D6.4: Validation of pilot plants circularity level

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EXECUTIVE SUMMARY

This deliverable presents findings regarding the validation of circularity in three pilot plants developed during the project: the semi-automated printed circuit boards (PCB) disassembly pilot, the hydrometallurgical pilot, and the in-mold electronics (IME) pilot. These pilot plants were designed to address the disassembly critical components from PCBs, the recovery of valuable materials (especially silver) through hydrometallurgical recycling processes and the valorisation of secondary materials in new generations of IME. Validation methods included thermodynamic rarity, life cycle assessment (LCA), and intrinsic economy value (IEV) indexes.

Regarding the semi-automated PCB disassembly pilot, a comparison was made between time (and thus economic cost) and recovered components. Despite potential lower profitability compared to manual disassembly methods, a significant percentage of critical components (such as tantalum capacitors) is recovered, by increasing the recyclability of almost 40% in terms of rarity compared with previous scenarios.

The hydrometallurgical pilot plant's efficiency and metal recovery were assessed based on thermodynamic rarity. LCD screens (with indium tin oxide as a primary metal composition) and IMEs (mainly containing silver) were tested, achieving a recovery ratio of 98.7% for ITO and almost 83% for IME, with high purity levels of the recovered metals, indium and silver respectively, represents high values compared to the current base case of recovering copper from traditional PCBs.

Lastly, the IME pilot plant was validated against a similar traditional component. Thermodynamic rarity, intrinsic economic value, recycling assessments and life cycle assessments were conducted to compare the two technologies' impacts. It has been shown that there is a reduction of almost 80% of the rarity of IME technology, while the IEV of this product represents only 7% of the traditional car part from SEAT.

With the results obtained, it has been possible to evaluate the circularity of the three pilot plants. It has been demonstrated that for the semi-automated PCB disassembly pilot, circularity in terms of rarity increases by 92%, while the IEV increases by 93%, compared with the base case.

For the hydrometallurgical plant, there is also an improvement in circularity in both indices. The circularity in terms of rarity increases by 96% for ITO and 80% for IME, while the circularity for the IEV increases by 88% for ITO and 77% for IME, respecting the base case.

These findings underscore the project's commitment to advancing circular economy principles in automotive manufacturing, demonstrating the feasibility and benefits of integrating innovative technologies for sustainable resource management and material recovery.

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1. Introduction

Circularity is defined as the concept of designing, producing, consuming, and disposing materials in a way that minimizes waste, increasing the reusability and recyclability, reducing the consumption of resources. The perfect circularity involves closed-loop systems, where materials and components are continuously circulating instead of being wasted after a single use.

The automotive industry is one of the largest consumers of materials in the world, due to the substantial volume of vehicles manufactured and the variety of metals utilized throughout the production process, as well as the significant quantities required.

Metals are not available as infinite resource, and thus, increasing circularity will also enhance the sustainability of this sector. Therefore, within the TREASURE project, efforts were aimed at improving the circularity of car components, especially those containing electronic components and critical raw materials. Given the complexity of vehicles, adopting a singular perspective on circularity is not feasible; instead, it necessitates multiple approaches (thermodynamic rarity, intrinsic economic value, life cycle assessment), with each perspective complementing the next step.

Accordingly, various pilot plants have been developed during the project with the aim of improving disassembly processes, enhancing the recoverability of metals after metallurgical processing, and redesigning printed circuit boards (PCBs) by application of IME technology for a lower use of critical raw materials and the improvement of recoverability at the end of the electronic component's life.

The assessment of the pilot plants will determine the circularity of the process, as well as the potential for reusing specific metals and related materials in the design of car electronics extracted from car components within the industry.

Accordingly, based on the information gathered from the three pilot plants, an evaluation will be conducted using various indices, including thermodynamic rarity, intrinsic economic value, recycling assessment and life cycle assessment (only for the design of new PCBs in-mold electronics). In some cases, comparisons will be made with traditional components. The following pilot plants have been evaluated:

- Semi-automated PCB disassembly pilot
- Hydrometallurgical materials recycling pilot
- IME eco-design and prototyping pilot

1.1. Scope of the deliverable and contribution to other WPs

The scope of this deliverable entails validating the circularity of the three pilot plants, which aligns closely with other deliverables within Work Package 6 (WP6), specifically the D6.1 Report on semi-automated PCB disassembly process, the D6.2 Report on bio-hydrometallurgical materials recovery, and the D6.3 Report on in-mold/structural electronics prototyping. Data derived from these deliverables will serve as the primary basis for assessing the circularity of the pilot plants. However, the development of these deliverables is dependent on preceding ones. For instance, the D5.2 Simulation of the semi-automated PCB disassembly process feeds D6.1, while D5.4 contributes to D6.2, and D5.7 aids in constructing D6.3. Furthermore, Work Package 4 (WP4) has been pivotal in providing guidance on understanding the design and manufacturing processes of vehicles, which is essential for developing the pilot plants. The methodologies for

EoL assessment as detailed in D3.3 and D5.4 have been applied for recycling assessment and calculation of recycling KPIs.

The outcomes of previous activities within the TREASURE project have been utilized to develop the pilot plants. The impact of TREASURE is now demonstrated by validating the networked pilot plants for their technical capabilities, with a focus on determining the extent to which circularity is improved and the reduced utilization of critical raw materials.

Considering the manner in which vehicles and their components are designed, various key parameters for circularity will be assessed. These parameters encompass disassembly times, routes, recycling options, material compositions, production processes, technical feasibility, economic and environmental assessments, and the rate of metals recovered, among others.

2. Description of the pilots

2.1. Semi-automated PCB disassembly pilot

A cobot is defined in the ISO/TS 15066:2016 (ISO/TS 15066:2016 - Robots and robotic devices – Collaborative robots. 2016. url: https://www.iso.org/standard/62996.html) as “a robot that can be used in a collaborative operation”, defined in turn as an operation “where purposely designed robots work in direct cooperation with human within a defined workspace”.

The freedom offered by cobots, which may operate without any obstructions close to the operator, makes it possible to design procedures that, in turn, are versatile and can adjust to various disassembly requirements. Focusing on the disassembly tasks to be completed for the project, the cobot can assist the operator in automating the processes when it comes to disassembling various types of PCBs. Though the number of PCBs that may be dismantled is quite vast, a human is still required to direct the cobot when it comes to a new set of tasks that need to be carried out, at least in the early stages of the process development.

In the process of semi-automated electronic component disassembly developed by Politecnico di Milano, the operator is supported by a cobot in two distinct phases. Initially, the operator undertakes the dismantling of the first type of components, namely the surface-mounted devices (SMDs). Subsequently, the operator proceeds to disassemble the through-hole components. During the removal of the SMDs, the cobot, guided by machine vision algorithms, desolders the electronic components from the printed circuit board (PCB) using an air-desolderer end-effector. Concurrently, the operator separates these components from the PCB using a specialized tool. Upon completion of this procedure, the PCB is placed on a preheating plate, and the operator removes the through-hole components easily by using appropriate disassembly tools.

More information related to the Cobot can be found in D6.1 named “Report on semi-automated disassembly ”. Figure 1 shows the laboratory where the pilot plant is located at Politecnico di Milano, while Figure 2 shows the new Universal Robot acquired specifically for the Treasure Project and used for PCB disassembly actions.

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Figure 1. Computer Vision Laboratory at Politecnico di Milano.

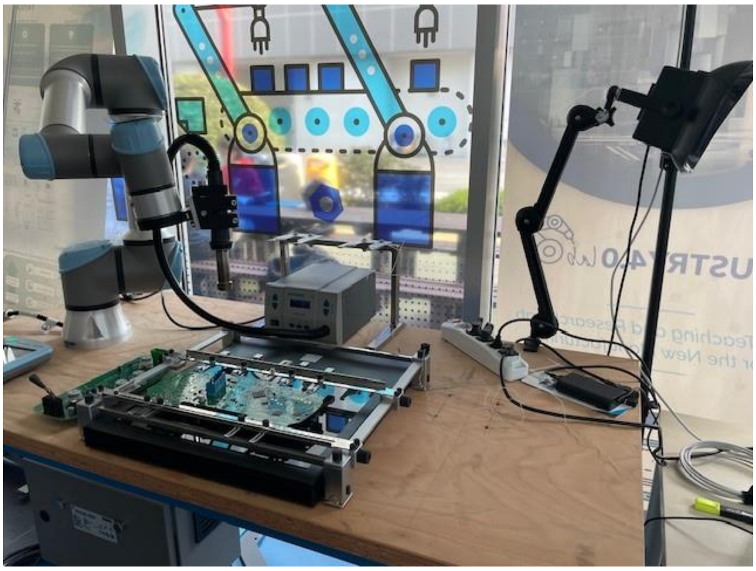

Figure 2. UR5e applied for PCB disassembly.

2.2. Hydrometallurgical materials recycling pilot

The hydrometallurgical pilot plant used during the Treasure project was constructed under a previous European project, H2020 FENIX, with grant agreement No. 760792. Its aim was to produce metal powders through the treatment of WEEE.

Within TREASURE, new implementations were needed to adapt this hydrometallurgical plant to the requirements of the project and to make it more flexible for processing different types of materials. A Declaration of Conformity (CE) was issued for the reconfigured plant (serial number 19003), which was originally constructed in 2019 and underwent subsequent revamping in 2022. This declaration ensured compliance with the provisions outlined in European Directive 2006/42/EC. The main implementations carried out are listed below:

- Addition of two chemical reactors with different characteristics.
- Addition of different filtration systems, such as cartridge and bag filters.

- Movement of the chemical storage tanks to an external area directly connected to the plant by a pipeline.
- Automatization of all the valves according to Industry 4.0
- PLC software revising with specific recipes for the materials of interest for the TREASURE project.

All the details and specifications of the hydrometallurgical pilot plant can be found in deliverable D5.4, named "Materials recovery pilot plant reconfiguration, testing & optimization". Figure 3 illustrates the layout in 3D of the pilot plant. Figure 4 shows the reactor incorporated to the pilot plant develop for TREASURE project.

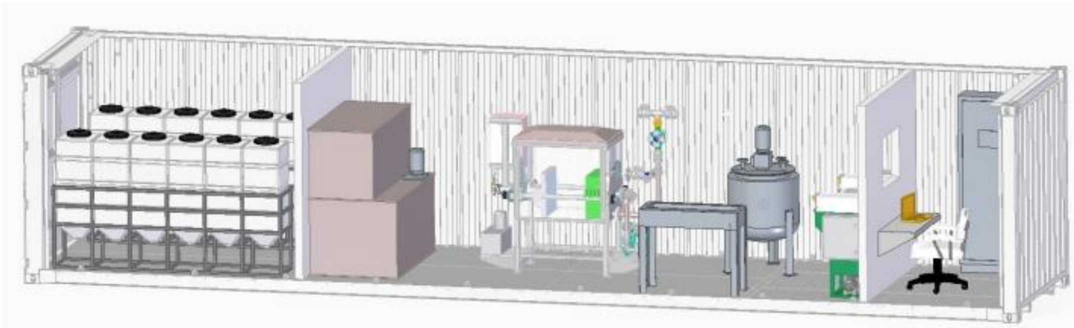

Figure 3. Layout of the hydrometallurgical pilot plant.

Figure 4. Reactor added to the pilot plant of TREASURE project.

The TREASURE pilot plant underwent testing and validation for two key recovery processes. Firstly, it was utilized to recover indium tin oxide glass from LCD displays commonly found in cars. Additionally, it was tested to evaluate the recoverability of silver from the in-mold electronics that were designed and produced in pilot 3, as described in section 2.3. Below, we provide a brief description of these two recovery processes.

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2.2.1. Recycling of indium-tin oxide glass from LCDS (In recovery)

The developed hydrometallurgical process aimed at selectively recovering indium from indium-tin-oxide glass (ITO glass) of liquid crystal displays (LCDs) according to a minimal liquid discharge (MLD) approach.

The ITO glass is preliminary washed with water to remove liquid crystals. This step is crucial to prevent any negative impact on the recovery stage of indium from the leach liquor. The water can be reused for washing up to 5 times before being discharged to the wastewater treatment section.

