a recyclability analysis applying HSC Chemistry software is carried out for the first time in the automotive sector (product-centric approach). Here relies on, as well, the innovative character of this study. The studies conducted in the past analyze the mass content of metals and their maximum potential recovery (material-centric approach), not taking into consideration the "real" recovery. That is the realistic recovery for having metals in chemical combinations within the car parts as well as applying the state-of-the-art recycling processes. And third, the recyclability potential is as well expressed in thermodynamic rarity terms, based on the second law of thermodynamics, thus providing valuable insights into the physical quality of the recycling processes. In other words, reflecting the efficiency of the current recycling technologies in recovering minor but valuable metals.

2. Materials and Methods

Our object of study is a SEAT León Generation III Diesel car, for which a thermodynamic criticality analysis is carried out. The material composition of the car under consideration was obtained from the MISS database (Material Information Sheet System), an IT system from VW Group that obtains the information from IMDS. In this system, all automotive suppliers incorporate material information sheets. The material composition of the selected car parts is presented in Table S1 of the Supporting Information.

2.1. Thermodynamic Rarity

The methodology used to analyze the criticality of the car parts is based on an exergy-based indicator called thermodynamic rarity, which has been successfully applied before to this same sector [28,49]. This indicator allows us to assess which specific car parts contain the most valuable metals from a physical point of view. The physical value of minerals is mainly due to their chemical properties and their degree of scarcity in the crust [50]. The scarcer a resource, the greater its extraction costs, and these, in turn, increase exponentially as ore grades decrease [51]. This methodology owns some similar aspects to LCA methodologies. However, it does not consider all the steps from cradle to grave (considering all the operations for assembling, using, and disposal after use). It only considers the scarcity and the energy intensity to extract and refine the materials contained in any given device.

Thermodynamic rarity incorporates two aspects. First, the embodied exergy cost (kJ), i.e., the useful energy required to extract and process a given mineral from the cradle to the gate (until it becomes a raw material for the manufacturing industry). The second is an avoided cost of having minerals concentrated in mines and not dispersed throughout the crust, which can be seen as a natural bonus [50]. As mines become depleted, it becomes exponentially harder to obtain commodities (embodied costs increase), whereas the bonus reduces. This bonus is calculated as a hypothetical exergy cost required if the given mineral would be restored to its initial composition conditions and concentration in the original mines from an utterly dispersed state.

For this reason, it is necessary to identify the reference state from which the reconcentration of every material can be assessed. This reference has been called "Thanatia" and represents a theoretical state where all materials become dispersed throughout the crust [50]. The model of Thanatia is composed of the 300 most abundant minerals found in the crust, with their corresponding composition and crustal concentrations [52]. From that baseline, which represents the "bare rock", any element from any mineral can then be concentrated until the state currently found in nature. The thermodynamic rarity values of the different elements analyzed in this study can be found in Table 1.

Table 1. Thermodynamic rarity values for the studied elements [51].

	Ag	**Al**	**As**	**Au**	**Ba**	**Be**	**Bi**	**Cd**
kJ/g	8937	661	428	654,683	39	710	546	6440
	Ce	**Co**	**Cr**	**Cu**	**Dy**	**Fe**	**Ga**	**Ge**
kJ/g	620	11,010	41	348	732	32	754,828	24,247
	In	**Li**	**Mg**	**Mn**	**Mo**	**Nb**	**Nd**	**Ni**
kJ/g	363,918	978	146	73	1056	4782	670	758
	Pb	**Pd**	**Pt**	**Ru**	**Sb**	**Sn**	**Sr**	**Ta**
kJ/g	41	2,870,013	2,870,013	2,870,013	488	453	76	485,911
	Tb	**Ti**	**V**	**W**	**Y**	**Yb**	**Zn**	**Zr**
kJ/g	732	203	1572	8023	1357	732	197	2026

This way to calculate the thermodynamic rarity R (kJ/g) of a specific car part, Equation (1) is used once the composition in terms of elements contained (m_i) in car part (A) are known:

$$R(A) = \sum_{i=1}^{n} m_i R_i \tag{1}$$

This indicator is complemented with the rarity intensity (kJ/g), as calculated with Equation (2), where mi is the weight of all metals in the given car part:

$$Rarity\ intensity\ (A) = \frac{R(A)}{\sum_{i=1}^{n} m_i} \tag{2}$$

With the rarity intensity, we can consider small parts that contain valuable metals but with a small relative weight. Such parts would be otherwise omitted if only Equation (1) were used. Both rarity and rarity intensity values of the selected car parts are included in Table S2 of the Supporting Information.

After the most critical car parts have been identified, the next step is to undertake a recyclability analysis. Before this happens, each car part needs to be manually disassembled into the smallest fraction possible to ensure that most of the materials can be recovered by sending them to the appropriate recycling route: ferrous, non-ferrous, or aluminum metallurgy (see Figure 1). The composition of each fraction is checked against the manufacturer's specification sheets, which give the exact compositions of each dismantled subpart. Note that, if no manual disassembly is undertaken, the vehicle undergoes fragmentation and conventional EoL treatment, leading to the loss of the minor metals to dust, complex particles mixtures, etc.

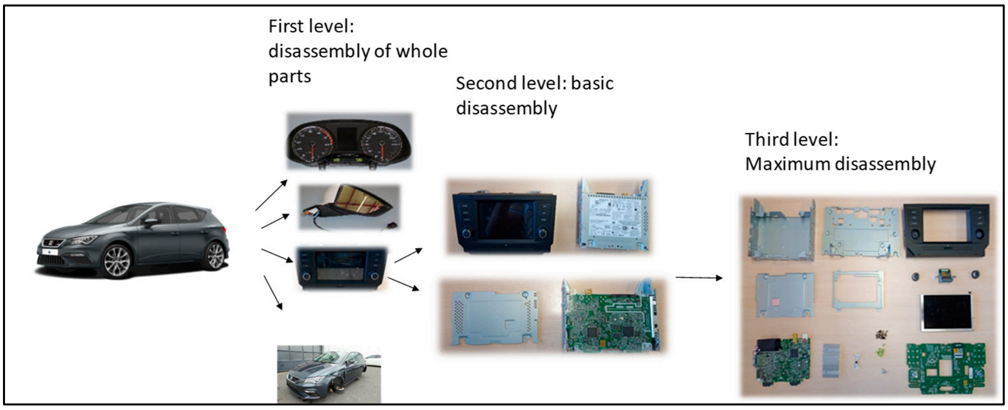

Figure 1. Steps in the manual disassembly of the selected car parts.