To dissolve indium, the cleaned ITO glass underwent a multistage counter-current leaching (solid-liquid extraction) process. It consists of three steps using a leaching solution of sulfuric acid (0.1 mol/L) that must be performed at 60 °C. Fresh leaching solution enters from one side (third step), and fresh solid (ITO glass) enters from the opposite side. The main advantages are a more efficient use of reagents and highly concentrated leach liquor from each it is easier to recover the indium.

Electrodeposition occurs at the following operative conditions: voltage = 2.5 V, current density 50 A/m2, graphite as cathode material, and titanium coated by a mixed oxide as anode. The indium metal powder has been recovered with a purity of 99.3%; impurities are due to tin, and calcium sulphate.

By increasing the free acidity after electrodeposition, up to 80% of the solution discharged from indium can be recycled. This recycling can be done in the counter-current leaching section, with partial sulfuric acid make-up (50%). This approach not only reduces waste and environmental impact but also saves costs leading to a more sustainable and profitable process. The remaining 20% of the solution and the water used to wash the ITO glass are sent to the wastewater section.

The wastewater treatment process involves a stage where lime (10%) is added to neutralize the solution and transfer the pollutants in the sludges. This results in a water quality that meets the standard for direct discharge to sewerage at low costs. Additionally, the treated water can be reused within the plant if necessary.

Water consumption of the process is 1960.3 kg per 1 ton of ITO glass, resulting in a water footprint of 1440.5 kg of water/kg indium product.

Table 1. Inputs and outputs of the process [kg].

Inputs		Outputs	
ITO glass	1,000	Glass	938
Freshwater	1,960.3	Indium powder	1.3
Sulfuric acid (50%)	79.9	Humidity	93.9
Lime (10%)	109.5	Treated water to sewerage	1,824.2
		Wet sludges	292.3

Table 2. Efficiency of the process and the equipment.

Indium recovery	98.7%
Indium powder (Final product)	In: 99.3%, Sn: 0.58%, CaSO4: 0.12%
R102 (leaching operation)	In recovery: 99.5%
CE102 (electrodeposition operation)	In recovery: 99.2%

2.2.2. Recycling of in-mold structural electronics (Ag recovery)

The developed hydrometallurgical process also aimed at recovering silver from in-mold structural electronics (IMSEs), developed under TREASURE project (pilot 3, described in section 2.3), according to a minimal liquid discharge (MLD) approach.

The hydrometallurgical process includes a two-step leaching (solid-liquid extraction) for the dissolution of silver and the subsequent recovery of silver from the solution by electrodeposition. The leaching solution is composed of thiourea (20 g/L) and ferric sulfate (6 g/L as Fe^{3+}) in a sulfuric acid media (0.2 mol/L). The second step of leaching is conducted by reusing the liquor solution obtained by the first step with a make-up of chemicals based on the amount that has been consumed, measured by titration. Electrodeposition occurs at the following operative conditions: voltage = 1.2 V, current density 50 A/m2, silver as cathode material, and titanium coated by a mixed oxide as anode. The silver metal powder has been recovered with a purity of 98.6%; impurities are due to iron, copper, and calcium sulfate.

The discharged silver solution is not wasted, but rather, it can be reused in a new cycle of the process, promoting a sustainable approach. This is made possible by the partial regeneration of thiourea and the increase of free acidity during the electrowinning, with a make-up of chemicals. The process can be conducted in this way for three cycles, significantly reducing the water footprint.

The wastewater treatment section is a crucial part of our process, ensuring that the water used is treated to the highest standards. It includes a Fenton treatment to decompose organic substances, and a lime treatment for an overall reduction of COD of 94% and of iron that exceeds 99%. This ensures that the water obtained from the wastewater treatment section is of high quality, with 70% of it being reused in a new batch of the hydrometallurgical process, and the rest being discharged in sewerage as the COD and metal content are below the required limits.

This way, water consumption was reduced to 464 kg to treat 1 ton of IMSEs. The water footprint equals 60.3 kg of water/kg silver product.

Table 3. Inputs and outputs of the process [kg].

Inputs		Outputs	
in-mold structural electronics	1,000	Polycarbonate	984
Fresh water	464.3	Humidity	47.2
Thiourea	130.7	Silver powder	7.7
Ferric sulphate	449.6	treated water to sewerage	

Sulfuric acid (50%)	131.5	Wet sludges	667
Hydrogen peroxide (30%)	571.7		
Lime (10%)	147.2		

Table 4. Efficiency of the process and the equipment.

Silver recovery	82.9%
Silver powder (Final product)	Ag: 98.6%, $CaSO_4$: 1.07%, Fe: 0.26%, Cu: 0.10%
R102 (leaching operation)	Ag recovery: 84.2%
CE102 (electrodeposition operation)	Ag recovery: 98.5%

2.3. IME eco-design and prototyping pilot

A roll-to-roll line for printed electronics has been developed at Holst Centre for prototyping purposes and research on roll-to-roll printing, assembly and optimization of processing. In the EU Treasure project, it has been looked into the details of the printing process, the power usage and its applicability to a specific rigid form of printed electronics: in-mold structural electronics (IME).

The pre-pilot line consists of two sections, each with winding and unwinding stations for rolls of plastic foil. These sections were not developed to provide a continuous process from printing of graphics to assembly of SMT components. This pre-pilot line was designed for research & development of printed electronics and is suitable for low volume prototyping. The power usage per station is provided in the corresponding figures for the graphics line and the SMT assembly line. It was opted for a single rotary screen for printing in the first section of the line, as each layer needs to be optimized for printing and drying. Industrial production using roll-to-roll methodologies would / could focus on multiple rotary screens and short bursts of drying, followed by a stage of more extensive drying. This line runs at a speed of at least 5 meters per minute.

Further details and information about this pilot plant can be found in deliverable D5.7, titled "In-mold/structural electronics pilot reconfiguration, testing & optimization." Additionally, Figures 5 and 6 have been included to illustrate some elements and components of the pilot plant.

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Figure 5. Middle part of the line with the curing box of of the pilot plant.

Figure 6. Elements inside of the curing box

Additionally, Figure 7a and Figure 7b illustrate the final result obtained from the pilot plant developed under TREASURE project.

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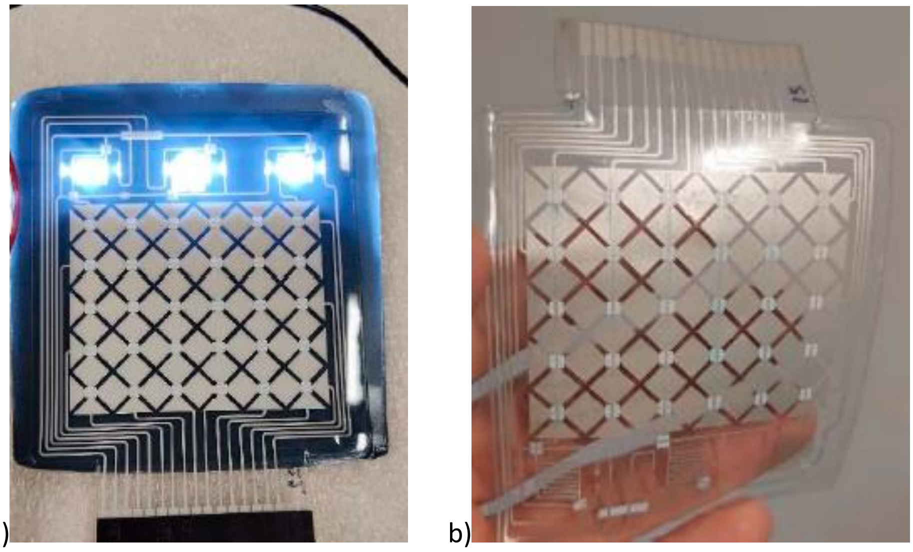

Figure 7. IME developed by TNO and Walterpack. a) device with LEDs, b) foil disassembled

3. Methodology

3.1. Methodological approach

For all case studies, the first step is to establish a base case for comparison. This base case represents the business as usual found in the current automotive sector. The three pilots are then evaluated relative to this base case.

The pilots are applied to and evaluated for specific car parts. The exact composition of all car parts are obtained from the MISS database provided by SEAT. Accordingly, the metallic and plastic characterization of the car part in mass terms (%wt) can be obtained, as well as the total detailed composition based on all elements/compounds/materials present. Particularly for the metals, as most of them are not in the form of the metallic element, but as part of a compound, a conversion through the corresponding molecular weights is carried out to perform rarity assessment. In recycling assessment simulation, the compound composition is applied. It should be noted, however, that the exact composition in terms of compounds and not elements has been considered when the virtual recyclability assessment (as explained further down in the text) has been carried out. In the detailed recycling assessment as applied in pilot 3 on the basis of the recycling simulation models as developed by MARAS based on BAT industrial (metallurgical) processing infrastructures and flowsheets, the full compositional detail of the base case and the IME is included in order to render succesfull and reliable recycling assessment results.

In all three pilots, a significant focus is placed on enhancing the recyclability of the various components under assessment. The cobot developed by POLIMI aims to enhance disassembly, thereby improving recyclability and recovering valuable components that might otherwise be lost in metallurgical slag or landfills. Alternative processing options relative to existing ones were explored by the UNIVAQ. And in combination with the cobot tools a new solution was explored. Lastly, the IME pilot developed by TNO and Walterpack, in addition to improving eco-design to reduce the use of critical raw materials in its production, is designed to be more easily recyclable.

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Even if only one pilot is exclusively devoted to develop specific recycling processes for car electronics (pilot 2), we were able to determine the improvement of the recyclability of the cobot and the newly created in-mold electronics parts through the application of recycling simulation modelling in which the full range of existing BAT (best available technique) metallurgical recycling processing infrastructures have been modeled. By application of these recycling simulation models different recycling routes/flowsheets for the processing of the car parts can be assessed and best recycling options can be defined for different car parts, disassembly levels and recycling objectives This simulation basis is similarly applied to design multi-million dollar plants and allows to virtually simulate plant performance and different flowsheet set-ups and was designed by partner MARAS and has been used to test the recyclability of several car parts such as the dashboard or the infotainment, according to different levels of disassembly (which include the cobot in the last stage), as described in D3.3. In the same way, the simulation based approach to recycling plant performance was applied to assess the recyclability of the In- Mold Electronic part (IME) developed in pilot 3. The predictive nature of simulation models allows for the physics-based estimation of how life-cycle systems respond to changes in, among others, feed material compositions, process configurations, operating conditions, and the technology used. Process simulation thereby enables DfR—the system-wide effects of product design changes on resource consumption and sustainability can be evaluated as early as during the product design phase so as to maximize recyclability. The simulation approach is exceptionally suitable to assess pilots, as the parts considered are so small in quantities and low in level of recoverable metals, that these always will have to be processed as part of a larger input (on the back of other materials) and can hence not be tested in industrial practice at these small scales as is also explained below for the recycling assessment in pilot 3.

3.2. Performance assessment indices

In addition to a mass-based assessment of the recyclability of each individual pilot, the validation has been conducted using various indices that go beyond a mass-based assessment. The recycling simulation models at the same time are based on energy as well as exergy balances. Accordingly, aspects of circularity, environmental performance, and economic enhancement are assessed.

Consequently, a set of parameters must be considered to translate the outcomes of the processes into the selected indices chosen for each case. The indicators that will be considered include thermodynamic rarity, intrinsic economic value (IEV), life cycle assessment (LCA) and recycling KPIs that are explained below.

3.2.1. Thermodynamic rarity

Thermodynamic rarity is an indicator grounded in the second law of thermodynamics, evaluating the physical quality of materials concerning their scarcity in the Earth's crust and the energy intensity associated with their extraction and refining. Its advantage over mass-based indicators lies in its ability to avoid comparing dissimilar materials, recognizing that, for instance, a ton of iron holds a different perceived value than a ton of gold. Unlike monetary indicators, it remains stable despite market volatilities and holds universal applicability.

Thermodynamic rarity values for each metal can be found in Table 5, with further explanation provided in other deliverables such as D3.1. Utilizing thermodynamic rarity as an indicator enhances the quality of processes aimed at recovering critical raw materials. For instance, while a minimum of 85% recycling is required for vehicles, metals like aluminum, iron, and copper, constituting over 95% of a car's mass, are more readily recyclable due to accessibility. However, recycling these metals can result in the loss of remaining, less accessible metals, leading to significant mineral capital depletion. Therefore, thermodynamic rarity enables efficiency calculation based on the quality of recovered metals rather than just quantity.

The information provided through MISS files makes it possible to characterize the car part not only considering its metallic content, but also in terms of its plastic content. All plastic types will be grouped into: PP, PA, PU, EPDM, PET, ABS, PC, PVC, POM, PVB and others and their corresponding share and thermodynamic rarity values calculated. This will be particularly relevant for the pilot 3 (design of IME), for which the thermodynamic rarity of polycarbonate (PC) needs to be considered, given the proportion of this plastic in these components.

Table 5. Thermodynamic Rarity values [kJ/g].

Ag	8,937	**Ge**	24,247	**Ru**	2,870,013
Al	661	**Hf**	32,364	**Sb**	487.9
As	427	**Hg**	28,707	**Sm**	732
Au	654,683	**In**	363,918	**Sn**	452
Ba	39.34	**Ir**	2,870,013	**Sr**	76.39
Be	709.9	**La**	336	**Ta**	485,911
Bi	545.6	**Li**	978	**Tb**	732
Cd	6,440	**Mg**	145.7	**Te**	2,825,104
Ce	620	**Mn**	73	**Ti**	203
Co	11,010	**Mo**	1,056	**U**	1,090
Cr	40.9	**Nb**	4,782	**V**	1,572
Cu	348.4	**Nd**	670	**W**	8,023
Dy	732	**Ni**	758	**Y**	1,357
Er	732	**Pb**	41	**Yb**	732
Eu	732	**Pd**	2,870,013	**Zn**	196
Fe	32	**Pr**	873	**Zr**	2,025
Ga	754,828	**Pt**	2,870,013	PC	70
Gd	4,085	**Rh**	103,087		

3.2.2. Intrinsic economic value (IEV)

Although thermodynamic rarity provides a physical indicator that measures the quality of the resources used in products, monetary indicators remain important for making strategic decisions. Therefore, we use the intrinsic economic value additionally as a way to evaluate the pilot cases.

Particularly, a method to evaluate recovery processes is to take into account the intrinsic economic value (IEV) of the materials to be subjected to the recycling processes.

The IEV of a specific material can be calculated based on its chemical composition and the market quotation of each element constituting it, according to the following formula:

$$\mathrm{IEV} = \sum_{i=1}^{n} m_i \times q_i \tag{1}$$

where m_i is the mass of a specific element determined by the chemical characterization in kg and q_i is the market quotation of the same element in €/kg. This product enables the determination of the IEV of each material. It also allows for the identification of the impact of each element on the overall IEV. This is a crucial step as it helps to identify the elements that have the most significant effect on the intrinsic economic value. Consequently, it becomes possible to determine the materials on which to focus the recycling process in order to obtain an economically viable process.

The performances of the developed recovery processes can be evaluated through an index that can be defined as $\mathrm{IEV}_{recovery}$, that is the economic value recovered with respect to IEV of the material. To be more realistic, however, it is also necessary to take into account the pureness and the forms in which these products are recovered from the recycling processes, particularly for the hydrometallurgical processes developed in pilot 2. Obviously, this affects the $\mathrm{IEV}_{recovery}$. To this purpose, an adjusted IEV index was first calculated, which takes into account the form of the recovered products, their purity, and their impact on the intrinsic economic value (Figure 3). The $\mathrm{IEV}_{adjusted}$ can be expressed by the following formula:

$$\mathrm{IEV}_{\mathrm{adjusted}} = \left(\sum_{i=1}^{n} \frac{p_i}{100} \times \frac{i_i}{100}\right) \times \mathrm{IEV} \tag{2}$$

where p_i is the purity of a generic product that is recovered by the process, while i_i is its impact on the IEV.

Additionally, when a product is not recovered in its metallic form but as a salt p_i is calculated also taking into account the ratio of the economic value of the salt that is recovered with respect to the economic value of the metal, so it must be considered a further depreciation. Therefore, before using the formula of equation 2 is necessary to adopt the following formula:

$$p_{i\ salt} = \frac{q_{i\ salt}}{q_{i\ metal}} \times 100 \tag{3}$$

Once the $\mathrm{IEV}_{adjusted}$ has been calculated, the $\mathrm{IEV}_{recovery}$ can be determined according to the following formula:

$$\mathrm{IEV}_{recovery} = \left(\sum_{i=1}^{n} \frac{r_i}{100} \times \frac{i_i}{100}\right) \times \mathrm{IEV}_{adjusted} \tag{4}$$

where r_i is the recovery of a generic element I, while i_i is its impact on the IEV.

The $\mathrm{IEV}_{recovery}$ index, defined by UNIVAQ as part of the EU treasure project, is an excellent tool to emphasize the economic value that can be re-introduced into the market instead of being lost. It is important to keep in mind that the method presented here is only meant to evaluate the performance of the hydrometallurgical processes, but there are many other aspects to be considered. These processes have proven to be highly sustainable from an environmental standpoint as well. They employ techniques that allow for the reuse of solutions multiple times through the make-up of some reagents. After multiple uses, the solutions are sent to a specific wastewater treatment section to obtain water with quality characteristics suitable to be reused in the recycling process. Therefore, these processes are developed in line with the minimal-liquid discharge (MLD) approach and have a low water footprint.

3.2.3. Circularity assessment

An improved circularity assessment that can be combined with a mass-based recyclability index uses thermodynamic rarity and the intrinsic economic value of the recovered metals. This approach gives more weight to physically scarce materials and/or valuable materials in monetary terms. The aim is to obtain the rate of circularity achieved with respect to the base case using both indices. As it is illustrated in Figure 8, two cases are compared, highlighting the circularity achieved in both the base case and the pilot plant assessed.

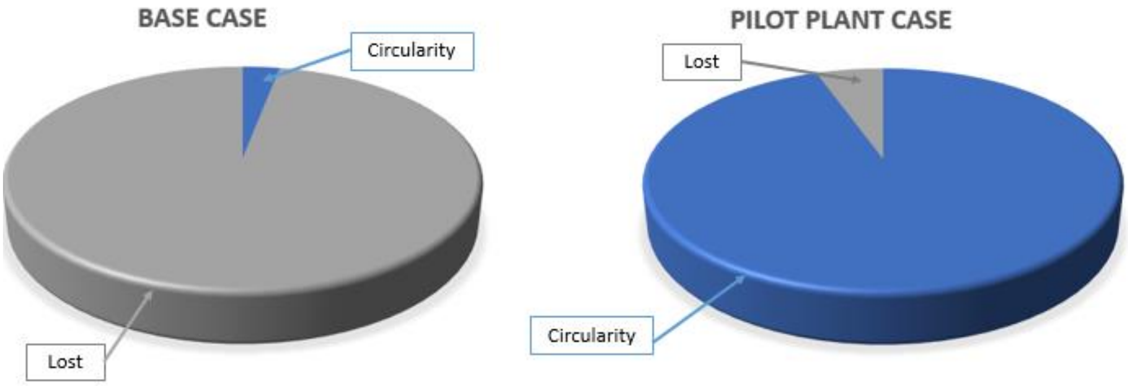

Figure 8. General explanation between a base case and a pilot plant.

The rigorous and flexible physics based recycling simulation based approach allows for the calculation of mass, energy, and exergy balances for the processing of all materials and elements, compounds, alloys, etc., present in products. These models, in which design parameters are also included, is based on industrial process physics, mass and heat transfer processes, reaction kinetics, and thermodynamics, as represented by, e.g., the software packages HSC Sim (2024) and FactSage (www.factsage.com). Whereas the thermodynamic rarity indicators are determined for elements, the exergetic balances in the models are based on full chemical composition of all materials and flows and at the same time cover the exergy of the entire processing chain of recycling. Hence, it permits the calculation of material-specific recycling rates, depending on, e.g., product, product category, and design. Maintaining material quality is crucial part of CE and recycling, thus minimize exergy dissipation through low energy quality or dilution. The unit for this is kW, the same as energy flow and hence harmonises the circular and recycling performance in one unit i.e. kW in the models. It allows for identification and minimization of residues and losses, which is crucial in CE indicators, i.e., to minimize the creation of entropy, across whole value chains of the CE in addition to closing material loops through EoL recycling. The digitalization platforms such as the recycling simulation models have evolved significantly to estimate the bulk, minor/technology element, metal/alloy, and material flows in addition to the exergy and energy flows of the complete CE system (Reuter, 2016).

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3.2.4. Life cycle assessment (LCA)

In addition to determine the circularity degree of the three pilots, the eco-design performance of the newly created In- Mold Electronic parts (IME) (pilot 3) will be assessed through the well-known Life Cycle Assessment (LCA) methodology.

Life Cycle Assessment (LCA) is a systematic and comprehensive method used to evaluate the environmental impacts of a product, process, or activity throughout its entire life cycle, analyzing different factors (energy, resources, water, etc.) across all stages of the life cycle—raw material extraction, manufacturing, distribution, use, and end-of-life disposal. It is a valuable tool for decision-making in sustainability and environmental management, providing insights into the environmental hotspots and opportunities for improvement along the entire life cycle of a product or service.

One of the key aspects of LCA is its ability to consider various environmental impact categories, such as greenhouse gas emissions, air and water pollution, resource depletion, and habitat destruction. This multidimensional approach allows stakeholders to understand the trade-offs and synergies between different environmental impacts and make informed decisions to minimize overall environmental harm.

LCA can be applied to a wide range of products and systems, including consumer goods, industrial processes, buildings, transportation, and energy systems. It can help identify opportunities for reducing environmental impacts considering resource use optimization in a circularity perspective. For example, LCA can inform design decisions to minimize material use, energy consumption, and emissions during the manufacturing phase, or guide end-of-life management strategies to maximize recycling and minimize waste generation. Thus, as it has been already mentioned, the pilot plant developed for designing new PCBs in-mold electronics will be assessed through the environmental impacts, since with LCA indicator is not possible to measure circularity.

In the case of TREASURE project, LCA has been used to model and assess the impacts of the In-Mold Electronic (IME) prototype developed by TNO and WALTERPACK, as described in D5.6 and D5.7, compared to a traditional car electronic component carrying out the same functionalities. This analysis has been performed in the broader context of the validation activities of TREASURE. From one side the analysis covers the need of the pilot to quantify, beside circularity improvements, the environmental impacts of electronics based on IME technology. From the other side, the analysis here reported serves the scope of testing the Eco-design Advisory functionalities with a real industrial case. The Eco-design Advisory, described in detail in D4.10, aims to support designers in the implementation of design improvements to enhance circularity and sustainability of electronics automotive sector: Design for Disassembly and Design for Recycling principles drive the designer choices in the implementation of circularity practices, while LCA methodology constitutes a tool to guide designer decision-making towards more sustainable practices.

3.2.5. Semi-automated PCB disassembly pilot

The recycling assessment results in different KPIs as obtained from the Recycling Simulation Models as developed and applied by MARAS (see also D3.3 and D5.4)

- Recycling rate for the entire car part: the recyclability assessments as performed for different recycling routes (as will be elaborated on below for pilot 3 – the comparison

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of recycling of the Airconsole unit with the IME), result in the calculation of recycling KPIs. The total recycling rate (mass/%) can be visually presented by the Recycling Index (as developed by MARAS) for the different car parts, processing routes assessed and different levels of recycling in terms of CE (defined and explained in D3.3). These indices are evaluated by application of a physics based approach to recycling, and are based on full mass balances for all materials/compounds/elements included in the car part (>310 included in model), for all process unit operations (close to 200 included in model) and all flows (over 840 flows), accounting for the mass of materials recovered from the initial component subjected to recycling as well as energy and exergy balances to evaluate sustainability and circularity performance at EoL

- Recycling rate of all individual materials in the car (sub) parts (mass/%): the individual recycling rates/KPIs are the basis for more precise CE assessment. Recycling of complex products is a trade-off between bulk and minor element recycling, where often the one material will (to a more or lesser extent) be 'sacrificed' for the recovery of the other. This is not always reflected by the overall recycling rates due to the lower weight of precious (scarce, critical) elements present. Therefore, individual recycling rates are important KPI's calculated from the recycling assessment models of MARAS. These can also be visualised by the use of the Material Recycling Flower (also developed by MARAS). An alternative and additional way to obtain a unified vision of the recyclability of individual materialsthe car parts considering the physical quality of the materials is using the thermodynamic rarity indicator, as explained below. These approaches can be very well combined.
- Energy recovery: most car part are characterised by a relatively high percentage of organics/plastics. Energy recovery from feed is included as a recycling KPI as organic content will be used in some of the processing routes as an energy carrier from which the energy content is (partially) recovered and/or as reducing agent. Energy recovery is also dependent on the required extra energy input to the process as a consequence of the low metal content/low grade of the car part recycling input. This indicator can be also included to present the results of the energy recovery route and also allow for comparison with the energy recovery.