2.2. Simulation-Based Estimation of Exergy Dissipation

Each recycling route can then be simulated using HSC Sim 10. To that end, a detailed flow chart needs to be created, defining all process inputs with the exact composition, mass flow, temperature, and pressure of the recycling subparts. The software then calculates all the properties of each flow, including its exergy. The outflows of each unit need to be then specified. In addition, all elements defined in the inflows with their specific composition require to be distributed among the units so that the mass balance is closed. Depending on the simulating process, the energy balance needs to be closed through different parameters, such as heat losses, chemical reactions, etc. Once all the balances have been closed, the simulation is completed, and all flows' composition and thermochemical properties are calculated. This way, the behavior of all metals throughout the recycling process can be analyzed and the total quantity of the recovered/lost metals determined. As HSC Sim is connected through GaBi and openLCA to, e.g., Ecoinvent, additional conventional life cycle assessments can be easily carried out, although this is out of the scope of this paper.

The simulation-based methodology is being proposed here, to be an integral part of the rarity estimation of the materials in products, materials, modules, etc. The approach has been discussed elsewhere [45–48] and is briefly explained here for convenience and also to show how it fits into the rarity concept. The approach is briefly the following:

- There are numerous flowsheets possible for the processing of different products, modules, scrap, etc. Chosen here are typical economically viable processes and flowsheets, of which data is available in the literature, and that can be estimated by the correct use of FactSage [53] to extract useful data for reactors and also use the know-how of reality to ensure results are in order. These data include phases in a reactor, possible compounds generated, elemental distribution, etc.
- In the unit models in this paper, mainly the distribution mode of HSC Sim is used, which is quite useful, as all reactors in high-temperature processing phases have different temperatures, i.e., slag, metal/alloy, flue dust, speiss, and offgas. This is of importance if the correct exergy content of each stream is to be estimated, as this is dependent on the temperature. This is not possible using Gibbs free energy minimization, given that results are calculated at the same temperature. Unless detail is required as shown in a recent paper [54], in which SimuSage (FactSage-based) was used for a multi-compartment model for a reactor. This, nonetheless, falls outside the detail required for this rarity analysis. For the hydrometallurgical unit operations, chemical reaction equations were used by applying the hydrometallurgical unit definition in HSC Sim.
- To apply the distribution and chemical reaction equation mode in HSC Sim requires a detailed understanding of the phase relationships in high-temperature metallurgy as well as reaction chemistry and equilibrium processes in aqueous media. In other words, setting up, e.g., the distribution model in HSC, requires an understanding of all phases in slag including solids, all as a function of temperature, partial oxygen pressure, and liquidus temperature, to distribute all elements correctly. For example, for Fe, this could be Fe(l) dissolved in black copper (a function of its activity coefficient), or present in FeO, Fe_3O_4 or Fe_2O_3, Fe_2SiO_4, etc., in the slag, which all affect the entropy and enthalpy of the phase. Species such as Pb also dissolve in copper (as a function activity coefficient at the temperature and flow operating point) but appear in the slag as PbO and in the offgas as gaseous species PbO, PbS, $PbCl_2$, $PbBr_2$ (there are numerous—consult HSC Sim for details), depending on the feed, reactor type, flow through the reactor, etc. This is where industrial experience helps to understand which species are important also in the context of the reactor type.

Figure 2 shows a typical example of the distribution of elements between a copper-rich alloy and various elements, which report to slag, flue dust, gas phase, etc. This is information that is generated using FactSage within the context of specific reactors, which may have a range of temperatures and thus equilibria.

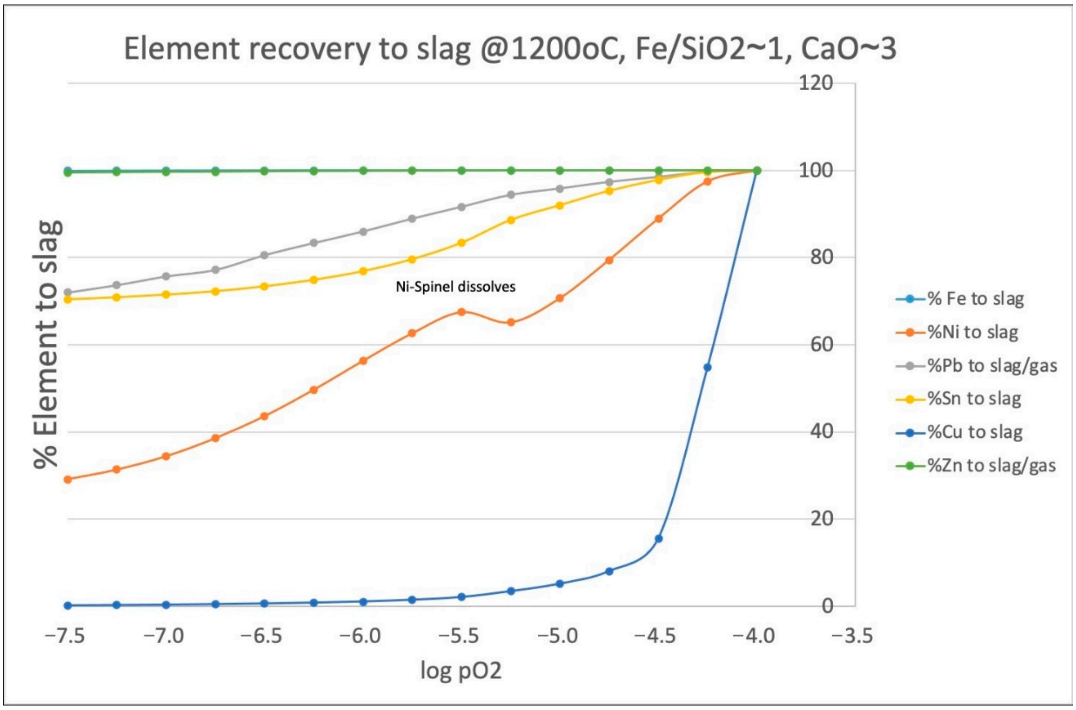

Figure 2. Distribution of elements between copper alloy and an olivine slag at the given processing conditions calculated using FactSage—these distribution data are used for example in the TSL reactors in Figure 3 at respective operating points.