The rigorous recycling simulations also provide a thermodynamic basis for the environmental impact analysis. The generated information can be linked to GaBi (2022) (www.sphera. com) or openLCA (www.openlca.org) software, for example. Through this link, it is possible to evaluate the environmental impact of different designs and scenarios based on actual environmental impact, linked to the mass and material flows and the detailed compositions of each stream. This includes the design and recycling route-dependent recoveries, losses, and the environmental footprint of any created residue. This has been tested for some cases in this project, but has not been applied to the pilots as discussed in this deliverable. The following section will outline the specific methodology to be used for the validation of each pilot plant.

3.3. Pilot plants assessment

3.3.1. Collaborative robot for identifying components in PCBs

In this particular context, the base case involves sending the car for shredding, resulting in the loss of nearly all critical raw materials in the vehicle. This choice is based on current industry practices. According to European regulations, vehicles must achieve a recycling rate of 85%, a

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target currently met by this method, with the predominant recovery of steel, copper, and aluminum. However, most of the minor but valuable materials such as gold, platinum, tin, tantalum, etc., end up in landfills or are recycled into low-quality alloys. In the TREASURE project, numerous disassembly and sub-disassembly tests of the parts were conducted, evaluating disassembly times (D3.2). Additionally, the recyclability of these separated parts was studied (D3.3). With the help of the Cobot, disassembly times are reduced, thus improving the economic viability of these processes.

In this deliverable, the objective is to assess the extent to which processing times are improved and, consequently, the recoverability of materials, including both bulk and critical raw materials. The scenarios analyzed are designed based on varying levels of disassemblability.

The disassemblability of car components has been divided into three different levels. The data composition is provided by the MISS system from SEAT, enabling the determination of each car part's composition. Consequently, the metal composition is known at various levels, with each level representing a subdivision of the immediately higher level. Accordingly, level 1 has been designated as the whole part, while subsequent levels represent the subparts derived from the higher level.

With this framework, the following cases have been defined:

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, which are depending on the plant and location, further separated into non-ferrous metal fractions, plastic fractions, etc Important to realise is that these fractions are never 100% pure due to inevitable imperfect liberation and separation and hence contain different materials (which through these lower grade fractions also go lost in subsequent metallurgical processing). Metallurgical processing has not been assessed for this case.

Case 2 (Car dismantling): In this scenario, the part is removed from the vehicle and assessed by use of the recycling simulation models, in which its recyclability was determined for different metallurgical processing options matching the composition and hence processing requirements to most optimally recover materials from these. This includes the Cu route (designed for copper and compatible metals recovery), steel processing route (for parts with a high ferrous content) and energy recovery route. Most suitable processing route can be selected from thisfor the entire part. This will always lead to a trade-off between recovery of the one material over the other, as not all materials can be recovered (due to thermodynamic incompatibility as depicted by the Metal Wheel) in one route .

Case 3 (Part disassembly): The component 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 the three different recycling routes are assessed but then applied for the separated and hence concentrated modules from disassembly (PCB rich, Fe rich and plastic/organics rich) which are then processed in the processing route best suitable, hence leading to optimised recycling results: (1) the Copper route (for PCB based parts) (2) the Steel route (for Ferrous rich parts) aimed at recycling steel and alloying elementsand (3) energy recovery route (for plastic/organics based parts)

The collaborative robot, known as cobot, is designed to assist operators in identifying specific components on printed circuit boards (PCBs). Consequently, due to the unique characteristics of the cobot, an additional use case is introduced, as it allows for the extraction of more metals from the selected PCBs.

This new development not only enhances the recoverability of critical metals from car components but also reduces the introduction of impurities into the hydrometallurgical process, thereby improving the efficiency of the recycling method.

For each level of disassemblability, the time required for each process, the cost of extracting different parts, and the potential revenue from recovering metals at each level are compared. Additionally, the circularity level achieved is assessed using thermodynamic rarity and IEV.

Figure 9 illustrates a summary of the methodology applied in this case. It must be mentioned that car electronics recycling originates from the virtual recycling process developed in Deliverable 3.3. As previously explained, the results obtained in D3.3 deliver optimum recovery values, as the processes have been designed considering best available technologies.

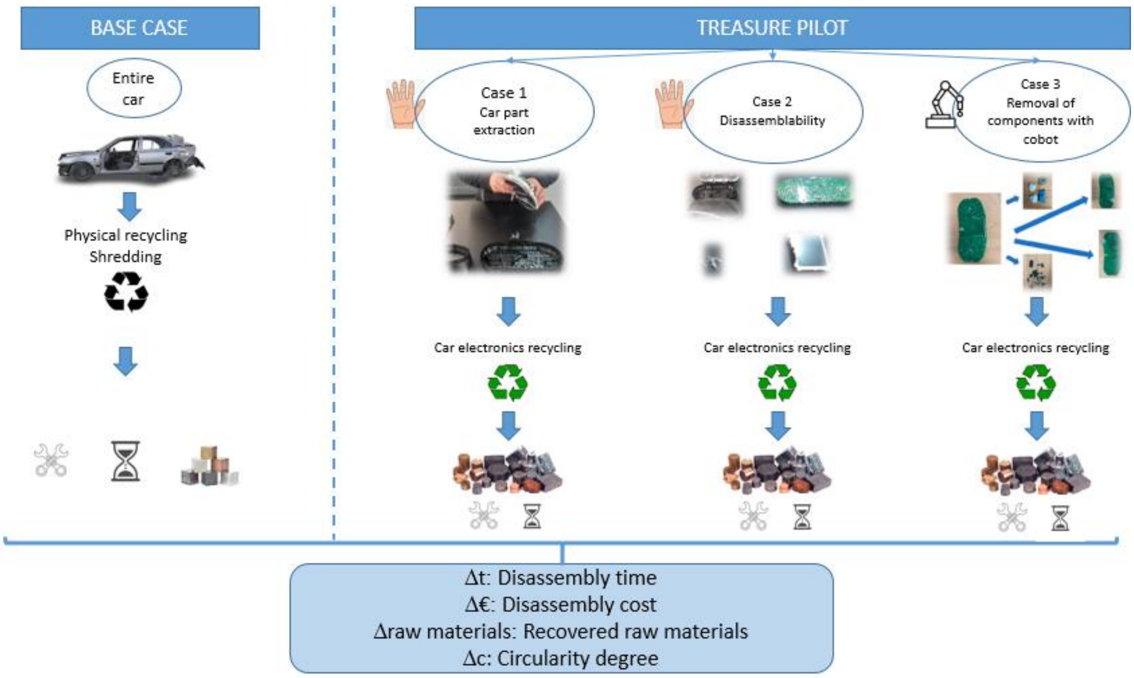

Figure 9. Summary of the methodology applied for the circularity of the cobot pilot plant.

3.3.2. Hydrometallurgical materials recycling pilot

As with the previous pilot, the reference case for comparing the performance of this second pilot is the end-of-life vehicle business-as-usual procedure focusing on two key technologies: namely the Indium tin oxide (ITO) from LCD screens and in-mold electronics (IME). When a vehicle reaches its end of life, this is sent to shredding. Then, the main metals recovered are steel, aluminium, and copper. However, metals other than lead in batteries or PGMs from catalytic converters (which are removed from the car prior to shredding) are typically not recovered or only to low rates and depending on the processing route in which the different metal fractions are recycled

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However, although this is the reference state, it has been decided to choose a new base case, since there are no hydrometallurgical processes in the reference state. Thus, instead of that reference case, we will compare the newly created hydrometallurgical route with a conventional metallurgical process used for the recycling of PCBs. This involves that the car part is extracted, disassembled, and then sent to the conventional metallurgical process. With this, an important amount of copper is recovered (values higher than 90%). However, the solid residue remains as an unrecoverable mix of several metals embedded in the PCBs for most WEEE facilities in Europe. Usually, this residue is then sent to larger facilities, sometimes outside Europe such as China. This is why we consider that only copper is practically recovered.

Two main analyses will be conducted. One will be based on thermodynamic rarity, focusing on evaluating the amount of mineral capital recovered with each product during the processes. The other will be based on intrinsic economic value, assessing the economic worth of the metals in the products both before and after the processes. The circularity degree achieved based on both indices will also be shown.

Figure 10 illustrates the different steps carried out for the validation, as well as the assessment conducted.

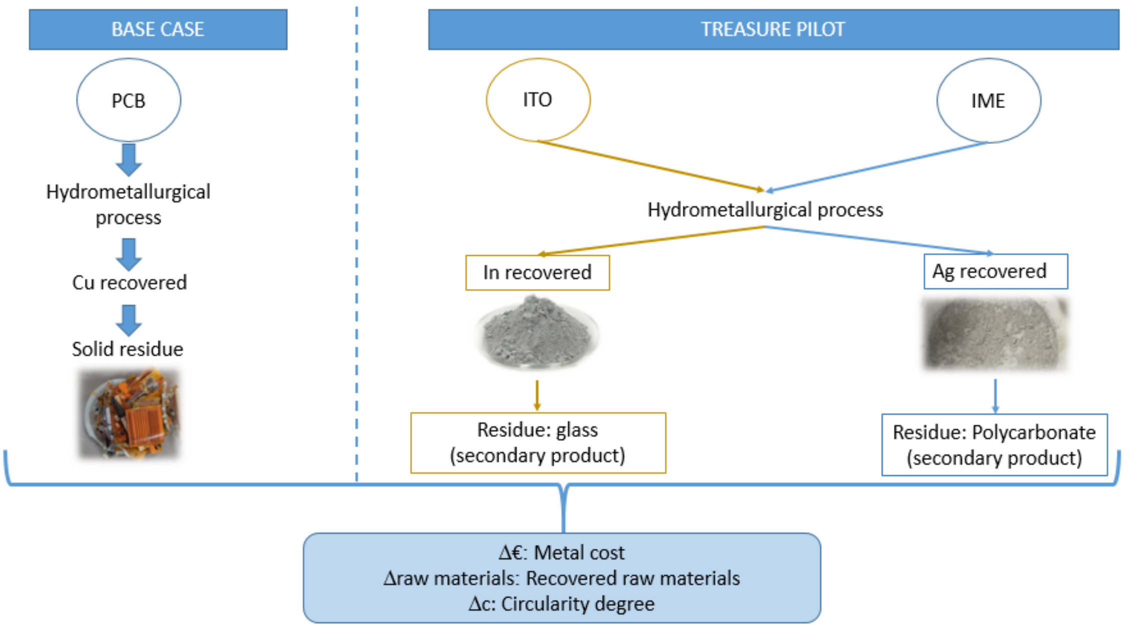

Figure 10. Graphical summary of the methodology applied for the circularity of the hydrometallurgical pilot plant.

3.3.3. New PCB designs: in-mold electronics

For the final pilot plant assessment, the newly developed product from the TREASURE project will be compared with a conventional car component from a SEAT Leon vehicle. After testing the new PCB, known as IME, and its specific properties, it was considered appropriate to compare it with the climate control module situated between the front seats for rear passenger usage.

With the aim of producing technologies with reduced and simplified metal compositions, several considerations must be taken into account, including the overall thermodynamic rarity of the car component developed and its lifespan compared to a traditional one. Therefore, the

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following information is provided to enhance understanding of how the pilot plant will be validated.

To determine which product contains greater rarity and hence, more embedded mineral capital, a thermodynamic rarity assessment was conducted, considering the composition of both items. Additionally, since the metal composition is known, the intrinsic economic value for manufacturing both devices will be calculated. Finally, a life cycle assessment is undertaken to analyze the environmental impacts of each product. Such analyses aims to provide insight into the sustainability and circularity between the two products.

To summarize the assessment conducted to validate circularity, Figure 10 has been added to illustrate the comparison between the two technologies based on the evaluation conducted.

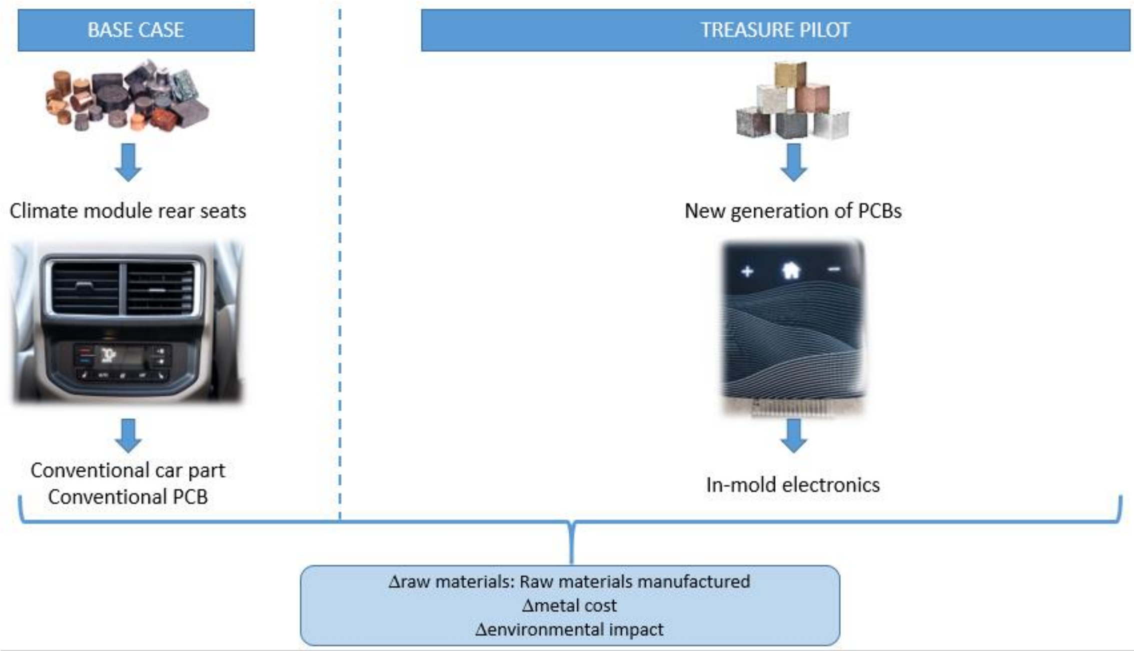

Figure 11. Assessments carried out to validate the circularity the IME pilot plant.

Last, Table 6 has been included to summarize the information regarding the assessments conducted in each pilot plant. As it is illustrated, the common evaluations carried out for the three cases are the intrinsic economic value and the recovered raw materials based on thermodynamic rarity. With these indicators, it is then calculated the circularity degree.

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Table 6. Summary of the indicators assessment carried out for the different pilot plants.

Pilot plant	Base case	Δt: Disassembly time	Δ€: Intrinsic economic value	Δraw materials: recovered raw materials	Life cycle Assessement	Δc: Circularity degree
Cobot	Vehicle sent to shredding	X	X	X		X
Hydrometallurgy	Hydrom. Process to recover Cu.		X	X		X
IME	Air console module from SEAT		X	X	X	X

4. Semi-automated PCB disassembly pilot's circularity assessment

4.1. Thermodynamic rarity assessment of the disassembly levels

Incorporating the thermodynamic perspective into the results of the various recycling processes and situations involving metals, we can assess the recyclability in terms of recovered materials, considering their physical quality.

Figure 12 illustrates the values for each aforementioned disassembly and recycling case. As illustrated, shredding the car leads to a low recovery of the mineral capital in each part, which is particularly low – almost negligible. This is attributed to the mixing of critical metals during the shredding process, making their recoverability unviable. Comparatively, Case 2 yields a higher value than Case 3, with a decrease from 59.09% to 58.55%, respectively, when the car part undergoes deeper recycling. This reduction is attributed to the limited quantity of ferrous fraction in this part. Only the screws were composed of steel, which also contained nickel, incompatible with the steel route but compatible with the copper route. Consequently, the gain in terms of Thermodynamic Rarity due to iron recovery does not offset the loss of nickel. In Scenario 2 (dismantling), the combimeter follows the copper route entirely, while in Scenario 3 (sub-disassembly into subparts), after dismantling and disassembly, the PCBs follow the copper route, and the metal screws are directed to the steel route.

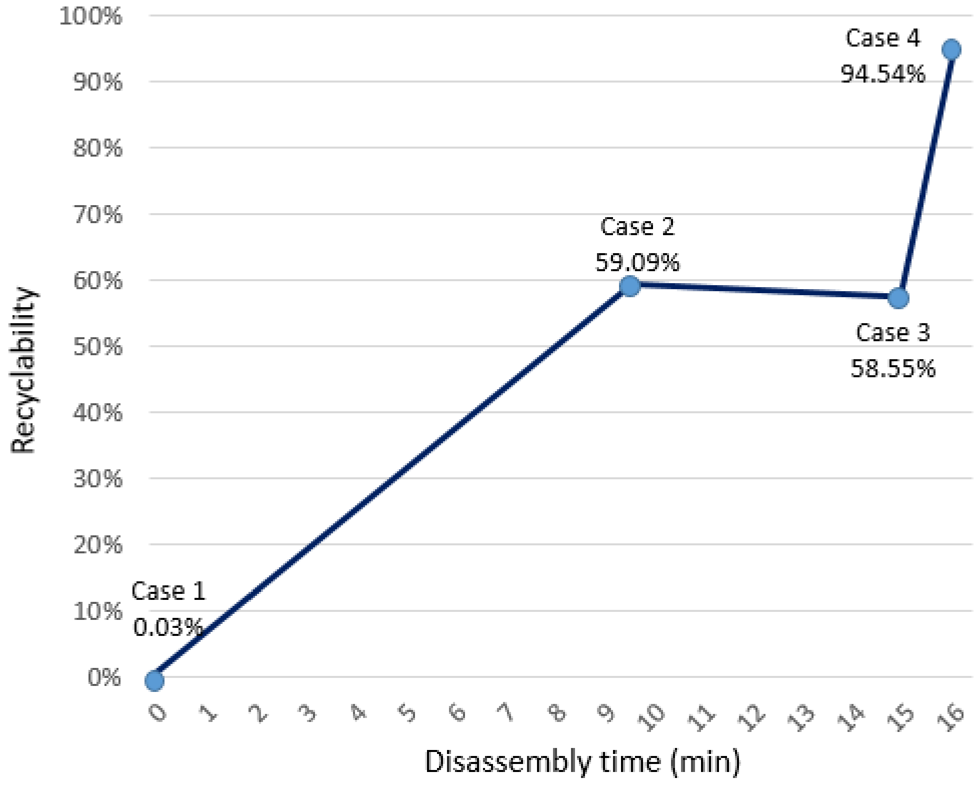

Figure 12. % of rarity recycled depending different cases assessed and disassembly time.

The last case has been added to incorporate the improvement brought by the cobot. In this scenario, with the PCB already dismantled and disassembled, the cobot efficiently identifies and desolders target components in the PCB, allowing the operator to remove them. Alongside human-robotic collaborative features, the cobot has been specifically designed to target tantalum capacitors, containing tantalum and integrated circuits. As a result, by incorporating this final step, the recyclability (measured in terms of thermodynamic rarity) increases to over 94.5%, representing a 60% improvement compared to the recycling rates achieved in Cases 2 and 3.

This chart can also be analyzed from the perspectives of disassembly time and the recovered rarity. As depicted, it requires 9 minutes to extract the car component from the vehicle, resulting in the recovery of 59.09% of the rarity within that timeframe. An additional 5 minutes are necessary to disassemble the car part into subparts, and merely 1.5 minutes, with the assistance of a cobot, to remove smaller components from the PCB. This latter aspect is crucial for enhancing the circularity of components and metals. It has been demonstrated that it takes 1.5 minutes to recover almost 40% more rarity than in Cases 2 and 3.

This chart becomes even more relevant when compared in terms of mass instead of rarity, as shown in Figure 13. When the activities are carried out in the first cases (case 1, 2, and 3), the difference in recyclability based on rarity is not significant because the recovered metals in these cases are not very scarce. However, in the last case, when the cobot is introduced, the recyclability in terms of mass remains at 45%, while in terms of rarity, it increases up to 94.5% (taking into account the simulation models provided by MARAS applied for these parts). This is because the component recovered in that scenario is tantalum, which is present in very small amounts by mass but is extremely rare, making it the most critical metal in this car part.

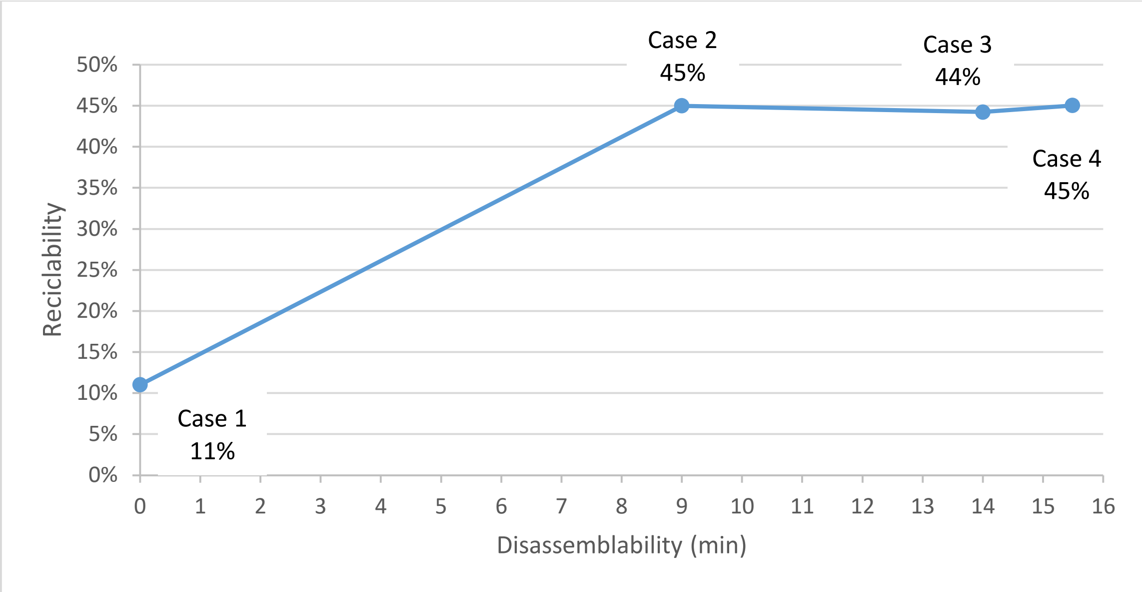

Figure 13.Recyclability (in mass) vs disassemblablility in min.

4.2. Intrinsic economic value within the disassembly levels

The economic value of the recovered metals in each case was calculated by multiplying their recovered mass by their market price in the year 2023, as it is included in the explanation of the intrinsic economic value in the section 3.2.2, with the Equation 1.

It should be pointed out that metal prices are very volatile which may have an impact on the obtained results. Moreover, the dismantling and disassembling labour costs have been calculated using the following equation.

$$P = C_{mh} \cdot t_w \qquad \text{(eq.1)}$$

Where *P* is referred to the total labor cost of dismantling and disassembling the car, C_{mh} is the man-hour cost, and t_w is the work time. 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 40.67€/hour. The dismantling time of the combimeter is 0.15 h (6.1 € labour costs), whereas the disassembly took 0.23 h (labour costs of 9.5 €). If the cobot is included, the total recovery time of tantalum would be 0.25 h, with 10.1 € of labour costs. It has been noted that the time and labour costs are added from the previous level, accounting in the last step of recovery the time for dismantling as well as disassembly.