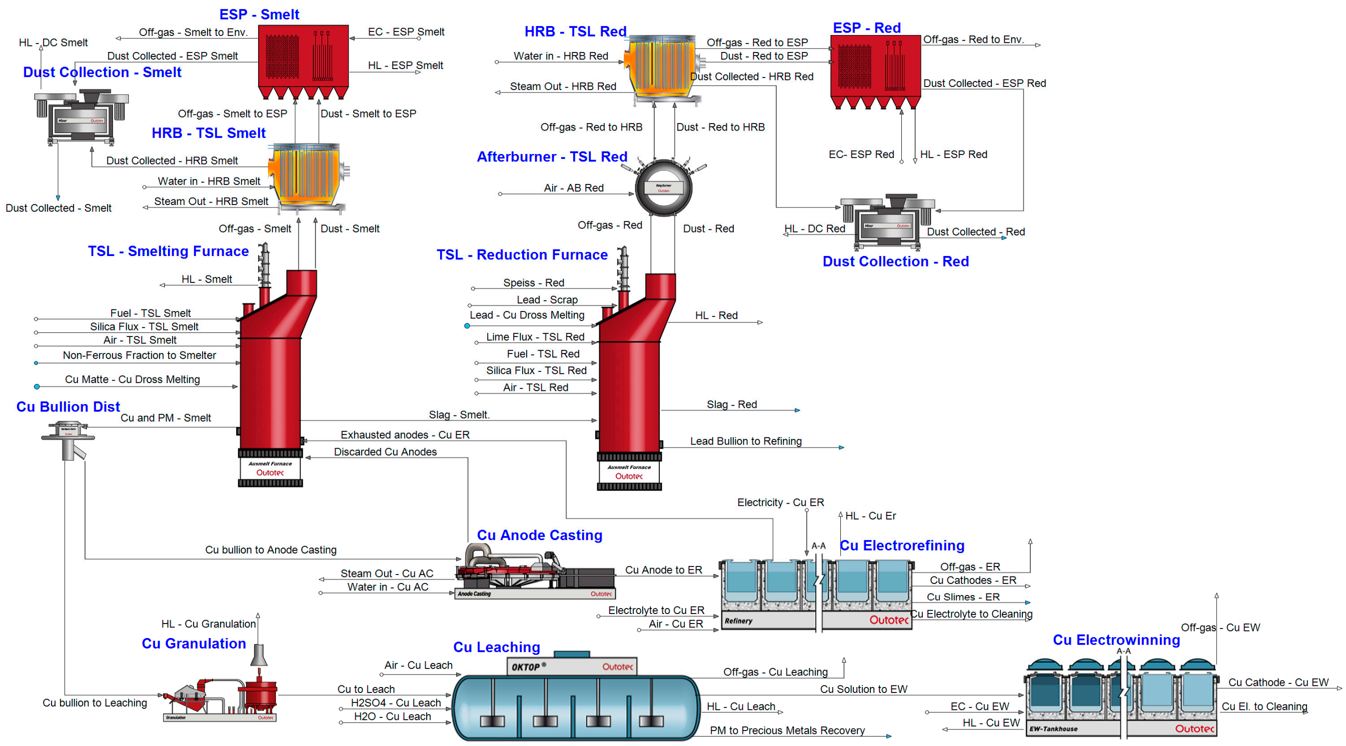

Figure 3. Smelting, reduction, and copper refining stages of the non-ferrous recycling flowsheet.

Of importance is always also to check enthalpies and entropies of solutions, using, e.g., FactSage and HSC data to ensure the differences are little and that results are meaningful.

- Once the detail in each unit operation has been defined, the next important aspect is the energy balance, as this determines the temperature of all phases. This is dependent on the reactor type and the size/capacity.
- To solve the mass and energy balance flowsheet with all its reactors, i.e., closing the balance for all elements as a function of all compounds, temperatures, reactors, and recycle streams in the flowsheet, requires a careful set-up of controls that help iterate to meaningful results.
- Once an iterative solution has been obtained, the consistent mass and energy balance can be used to do an LCA analysis. Above all, it permits the analysis of the complete system exergetically, as discussed in various papers referred to above. This produces the exergetic dissipation of the elements and their compounds in the different metallurgical phases of the system, which then can be used in the rarity analysis. As discussed in the various papers cited in this document, this approach provides the true resource efficiency of the system and quantifies the exergetic dissipation, which ultimately is reflected in the economics of the system.

The next section briefly shows the basics of the model, without going into the distribution behavior of all elements in the system, given that this is outside the scope of the paper.

3. Simulation Models

For the illustration of using thermochemical-based flowsheeting tools in the estimation of the rarity of the elements (and their compounds) in products, a recycling infrastructure simulated based on the base-metal metallurgies of copper, lead, and zinc was defined. Additionally, recycling flowsheets for steel and aluminum have been performed, being more of a dilution type of chemistry in comparison to the base metal chemistry that requires a detailed understanding of the different phase relationships. HSC Chemistry has been used for the simulations. Accordingly, an extensive simulation model composed of 132 unit operations, 631 streams, and over 50 chemical elements along with their associated compounds was developed for this study. These flowsheets are explained in detail in the following sections. The unit operations were defined as explained previously.

The feed materials used are the car parts mentioned above and the fuels, reagents, and raw materials used in the state-of-the-art processes modeled. The information required to model these flowsheets was obtained from the state-of-the-art industrial literature on the simulated processes, given throughout this section. This information also included operating parameters and element distribution ratios between different streams/phases. Accordingly, the model's different phases, streams, and products are obtained based on the operating parameters and distribution ratios obtained from the industrial literature. This information has been completed with other data sources such as FactSage or industrial experience, when some information was missing, e.g., data on the distribution of particular elements or potential compounds generated (see Section 2.2). This section does not give a thorough description of the operating parameters as the flowsheet models are not the central message of this article. Nevertheless, these parameters can be obtained from the references given if the reader wants to learn more about the metallurgy behind the flowsheet.

3.1. Non-Ferrous Flowsheet

The non-ferrous fraction, excluding aluminum, was treated in a non-ferrous flowsheet, with the smelting section depicted in Figure 3. This model was developed using state-of-the-art operating parameters for the base metals' industrial processing infrastructure. These operating parameters were obtained from the literature (FactSage, industrial experience, reactor type), which include typical phases and their most possible compounds in the various streams, their different temperatures, etc., so that especially their entropy can be calculated, key for rarity analysis. This has been explained in Section 2.2.

Note therefore that this is not an element flow through the system but the most likely compounds, that would exist under normal operating conditions, for example during copper processing. Further note that, while two reactors are shown, these represent two steps, i.e., first creating a raw copper and slag, then the copper is tapped from the furnace, the remaining slag is then reduced to clean it and recover valuable elements while creating a multi-metal alloy (lead rich) that is processed elsewhere.

The smelting process is based on copper metallurgy, particularly on the processing of various grades of scrap, eWaste, and residues in a secondary copper smelter. The simulated smelter operates under oxidizing conditions to remove the copper scrap's impurities to produce raw copper. State-of-the-art operating parameters were used to develop this stage, e.g., temperature around 1300 °C, slag chemistry, or metal/slag/off-gas distribution ratios.