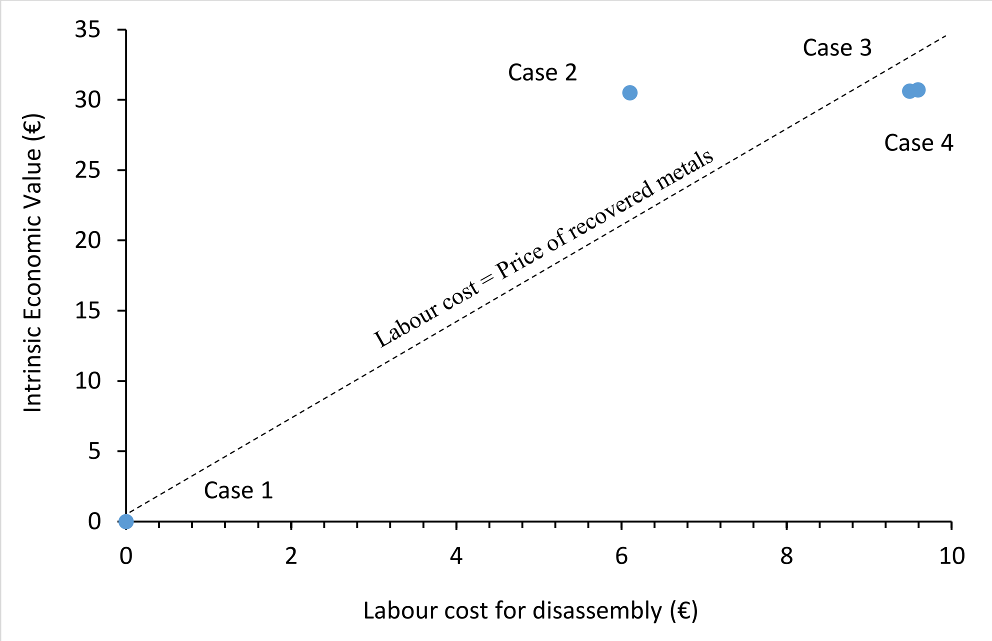

Figure 14. Price of recovered metals vs labour cost for disassembly for the combimeter case.

As it is seen in Figure 14, the case 1, labour time and cost were considered to be negligible, since it is the base case considered. For the case 2 (dismantling), the recovered economic value was approximately 31€ for the combimeter, primarily obtained from the amount of gold (56 g). These results suggest that a maximum of 25€ additional revenue could be obtained from recycling the combimeter. Notably, Case 2 yielded the greatest economic benefit compared with the case 3 and cobot case (case 4), not justifying the required disassembly time and its corresponding additional cost. It is important to note that the dashed line in Figure 14 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.

The recovery of metals from the cobot case must be explained. As illustrated in Figure 12, the cobot case falls below the dashed line, indicating that labor costs exceed the price of the recovered metal. For the combimeter, four integrated circuits (IC) were considered, with an average disassembly time of 9 seconds each and a total energy consumption of 0.15 kWh. The amount of tantalum in the combimeter is very low (0.51 g), and while the market price of tantalum may be high, it would not be profitable when compared to the other cases.

4.3. Circularity assessment

For the pilot plant assessed in this chapter, the validation of circularity will be carried out by comparing the indices obtained from the assessments conducted, including thermodynamic rarity and intrinsic economic value. To illustrate the results, Figure 15 and Figure 16 have been included.

As seen in Figure 15, the circularity in terms of rarity for the base case is around 3%, while in the cobot case developed during the TREASURE project, it increases to up to 95%, improving the circularity of rarity by 92%.

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On the other hand, the intrinsic economic value shown in Figure 16 illustrates that the circularity with this indicator for the base case is around 1%, while the cobot case achieves 94%, increasing the circularity of the intrinsic economic value by 93%. This demonstrates the improvement in the circularity of the tasks carried out in the pilot plant. It should be stated that only the monetary value of the recovered materials has been taken into account. Thus, electricity costs, labour and the corresponding costs associated to the metallurgical processes are not considered, as opposed to the outcomes provided in Deliverable 4.1.

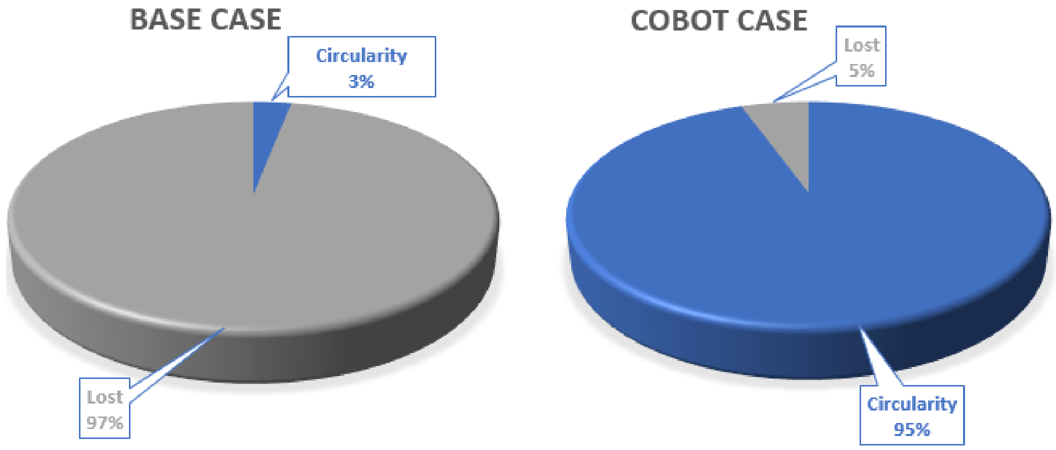

Figure 15. Circularity rarity comparison between the base case and the cobot case.

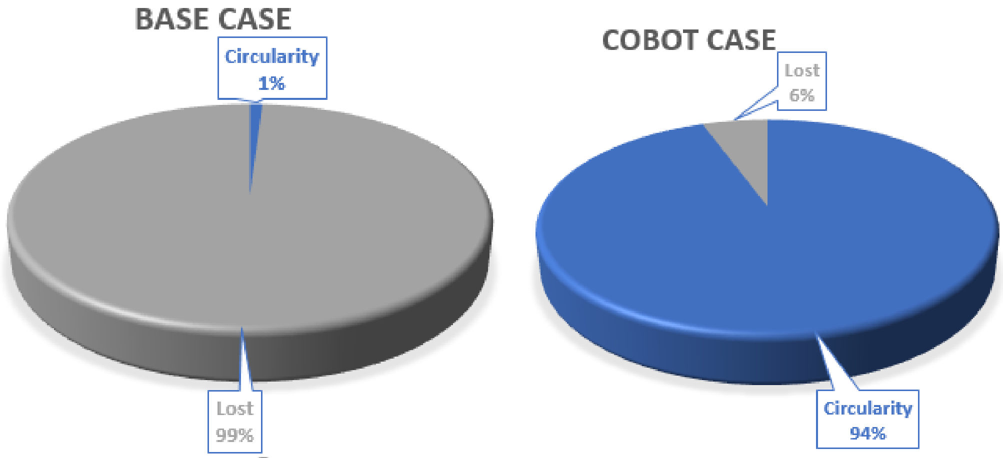

Figure 16. Circularity IEV comparison between the base case and the cobot case.

5. Hydrometallurgical materials recycling pilot's circularity assessment

5.1. Thermodynamic rarity assessment of the hydrometallurgical processes

Circularity will be assessed in this case through the thermodynamic rarity approach, which will be determined by the efficiency of recovery of the majority of components and metals in the different cases studied. The information of the metal content is also provided by the TREASURE platform, as explained in deliverable 4.8, where information regarding the car parts is provided, including total recycling rate, the ferrous metal recycling rate, the CRM recycling rate, the organic recycling rate, the general composition, and recycling KPIs.

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Accordingly, the first scenario analysed is the base case, where the printed circuit board (PCB) from an electronic component is processed through a hydrometallurgical process, with the aim of recovering copper. The efficiency of this process is very high, with copper recovery rates exceeding 90% (in terms of mass) and almost 30% of recovery of the total mass of a typical PCB from a combimeter. However, when these values are transformed into thermodynamic rarity, the efficiency of recovering copper is less than 1%. This occurs because very scarce metals, such as gold and silver, are not recovered and are lost as solid residues after the hydrometallurgical process.

On the other hand, the last two scenarios analysed are the hydrometallurgical processes for ITO and IME. The results show an efficiency recovery of 98.7% for indium in ITO glass and almost 83% for silver recovery in IME.

For this purpose, Table 7 has been included to illustrate the metal composition and the corresponding rarity of the product. It is important to note that the values shown are an average calculated from several ITO glasses and IME.

Table 7. Mass and thermodynamic rarity of ITO glass and IME (metal composition).

ITO GLASS [1 ton]	Mass [kg]	Rarity [MJ]
Indium	1.324	481,827
Tin	0.186	84.24
TOTAL	1.51	481,911
IME [1 ton]		
Silver	9.3	83,114
Iron	0.0033	0.105
Copper	0.12	41.80
Titanium	0.156	31.69
Manganese	0.108	7.89
Silicon	0.005	-
TOTAL	9.722	83,195

Given the efficiency of the recovery process during the hydrometallurgy stages, the focus has been on indium extraction from ITO glass due to its critical nature. It is worth noting that there are technologies available for tin recovery as well. However, considering the low tin content in ITO glass, attempting its recovery alongside indium would not be economically sustainable.

Hence, the hydrometallurgical method for ITO case outlined proves to be highly effective, facilitating the recovery of over 86% of the total mass, accounting indium a recovery of 98.7%, while tin recovery remains absent. If the thermodynamic rarity is calculated at the end of the process, it is observed that the efficiency of the recovery of the total metal content is 98.1%, providing more weight to the most critical metal in ITO glass, in this case indium. Additionally,

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this process yields 938 kg of reusable glass as a secondary product, being under research possible applications for this glass recovered, increasing the sustainability and circularity.

As it is illustrated in Table 7, there are more metals involved in IME than the ITO glass. However, the content of them is up to 3 orders of magnitude lower than the main metal embedded, silver. Accordingly, the process has been designed to recover this metal. The efficiency of the process in terms of mass (metal composition) is 79.2%, while if it is converted into thermodynamic rarity this value achieves almost 83%.

Nonetheless, it is essential to consider the solid residue generated during the process, as approximately 984 kg of polycarbonate is recovered as a secondary product, being suitable for various applications. This recovery not only adds value to the process but also enhances material circularity and technology efficiency. Consequently, out of 1000 kg of IME input, nearly 992 kg is recovered, comprising 984 kg of polycarbonate and 7.7 kg of silver powder.

These recovery processes enhance strength compared to current activities and the hydrometallurgical processes of traditional PCBs. When a PCB undergoes metallurgical processing focused on recovering specific metals, it often leaves a significant solid residue with several unrecovered metals, fiberglass, and plastics, which are challenging to valorize.

5.2. Intrinsic economic value of ITO and IME

The materials that are processed through hydrometallurgical recovery methods are related to the automotive industry. These materials include IME, an emerging technology that has the potential to replace traditional printed circuit boards in the future, as well as the PCBs of combi-meters and ITO glass of LCDs that are commonly utilized in car navigation screens. After identifying the chemical composition of these various materials, we can determine their economic value by considering the market value of each element. Table 8 reported the IEVs of each material.

Table 8. Intrinsic economic values of the different materials subjected to the hydrometallurgical recycling processes.

Material	Intrinsic Economic Value, €/kg
In-mold electronics	7.25
Printed circuit boards of combi-meter	9.05
ITO glass of LCDs	0.55

Figure 17 shows the pie charts for the different materials that illustrate the impact of each element on the overall IEV. Specifically, Figure 17a is referred to IME, Figure 17b for PCBs, and Figure 17c for ITO glass of LCDs.

From this study, we can observe how, as regards IME, the IEV depends almost entirely on the presence of silver, which has an impact of almost 98% on the total value, followed by the substrate of plastics with an impact of 1.4%. On the other hand, in PCBs, gold is the main contributing element with an impact of almost 60%, followed by copper with about 17%. Even though copper does not hold high economic value, it has a significant impact due to its high content in PCBs. Other materials such as palladium, neodymium, fiberglass, tin, and silver also contribute to the IEV. As for ITO glass, over 95% of the IEV value depends on the presence of indium, followed by glass with almost 4% and tin with 1%.