For more detailed information on the operating parameters used, please see the industrial data sources used by the authors [55], FactSage to estimate different phases as well as activity coefficients, reflected by the data in Figure 2. This smelting process generates three phases:

- Raw copper phase: The chemistry is broadly explained in Figure 2 and is composed of metallic copper, which acts as a collector of the precious metals contained in the feed. This metal phase can follow two routes: (i) copper electrorefining, where copper cathodes are produced, and the precious metals are collected as anode slimes, and (ii) copper leaching of granulated copper and subsequent electrowinning. In this latter route, copper is leached and electrowon to produce copper cathodes, while the precious metals are collected as leaching residue. Precious metals are further refined in the "Precious Metals Recovery" process, explained later. Copper electrorefining and electrowinning, and precious metals recovery are state-of-the-art processes. Their corresponding operating parameters were obtained from industrial literature sources [56–58].
- Slag phase: Metals that oxidize more easily than copper are collected in the slag generated in this reactor, which is mainly an olivine-type slag, i.e., SiO_2-FeO_x-CaO. These elements may include lead, tin, zinc, iron, aluminum, tantalum, or rare-earth elements (REE), etc., all present as oxides. This slag is reduced further on to recover some of the collected elements [59], while creating a clean possible slag phase, which then would be mainly a mixture of compounds of Si, Fe, Ca, Mg, Al, O, and lesser quantities of the oxides of Cu, Zn, Pb, Sn, Ni, etc. This would mean, one would be operating at low pO_2 reaching a max. 10–11 atm (at least before reducing too much Fe from slag) and further to the left on the axis of Figure 2.
- Gaseous phase: Several metals volatilize to some extent under these smelting conditions, such as lead, tin, or zinc in metallic, oxidic, halide, etc., form depending on what is in the feed. These metal-containing compounds are recovered as dust in the filters after oxidation and cooling and further treated to increase recovery via reductive processes [59].

Once the copper and precious metals have been separated from the non-ferrous fraction, the slag is treated under reducing conditions in the "TSL—Reduction Furnace" unit operation. This stage is based on lead metallurgy because it is used as a carrier metal to recover oxidized metals in the slag. Accordingly, state-of-the-art equipment and operating parameters were used to simulate this process—for example, a temperature around 1250 °C or industrial-based FeO_x-SiO_2-CaO slag chemistry. For the specific operating parameters used for developing this mode, please refer to the industrial literature used [60]. Again, three phases can be distinguished:

- Lead bullion: The lead in the slag is reduced, and lead bullion is generated. This phase also collects other metals that are reduced under the operating conditions, e.g., copper or cobalt, nickel, or bismuth to some extent. Therefore, lead acts as a collector of minor metals such as Co, Ni, Sn, etc., which are recovered along the refining process of the lead bullion.

- Slag phase: This slag collects refractory metals that are usually stable oxides, e.g., Fe, Al, REEs, Ta, or some Co and Ni. This slag may be discarded because of the high cost of recovering the remaining metals. However, a slag reduction furnace was included in this example to recover the Co and Ni entrained in the slag and show how the resource consumption of the recycling plant increases [61]. This process is explained later. Through this, at a cost, a cleaner slag is created that may be used as building material if meets the building requirements.
- Gas phase: The reducing conditions of this furnace volatilize some of the metals of the slag. For instance, Zn and Cd are volatilized to a large extent and collected as dust after oxidation and cooling.

Lead bullion refining is crucial in recycling since many metals are recovered in it as by-products. All the operating parameters are based on the state-of-the-art process obtained from the industrial literature [62]. Therefore, please see the cited literature for a comprehensive description of the operating parameters, which are rather well-documented [63]. The first step is the removal of the copper contained in the bullion. This is carried out by reducing the temperature of the lead bullion to around 400 °C, which reduces the solubility of copper. Therefore, the copper, along with cobalt and nickel, can be removed as copper dross, which is further treated to recover the metals that it contains [63].

Once the copper is removed from the bullion, a caustic extraction is carried out to extract the antimony, arsenic, tin, tellurium, and indium in the bullion. This is conducted in a two-stage Harris process. The caustic slags generated are then treated to recover all these metals [63].

The main impurities remaining in the lead bullion at this point are silver and bismuth. If silver has been collected in the lead bullion, it is recovered in the Parkes process, where a high melting point silver-zinc alloy is generated and separated from the bullion as a crust. This crust is further treated to recover the zinc and silver and sent to the "Precious Metals Recovery" flowsheet to produce silver cathodes. Then, bismuth is obtained through the Betterton-Kroll process as dross [63].

As explained before, the precious metals are collected as leaching residue during the copper leaching or as anode slime if the copper is electro-refined. They are treated in a state-of-the-art precious metal refinery [58]. The first stages of this flowsheet remove the impurities of the precious metals feed. Once removed, a silver anode is produced. During the electrorefining process of the silver anode, silver cathodes are produced, while the rest of the precious metals are collected as anode slimes. These slimes from the electrorefining of silver are treated and cast in gold anodes. Then, gold is electro-refined to generate pure gold, while the precious metals are collected again as anode slimes.

The dust collected from the pyrometallurgical reactors of the recycling flowsheet still has many metals that can be recovered, e.g., Zn, Pb, and Sn, among others. For this reason, the different dust streams generated are treated for metal recovery. For example, the tin-containing dust generated during smelting is treated in a reduction furnace to produce a tin-lead alloy [59]. Furthermore, the zinc-containing dust generated during the reduction processes is leached and electrowon to produce zinc cathodes.

Depending on the cobalt and nickel content of the slag generated in the reduction stage, where the lead bullion is generated, a further treatment to recover these metals, e.g., electric furnaces for the required higher temperature to create Co-Fe-Ni alloys, can be interesting to carry out. This treatment reduces the slag to obtain cobalt and nickel metal along with some iron [64]. The alloy produced in the reduction furnace can be refined to eliminate some iron before leaching. During leaching, an electrolyte containing cobalt and nickel is produced and further purified through a solvent extraction process.

The cobalt and nickel originating from the copper drossing in the lead bullion refining can be leached to produce another electrolyte containing cobalt and nickel. Therefore, this electrolyte can be purified together with the one produced in the reduction furnace flowsheet so that cobalt and nickel are produced in pure form. The first step to purify these electrolytes is to remove the dissolved copper through solvent extraction. Then, iron and zinc are removed from the solution through precipitation and solvent extraction. Once the impurities of the electrolyte have been reduced to acceptable levels, cobalt is separated from nickel through solvent extraction so that both metals can be electrowon.

The flowsheet configuration, the aqueous-to-organic ratios of the different solvent extraction stages, and other operating parameters used in this model were obtained from state-of-the-art literature on nickel and cobalt production from intermediates. Please refer to the cited documents to find the detailed operating parameters used in the model [65–68].

3.2. Ferrous Flowsheet

The steel fraction is recycled in a generic steel recycling flowsheet, depicted in Figure 4. For illustration, the usual operating parameters for dilution chemistry were used to model the steel recycling flowsheet, e.g., operating temperatures of each unit operation, slag chemistry, element distribution between the different phases, etc. They were obtained from industry-relevant literature [69]. Therefore, please see the cited research for a thorough overview of the process parameters [69]. The steel scrap is melted in an electric arc furnace (EAF) reaching temperatures of 1800 °C, where the impurities with more stable oxides than iron are collected in the slag. Therefore, elements such as aluminum, and magnesium, if present as alloys linked to the steel scrap, report to the CaO-rich slag.

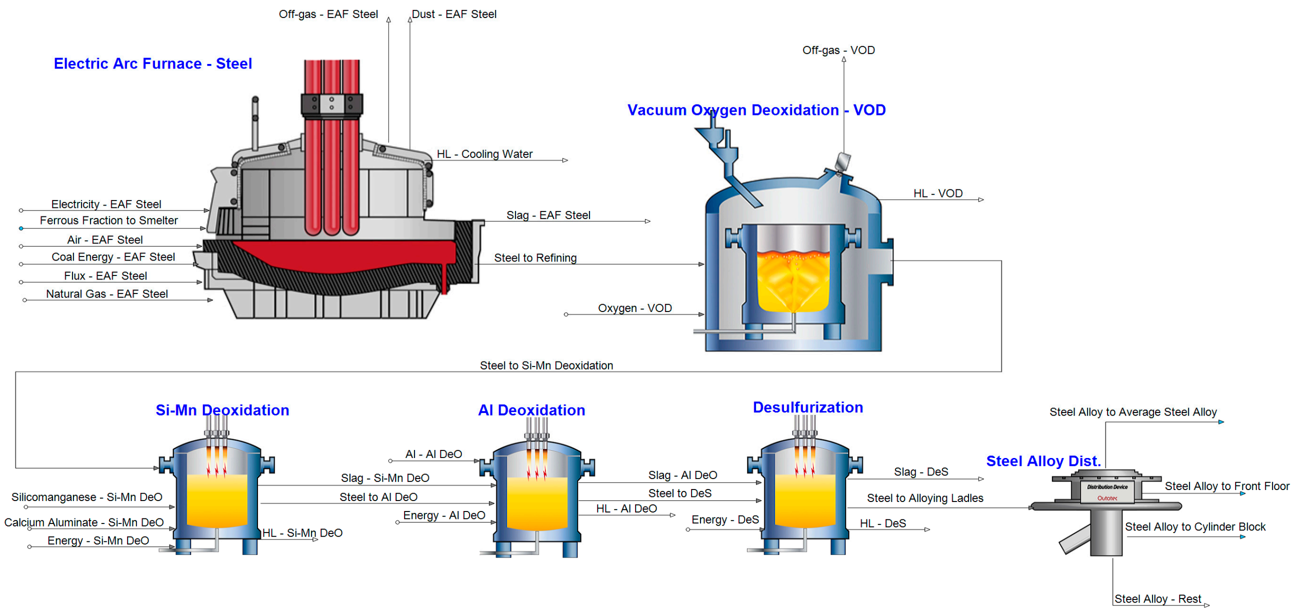

Figure 4. Steel recycling flowsheet composed of an electric furnace and ladle metallurgy to produce the required steel alloy quality used in this study.

The molten steel is further refined through ladle metallurgy to remove impurities and adjust the alloy composition through suitable alloying elements. However, impurities such as copper or nickel cannot be removed because they cannot be chemically removed under the operating conditions of the EAF. Accordingly, high-quality alloys may need to be diluted with high-quality scrap, pig iron, and direct reduced iron (DRI) to produce the specific composition of the alloy. For this reason, an iron dilution stream along with the alloying elements in the alloying ladles is included so that the quantity of iron required is estimated. In this study, the impurity dilution is carried out with pure iron (instead of using high-quality scrap) to evaluate the dependence on primary resources. For more accuracy, DRI must be used.

Three different final alloys were defined to show how the demand for alloying elements and pure iron changes with the quality of the alloy. The composition of these steels is shown in Table 2.

Table 2. Composition of final steel alloy types [wt.-%].

	Average Steel Alloy	Front Floor	Cylinder Block
Al	0.75	1.41	0
Cr	0.73	0.06	0.18
Cu	0.46	0	0.08
Fe	96.38	97.37	99.2
Mg	0.02	0	0
Mn	0.63	0.95	0.39
Mo	0.03	0.02	0
Nb	0.04	0.02	0
Ni	0.14	0	0
Sn	0.13	0.04	0.01
Ti	0.06	0	0.14
V	0.01	0.13	0
Zn	0.62	0	0

3.3. Aluminum Flowsheet

The aluminum recycling flowsheet is composed of the re-melting and refining stages, as shown in Figure 5. As done for the steel model, usual operating parameters were used to develop the model, e.g., temperature, salt consumption, or fuel consumption [70]. They are industrial operating parameters from the cited literature. In the re-melting, the aluminum scrap is melted along with a salt flux that protects the molten aluminum from being oxidized. The high reactivity of aluminum makes it very important that the impurities of the feed are controlled. They can react with aluminum and generate material losses, e.g., aluminum reacting with the plastics in the feed to form aluminum carbides. These factors have been considered in the model to be evaluated. Furthermore, an aluminum refining stage is considered to decrease the magnesium impurities in the molten aluminum.

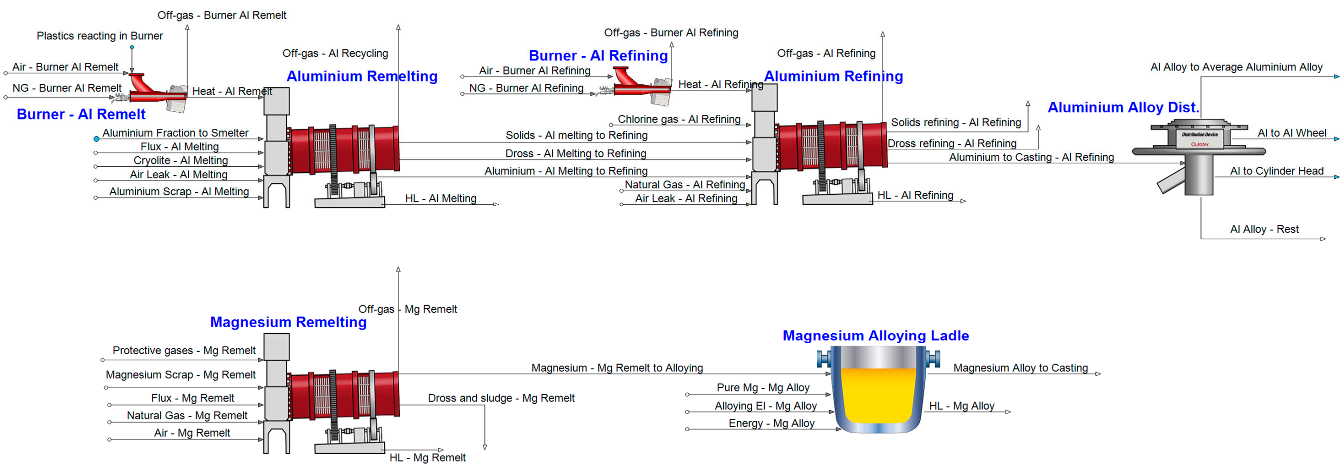

Figure 5. Aluminum and magnesium recycling flowsheets—see [41] for more details.