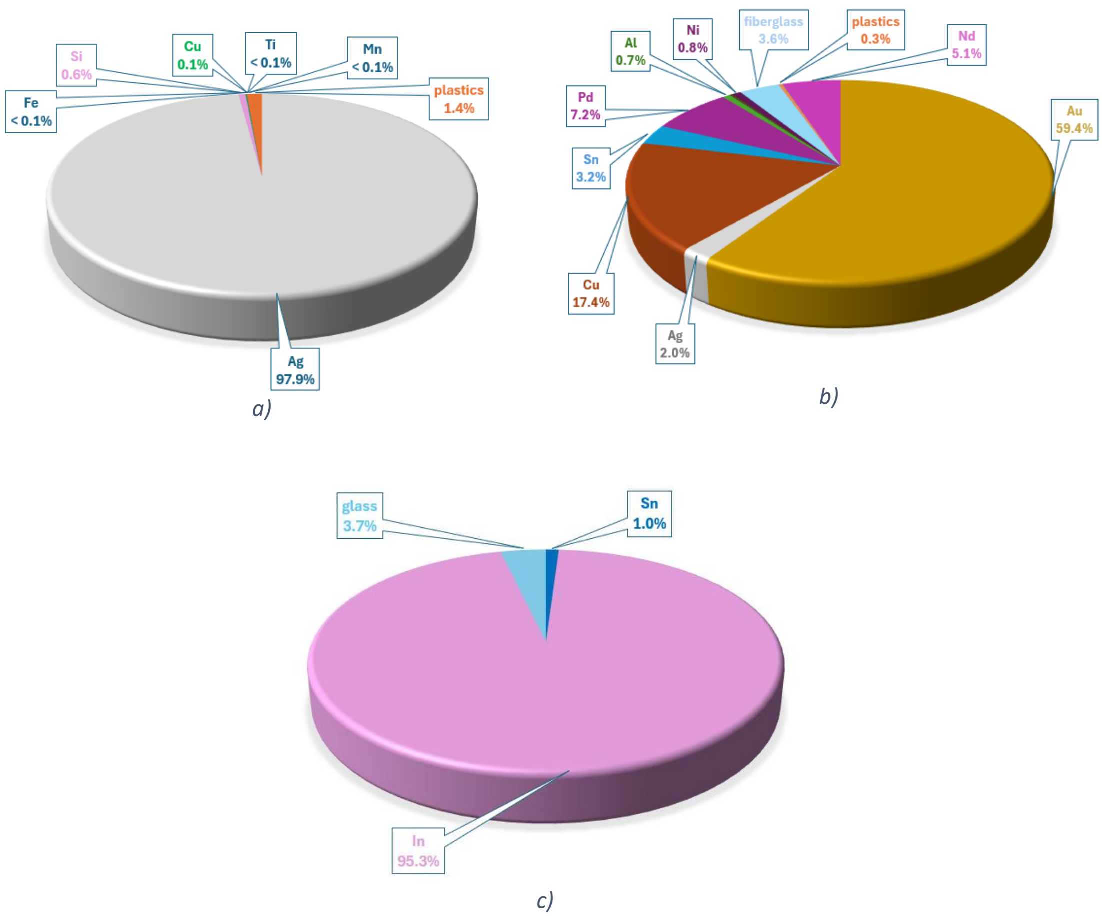

Figure 17. Incidence of the different elements on the overall IEV. a) IME; b) PCBs of combi-meter; c) ITO glass of LCDs

Based on the results and technical considerations related to hydrometallurgical operations required for extracting different metals, it was possible to define the metals to be recovered through hydrometallurgical processes.

Therefore, the focus was on recovering silver from IME, gold, silver, palladium, copper, and tin from PCBs, and indium from ITO glass. It should be noted that the hydrometallurgical process often generates solid residues that can be reused in other productive activities. For instance, TNO has investigated the recovery of polycarbonate from the polymeric substrate of the IME. Additionally, UNIVAQ has established connections with various companies in the sector for reusing glass, which is the solid residue of the hydrometallurgical process aimed at recovering indium.

With regard to the PCBs, a preliminary disassembly of some electronic components was carried out and three streams of matter were obtained. Two of these material flows have been subjected to hydrometallurgical processes for the recovery of precious and base metals. The Gold-REC 1 process was adopted for the treatment of 78.4% wt. compared to the initial weight of PCBs; this material has an IEV of 9.65 €/kg. The Gold-REC 2 process has been used for the treatment of specific electronic components with gold plating, about 4.4% by weight compared to the initial PCB; this material has an IEV of 19.85 €/kg. Further details are described in D6.2. Therefore, with regard to the evaluation of the performance of the recycling process of PCBs, the two processes, Gold-REC 1 and Gold-REC 2, were individually evaluated, and then the overall $IEV_{recovery}$ was calculated.

Table 9 summarizes the recovery rates, final products, and purity of different metals recovered from hydrometallurgical processes.

Table 9. Efficiencies of hydrometallurgical recycling processes.

IME			
element	**recovery, %**	**form**	**purity, %**
silver	82.0	metal	98.57
PCBs (78.4% wt. by Gold-REC 1 process)			
element	**recovery, %**	**form**	**purity, %**
gold	78.9	metal	99.1
silver	67.7	chloride	99.8
copper	97.3	metal	99.4
tin	91.6	oxide	99.1
PCBs (4.4% wt. by Gold-REC 2 process)			
element	**recovery, %**	**form**	**purity, %**
gold	93.7	metal	99.2
silver	72.8	chloride	95.0
palladium	38.0	metal	95.3
copper	88.4	metal	89.4
tin	76.0	metal	79.5
ITO glass of LCDs			
element	**recovery, %**	**form**	**purity, %**
indium	98.7	metal	99.3

On the basis of these results, the $IEV_{adjusted}$ and the $IEV_{recovery}$ indices for the various pilot scale validated hydrometallurgical processes are calculated and reported in Table 10.

Table 10. Evaluation of the performance of hydrometallurgical processes by estimating the $IEV_{recovered}$.

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Hydrometallurgical process	IEV, €/kg	$IEV_{adjusted}$ €/kg	$IEV_{recovery}$ %	
IME	7.25	7.00	78.3	
PCBs (GDR1) – 78.4%	9.65	7.72	54.9	54.4
PCBs (GDR2) – 4.4%	19.85	18.74	87.6	
ITO glass from LCDs	0.55	0.52	89.1	

Based on this study, it is evident that the process of extracting silver from IME can recover 78.3% of the IEV after accounting for any impurities that are present in the final product. Furthermore, TNO has investigated the recycling of the polymer substrate, which could potentially improve the performance of this process.

As for PCBs, the Gold-REC 1 process was less performing with an IEVrecovered of about 55%. This is because of the multiplicity of different materials and especially because of the relatively low concentration of gold compared to other types of PCBs. In fact, the incidence of gold on the overall IEV is less than 60% against values around 85% for other types of PCBs. To increase the performance of this process according to this index would be necessary to recover other metals, such as neodymium. The process Gold-REC 2 instead has allowed to reach an $IEV_{recovery}$ very satisfactory 87.6%. On the basis of these two processes, the overall $IEV_{recovery}$ for the processing of PCBs was then calculated to be 54.4%, which also takes into account that there is another matter flow of 17.2% by weight that has not been considered since it is not suitable for recovery of metals by hydrometallurgical routes.

Finally, the performance of the process for indium recycling by ITO glass has reached high performance considering that an $IEV_{recovery}$ very high of 89.1% has been obtained, determined by the fact that indium has a high incidence on the overall IEV of ITO glass and due to the high recovery and purity obtained by the hydrometallurgical process developed. It could even grow by also considering the secondary product obtained, which is glass that can be recycled; for the moment, it has not been included in the calculation of the $IEV_{recovery}$, as further assessments are necessary.

5.3. Circularity assessment

Two hydrometallurgical processes have been evaluated and compared with the base case, where a car is sent to shredding, recovering only abundant metals. While the rarity recovered from this base case is only 3%, the processes evaluated achieve a circularity of around 99% for ITO and around 83% for IME technology.

Additionally, the intrinsic economic value has been considered for circularity. The results show an increase in circularity by 88% for ITO, while circularity for IME technology increases by 77%.

Therefore, as it has been seen, there is an important improvement in the circularity with the activities developed during the project and carried out in the hydrometallurgical pilot plant.

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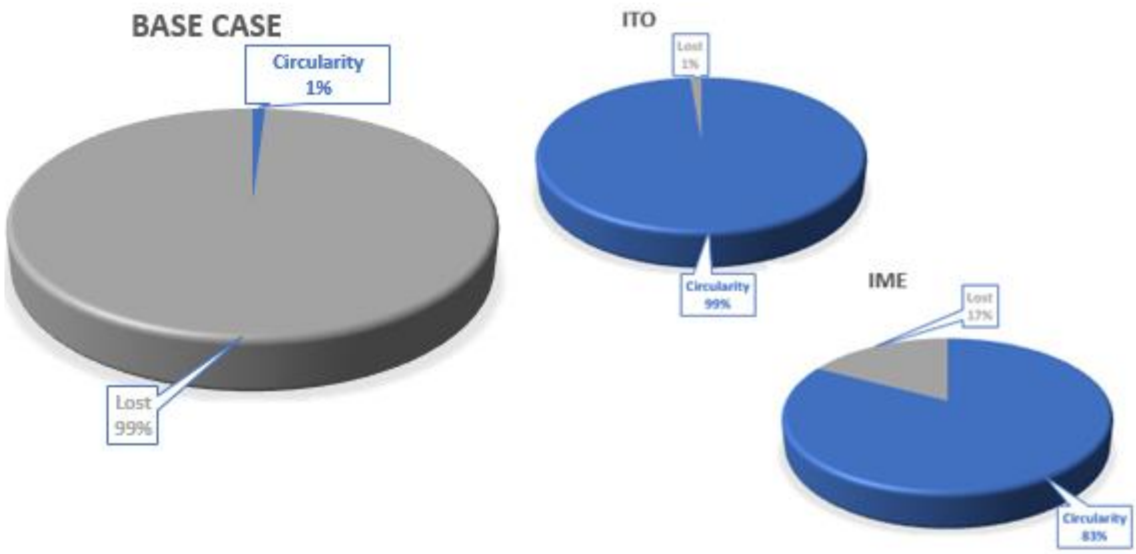

Figure 18. Circularity rarity comparison between the base case and the metals recovered in the hydrometallurgical plant.

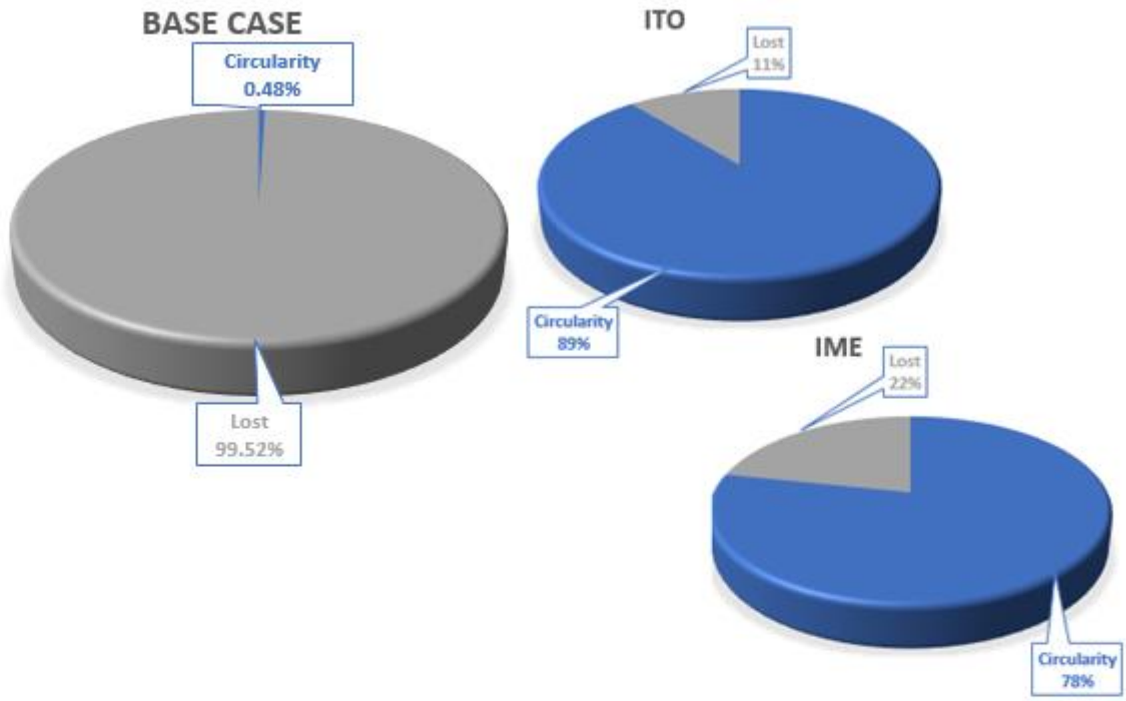

Figure 19. Circularity IEV rarity comparison between the base case and the metals recovered in the hydrometallurgical plant.