As with the iron recycling flowsheet, three aluminum alloys have been defined so that the alloying elements and virgin electrolytic aluminum required can be calculated depending on the quality of the alloy. The exemplary composition of these aluminum alloys is shown in Table 3, which can be obviously extended to any degree of complexity. Note that the 100% purity value given for the cylinder head alloy does not mean that aluminum has no impurities. In fact, there are impurities but at very low concentrations, that the decimal accuracy of the value given in the material data sheet could not reflect.

Table 3. Composition of final aluminum alloy types [wt.-%].

	Aluminum Average Alloy	Aluminum Wheel Alloy	Cylinder Head Alloy
Al	96.46	99.39	100
Cr	0.03	0	0
Cu	0.88	0.02	0
Fe	1.63	0.08	0
Mg	0.35	0.32	0
Mn	0.18	0.03	0
Ni	0.08	0	0
Pb	0.04	0	0
Sn	0.04	0	0
Ti	0.07	0.1	0
Zn	0.24	0.06	0

4. Results

4.1. Thermodynamic Rarity Assessment

From a list of nearly 800 car part numbers containing metals, 40 were identified as critical, applying both indicators described in the methodology: thermodynamic rarity [kJ] and rarity intensity [kJ/g]. Then, the list was further reduced according to other criteria. The engine, battery, and gearbox were excluded as they are too complex (including many different sub-parts), and authorized treatment centers usually keep them for eventual reuse. It is essential to highlight that iron and aluminum were excluded from the list of all elements found in the car selected. Both metals are already almost fully recovered with conventional vehicle recycling processes, and this helps to focus on those that are currently lost or downcycled.

This pre-selection was further reduced to 11 car parts based on a preliminary recyclability assessment, considering the possibilities of separating to a reasonable extent: (i) iron and steel alloys; (ii) aluminum; and (iii) non-ferrous metals (such as Cu, Zn, Pb or PGMs). The selection of these parts was also made considering: (1) the dismantling possibilities of the components of each part and (2) making sure that these are representative of a broader amount of car parts. This last part is especially crucial to apply the same recycling processes to the given selection and other valuable parts. All the selected car parts, except one, correspond to electric and electronic equipment, confirming the importance of this type of car parts in terms of critical metal content. In addition, the side car part was selected for considering another type of car part. This part is composed of several types of steel alloys. Thus, it is a good example to evaluate the dilution of all these alloys once the car is recycled and can be used as a "bad example" of "design for recycling".

For each of the 11 car parts, information regarding the composition in terms of metals and metallic compounds was analyzed in detail in the Material Data Sheets, based on the information provided by the MISS database. This is an important step for calculating the recyclability, given that it depends on the composition in terms of the chemical compounds and how these are found in the part.

The replicability potential was also assessed by evaluating the number of car parts produced every year by the Volkswagen group. Hence, the assessment is not limited to the car selected but further Volkswagen group models. Table 4 shows a summary with data about the selected parts. As can be seen, different types of electronic car parts were selected, including actuators, control units, sensors, and wiring, for making the assessment as complete as possible.

Table 4. Summary of some key aspects of the selected parts.

Part Name	N° of Million Units Produced/Year	Rarity Intensity (kJ/g)
Generator	3.6	71.54
Infotainment unit	0.5	386.19
Dashboard	0.2	367.46
Additional brake light	1.4	354.48
Exterior mirror	0.4	230.21
Air quality sensor	3.6	346.8
Cable shoe	0.5	352.43
Rain sensor	6.4	431.08
Speed and ABS sensor	14.6	450.91
Wiring for battery	0.16	319.98
Side	0.32	39.00

4.2. Recyclability Assessment

4.2.1. Recyclability Per Fractions (Non-Ferrous, Ferrous, and Aluminum)

Some important metals are not recovered along the metallurgical process applied for the non-ferrous fraction (Table 5). For instance, tantalum, which is present in the capacitors of the PCBs, is a critical metal that cannot be recovered since it is collected from the slags of the process because of its thermochemical properties. The same happens for rare earth elements (REEs). Specifically, the neodymium of the magnets used in the motors, moving the needles of the infotainment unit. Its thermochemical properties make its recovery impossible from the non-ferrous fraction, due to them reporting to slag if processed through the routes presented in this paper. One can also argue to use hydrometallurgy options, but then separation of all materials must be pushed to their limits to ensure that during hydrometallurgy economics and environmental impact are not impaired by, for example, having to deal with complex residues such as jarosite, Goethite, and all other compounds co-precipitated. Thus, the disassembly of these magnets is required so that the neodymium is not lost. However, reaching the magnet in the motor is not straightforward. Therefore, a new design of the motors that facilitates the disassembly of the magnets is required. Furthermore, there are some parts whose non-ferrous fraction contains large quantities of iron and aluminum that cannot be removed. This occurs especially in the "exterior mirror", "generator", and components that are impossible to disassemble, such as the "speed and ABS sensor" or "rain sensor". Here, the iron and aluminum cannot be recovered along the metallurgical process for the non-ferrous fraction. Therefore, a conventional shredding and physical separation of some components where the concentration of minor metals is low, e.g., the generator, is recommended.

Table 5. Summary of the elements recovered from the non-ferrous fraction represented here in elements but must be considered in the context of the alloy, compound, or pure metal that is produced. Percentage expressed in mass terms.

	0–25% Recovery	25–50% Recovery	50–75% Recovery	>75% Recovery
Non-ferrous fraction	Al, Ba, B, C, Ce, Cr, Dy, Ga, H, Fe, Li, Mg, Mn, Mo, P, Si, Sr, Ta, Tb, Ti, W, V, Yb, Y, Zr	-	Ge, Sn	Sb, As, Bi, Cd, Co, Cu, Au, In, Pb, Pd, Pt, Ru, Ag, Ti, Zn

For the ferrous fraction, an effective separation should be carried out so that the impurities of the molten steel generated are as low as possible. The impurities that can be removed from the steel fraction during recycling are shown in Table 6. Steel scrap with a high impurity content will generate an impure steel alloy after the EAF. Depending on the quality of the steel alloy to be produced, it requires dilution with high-quality steel scrap or pure iron so that the final steel alloy can match the specifications. For instance, the pure iron required to obtain the three steel alloys considered is 0 for the low-quality alloy, 1052 t/h for the medium-quality alloy, and 8006 t/h for the high-quality alloy. Considering that the quantity of steel entering the alloying ladle is lower than 2 t/h, the amounts of iron required for dilution are shocking. This shows that the quality of the alloys is downgraded after every recycling process. The only way of bringing that alloy back to higher quality is to dilute it with pure metals or high-quality alloys or develop smart sorting. Therefore, the downgrading of metal alloys hinders the recycling infrastructure from not being dependent on primary resources. Additionally, this downgrading may generate a large resource consumption and environmental impact associated with primary metallurgy.

Table 6. Elements that can be removed from the steel and aluminum alloy during their recycling process.

	Elements Removed from the Alloy	Elements Not Removed from the Alloy
Steel fraction [1]	Al, Ba, B, Pb, Li, Mg, Mn, Si, Ti, Zn	Cr, Co, Cu, Fe, Mo, Ni, Nb, V
Aluminum fraction [2]	C, Cl, H, Mg	Al, B, Cd, Cr, Co, Cu, Au, Fe, Pb, Mn, Ni, Sn, Ti, Zn

[1] The iron reporting to the slag as FeO_x is low, around 1%. [2] The aluminum reporting to the dross is around 5%.

However, this downgrading can be reduced if a proper pre-treatment, sorting, and separation of the different alloys and impurities of the ferrous fraction, is carried out. To do so, an efficient "design for recycling" must be conducted. For instance, the "side" has over 40 different steel alloys ranging from 95 to 99.6%, which enter the metallurgical process altogether downgrading the quality of the recycled alloy. Therefore, this component should be more homogeneous so that the quality of the final alloy is not downgraded when it is recycled. If this is not possible due to functionality issues, the design of the car part could be reconsidered to allow good separation of the different steel alloys.

As for the aluminum fraction, impurities have a more important impact on aluminum recycling because there are fewer possibilities to remove them from the alloy, especially as aluminum is particularly reactive (Table 6). First, it is more difficult to remove them from the molten aluminum. Second, some impurities such as plastics can react with the molten aluminum and generate losses. The previous separation of all plastics should be the ideal situation. However, it is not always possible, considering that a lot of parts are glued. For instance, the plastic covers of electronic units are glued to the electronic boards.

Therefore, an efficient pre-treatment of the aluminum scrap is essential so that the aluminum alloys produced are as pure as possible. The aluminum fraction of the infotainment unit has wrought aluminum purity as required for that specific part, while the generator one has a high copper content (4%). Therefore, mixing them downgrades the quality of the aluminum alloy, and a large quantity of virgin aluminum would be required to bring the alloy back to its initial quality, as required by the aluminum alloy. For instance, simply as a theoretical example, the 374 kg/h of molten aluminum generated from the re-melting and refining of the aluminum fraction, including all its dissolved impurities, would require 18,000 t/h of pure 100% aluminum (theoretical example as usually electrolytical aluminum is max. 99.9% pure) to produce aluminum of high purity, i.e., >99.9995 5N5 (see [71]). Obviously, this is all subject to the solution chemistry of different phases as predicted by FactSage, but, in the end, it is dilution chemistry. The exergetic consequences of this dilution have been discussed by Hannula et al. [48] using among other Gibbs free energy minimization to calculate the different species possible in alloy and solids in the salt slag.

Thus, creating 5N5 aluminum for dilution obviously has an additional exergetic footprint above that of the already high exergetic footprint of electrolytic aluminum (max 99.9% Al). Therefore, as explained for the steel fraction, the aluminum alloys should be very well identified so that an efficient dismantling and disassembly can be carried out to avoid exergetic downgrading. This would improve the classification of the different aluminum alloys based on their quality, avoiding the problem of mixing them as it is done through the current fragmentation technologies. Thus, the key also from an exergetic consideration would be always to minimize exergetic downgrading, by ensuring that product designs minimize possible contamination of alloys by functional material combinations in products [16].

Another aspect that should be considered during the recycling of aluminum is the number of plastics introduced to the feed. The carbon, hydrogen, and other compounds such as oxygen and chlorine react with the molten aluminum to generate carbides, hydrides, oxides, or chlorides, generating substantial aluminum losses since these compounds would report to the dross.

4.2.2. Overall Recyclability and Potential Revenue

Table 7 summarizes the metal recyclability of the car parts analyzed in terms of mass and thermodynamic rarity. Here, all metal fractions are considered (ferrous, aluminum, and non-ferrous). By comparing the recyclability values, interesting conclusions can be drawn. The generator tops the list, mainly due to its high copper content and many components produced. Even though the recyclability potential of the generator using dedicated metallurgy is low in mass terms (49%), expressing it in rarity terms, the obtained value is high (88%). The low mass value is due to the iron lost in the non-ferrous fraction because separating copper and iron in the rotor and stator subcomponents was impossible through dismantling. Therefore, fragmentation (the current recycling procedure) is the best option to recover the maximum amount of raw materials for this specific case. The second most important car part is the infotainment unit, which contains a high amount of valuable raw materials. Once it is adequately dismantled, the recyclability of the infotainment unit is excellent in mass terms (over 90%). However, measured in rarity terms the recyclability dramatically decreases due to the loss of tantalum (located in PCBs). Noteworthy to mention is that tantalum represents almost 60% of the thermodynamic rarity of the infotainment unit. The same happens with other car parts on the list (dashboard, air quality sensor, and rain sensor), which show lower values in thermodynamic rarity terms because of the loss of tantalum. In the case of the additional brake light, the recyclability drop in thermodynamic rarity terms responds to the loss of gallium. Worth mentioning is also the dashboard, as its raw material content is remarkable even if the number of units shared by different models of the VW group is low. The recyclability of this component is rather low compared to the rest, both in mass and thermodynamic rarity terms, but could be improved through eco-design by avoiding the loss of tantalum and neodymium. Furthermore, due to the large amount of speed and ABS sensors produced in the VW group, these car components also have a very high raw material value per year. Albeit their recyclability in mass is very low (21%) due to the loss of iron in the non-ferrous fraction, expressed in thermodynamic rarity terms the recyclability is high (94%), given that tantalum is not contained in this car part, and thus it is not lost in the recycling process.

In addition to the recyclability results, it is fundamental to calculate the potential economic revenue by properly treating the non-ferrous fractions of the ten car parts (the side car part is excluded). To this aim, the potential revenue for each car part is calculated by multiplying the recycled quantities obtained after the non-ferrous recycling by the economic value of the different commodities. Considering all models of the VW Group including the given car part and assuming that all cars can be collected and sent to the appropriate recycling plants at EoL, the maximum value obtained for the recycled commodities would be up to 18 €/car, as shown in Table 8.

Table 7. Summary of the recyclability of the selected car parts.

Part Name	Recyclability in Mass (%)	Recyclability in Thermodynamic Rarity (%)
Generator	49	88
Infotainment unit	91	37
Dashboard	63	21
Additional brake light	82	24
Exterior mirror	77	58
Air quality sensor	85	14
Cable shoe	94	94
Rain sensor	84	21
Speed and ABS sensor	21	94
Wiring for battery	90	93
Side	97	85

Table 8. Summary of the potential revenue for the selected car parts.

Part Name	Potential Revenue (€)
Generator	6.72
Infotainment unit	6.51
Dashboard	2.09
Additional brake light	0.27
Exterior mirror	0.72
Air quality sensor	0.02
Cable shoe	0.02
Rain sensor	0.05
Speed and ABS sensor	0.20
Wiring for battery	1.40

We can now compare the increase in the recovered materials' value of the presented recycling processes concerning conventional recycling if the ten car parts analyzed (excluding the side) are dismantled from the car and appropriately disassembled and recycled. Thus, the proper recycling of the given ten car parts would increase the raw materials' value by 6%, as presented in Table 9. This figure obviously increases if more car parts that contain minor metals are treated.

Table 9. Increase in raw material value through the improved recycling process.

Current Recycling Process—Fragmentation and Material Recovery at 85% of Steel, Aluminum, and Copper			
	Metal input (kg)	Metal output (kg)	Revenue (€/car)
Steel	654	556	130
Aluminum	54	46	57
Copper	9	7	35
		Total	222
Improved Recycling Process—10 Selected Car Parts are Appropriately Recycled			
	Metal input (kg)	Metal output (kg)	Revenue (€/car)
Steel	654	556	130
Aluminum	54	46	57
Copper	7	6	30
Non-Ferrous Fraction Recovered from the Selected Car Parts			18
		Total	235
Increase in Raw Material Value Per Car through the Improved Recycling			6%

It is important to mention that dismantling costs have not been taken into consideration in this study, and therefore we are addressing potential revenues and not the overall profitability of the recycling processes. Dismantling costs will be analyzed in future research to be carried out by the authors, due to their relevance in the profitability of the whole recovery process.

5. Discussion

The purpose of this study is to gain a better understanding of the most valuable car parts in terms of the metal content and recyclability potential. As the literature suggested, we found car electronics show the highest concentration of rare metals, mainly due to the printed circuit boards [24,28,31,32,34,36–38]. Particularly, control units, sensors, and actuators have been identified as the most significant rare metal-containing components, coinciding with previous studies [31,32,37,40]. In addition, we address the recyclability potential considering a product-centric-approach. Specifically, we have applied the HSC Chemistry software for the first time to assess the recyclability of car parts. In this way, the real recyclability potential can be obtained, in contrast to the material-centric approach. By doing so, we have verified that more than 75% of the precious metals in Printed Circuit Boards can be recovered by applying the copper metallurgical route. Nonetheless, a significant amount of other metals (e.g., tantalum and rare earths) are lost when implementing state-of-the-art recycling technologies, owing to the design of the car parts. Moreover, by assessing the recyclability of the metals contained in the car parts through thermodynamic rarity, it is possible to consider the physical quality of the metals recovered.

As mentioned above, the identified valuable car parts correspond to those detected in previous studies. Even though other works perform the assessment in economic terms, considering the economic value of the metal, the results are similar given that rarity mostly correlates with the economic value [72]. Indeed, the scarcer and more difficult to process a particular metal is, the stronger the correlation with price. This is so because sooner or later economics meets physics. Rare and valuable metals, for instance precious, platinum group, and rare earth metals are embedded in printed circuit boards and magnets. For this reason, car parts containing them, such as control units, actuators, and sensors are the most valuable ones. Moreover, applying the thermodynamic rarity as a resource use indicator instead of the price is a more robust method, because of the volatility and arbitrariness of the latter.

Regarding the recyclability potential, our study provides unique insight compared to previous work. In this research, a product-centric-approach, which considers the combinations of the elements within the car part, is applied in contrast to a mass-centric approach. By doing so, we are able to determine the real recyclability potential of the selected car parts, and not merely calculate a theoretical recycling potential. In addition, the combination of the product-centric approach with the thermodynamic rarity methodology has been applied in this article for the first time. Thus, this assessment allows us to detect improvements in the design of the car parts, in order to enable the future recovery of metals.

The main limitation of our study consists of the processing of the data source. The composition of the car parts comes from the IT tool MISS, which contains extensive and detailed information. Nonetheless, feeding this information into the HSC Chemistry software requires considerable work, because of the need to manually process the data into the proper format. In this regard, we are working to automate the process, so it is less time-consuming and thus more efficient.

In terms of future research, it would be useful to extend the current findings by examining the recyclability potential according to different disassembly levels of the selected car parts. Furthermore, we plan to carry out the same analysis on specific car parts contained in electric vehicles, providing valuable insights for future circular economy strategies.

6. Conclusions

This paper has shown how exergy analysis performed with thermodynamic rarity indicator can help identify the most critical parts in terms of metals used in a car using the composition of the SEAT León Generation III Diesel car as a case study. This assessment and a detailed recyclability analysis, using a product-centric approach, which considers the full compositions of all materials, products, and functional linkages between all materials, is vital to understand the EoL of products and gaining valuable insights for "design for recycling". Notably, in this paper, we have demonstrated that the potential to recover most of the critical metals currently lost or downcycled through conventional recycling processes relies on the disassemblability potential or, in other words, modularity of each component and further treatment in dedicated recycling plants. If we do so, only by treating appropriately the ten electronic car parts analyzed (excluding the side which is already sent to a ferrous smelter), it increases the raw materials recovered value of the car by 6%.

Excluding the side part, all car parts selected in the study as valuable are electric and electronic equipment. This is logical as these are precisely the components in which more critical raw materials are used (excluding the battery of electric cars, which was not the object of analysis). And currently, these materials are being downcycled as they are not functionally recovered. This aspect should be specially considered. More eco-design measures should be implemented in cars to easily recover critical elements so they can re-enter the value chain. For this reason, a product-centric-approach has been applied in this study in order to estimate the real recyclability potential of selected car parts, in contrast to previous studies with a material-centric-approach. Furthermore, the methodology presented in this paper is not restricted to cars or other vehicles but can be used for any product to produce valuable inputs regarding metal recovery and recycling processes. Here the modular design shows how to order functional materials in modules in a manner that the material mixtures can be optimally "unmixed" into valuable compounds, alloys, materials, energy recovery, etc., so that the material loop can be optimally closed to produce products that can find their way back into the same or similar car parts. This would be a true circular economy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15010091/s1. Table S1: Metal composition of the selected car parts (in mass). Table S2: Overall rarity (kJ) and rarity intensity (kJ/g) values of the selected car parts.

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