6. IME eco-design and prototyping pilot's circularity assessment

6.1. Thermodynamic rarity comparison between the two products

The aim of the IME is to develop a foil enabling the performance of electronics compositions through manufacturing in a more simplified manner. Therefore, when assessing the validation of this pilot plant, it must be compared with a traditional car component. In this case, the IME has been tested and can be compared with the climate control module located between the two front seats, for use by rear passengers, from the SEAT Leon.

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As shown in Table 11 and illustrated in Figure 20, there is a significant difference between the two components compared, not only in weight reduction (almost one third) but also in other essential parameters for circularity and sustainability. For example, the metal weight has been reduced by nearly three orders of magnitude, while the number of elements has decreased from 36 in the traditional SEAT component to 9 in the IME.

Table 11. Comparison between traditional component from SEAT and IME

	Traditional component	IME
Total weight [g]	90.62	36.51
Metal weight [g[	13.53	0.07132
Total rarity [kJ]	12,902.04	2,968.40
Metal rarity [kJ]	7,478.41	417.83
N of elements	36	9

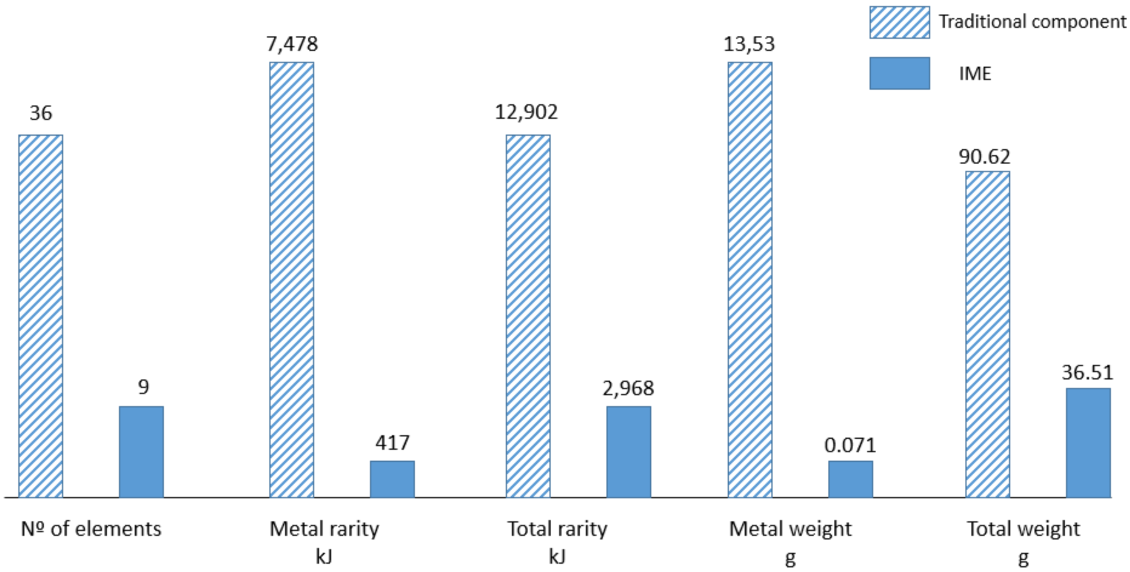

Figure 20. Chart comparing a traditional component and IME

There is also a significant difference in thermodynamic rarity between the two components. As observed, the IME contains approximately 77% less rarity when considering metals and polycarbonate (PC). The amount of PC is substantial in both components, with over 77 g for the traditional SEAT car part (representing almost 85% of the mass and around 42% in terms of rarity), and over 36 g for the IME (representing 99% of the mass and nearly 86% in terms of rarity). It is important to note that the data obtained has been calculated based on the metal composition and PC, as it is the primary plastic present in both technologies.

Hence, while metals constitute roughly 58% of the rarity in the conventional SEAT component, in the IME, this proportion decreases to values around 14%, emphasizing the substantial reduction in the criticality of this innovative technology, as well as improving the sustainability of this electronic components.

Furthermore, it must be mentioned that the primary composition of IME consists of a foil made of silver and PC, along with ten power LEDs. This implies that the majority of the rarity of this product stems from the quantity of plastic manufactured (PC in this case), whereas the criticality of metals is attributed to the silver embedded in the foil and the metals incorporated in the power LEDs.

Accordingly, the thermodynamic rarity, accounting only metals, associated with the silver manufactured in the foil and the ten power LEDs, has been calculated and compared. As illustrated in Figure 21, the amount of different metals in this product is caused from the various metals manufactured in the power LEDs, as silver is the only metal present in the foil.

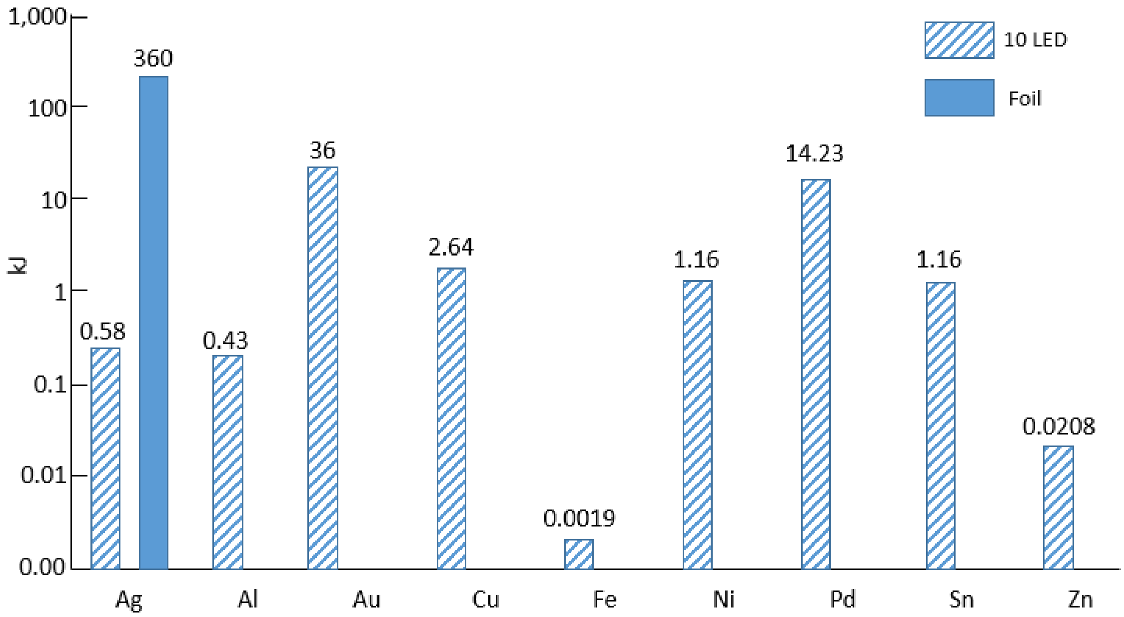

Figure 21. Mass and rarity contribution by metals for IME.

However, the main factor responsible of the criticality of this product is the silver content within the foil, which comprises more than 86% of the total thermodynamic rarity. In contrast, the ten power LEDs contribute less than 14%, highlighting the small contribution of power LEDs in this product due to the low amount of metals (in mass) embedded.

The sustainability and circularity of this product are evident, especially at the end of its lifecycle when recycling is required. The ease of removing power LEDs facilitates their extraction during recycling, ensuring that only the foil containing silver and PC needs to undergo hydrometallurgical processes. This process enhances metal recovery efficiency and underscores the product's sustainability and circularity objectives (see section 2.2.2 for more information related to the recyclability of silver and PC from IME and section 6.4 below in which the comparison of recycling performance is discussed based on detailed assessments performed).

Therefore, IME not only offers a new generation of PCBs manufactured with fewer metals, thereby reducing thermodynamic rarity, but also facilitates the effective recovery of metals at the end of their lifecycle. This capability can save up to 70% of the thermodynamic rarity from the original component (considering LED extraction and excluding PC as a secondary product, which could increase the share recovery in terms of thermodynamic rarity). Consequently, IME contributes significantly to sustainability efforts by promoting resource efficiency and enabling the recovery of valuable metals for reuse, thereby enhancing circularity in the automotive industry.

6.2. Intrinsic economic value (IEV)

The intrinsic economic value must be present when the eco-design is developed. The car parts compared are manufactured in millions of vehicles, and therefore, it could be a critical factor that could make profitable the device developed, or on the other hand, make unviable economically the process.

Accordingly, it has been calculated the IEV for both car components. To carry out the assessment, it has been taken into account the average prices from 2023 of every metal manufactured. Then, these prices have been multiplied by the mass included in the traditional PCB and the IME, applying the Equation 1 aforementioned.

The results are shown in Figure 22. As illustrated, the traditional car part from SEAT has an IEV of almost 0.44€, with gold contributing more than 86%, copper over 7%, and tin almost 2.5%. In contrast, the IEV for IME is 0.03€, with silver contributing nearly 89% and gold almost 10%. This highlights the significant difference between the two products, as the IEV for IME is an order of magnitude lower than that of the traditional car part, representing only less than the 7% when they are compared. Thus, it is demonstrated the better sustainability of the IME product developed during the TREASURE project, not only from the amount of metals manufactured, but also from IEV embedded.

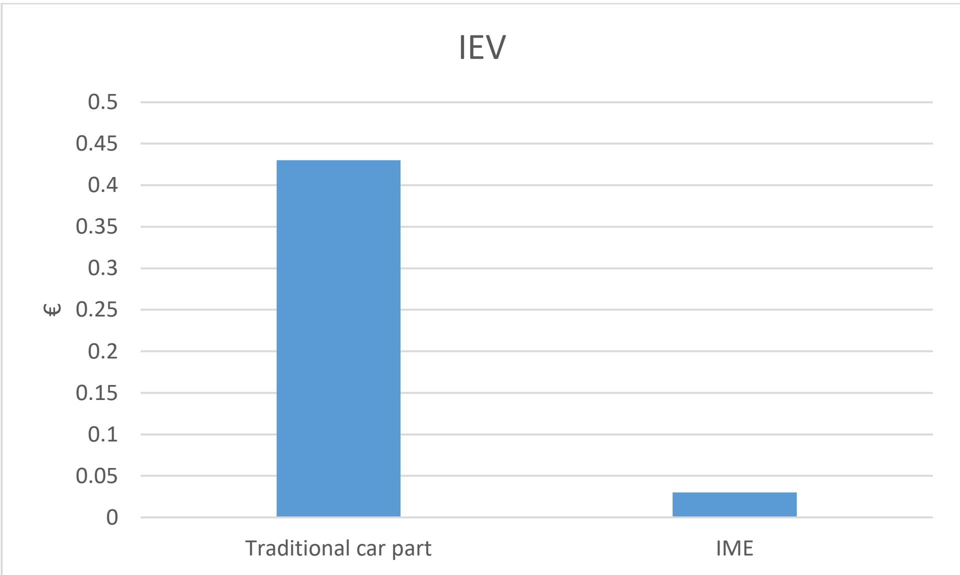

Figure 22. Intrinsic economic value for the traditional car part of SEAT and IME.

6.3. Life cycle assessment (LCA)

The IME climate control module developed in the pilot case and described above have been tested and compared in terms of (environmental) sustainability performance with the traditional climate control module located between the two front seats, for use by rear passengers, by SEAT.

LCA methodology has been applied to model and assess the impacts of the two components using GRETA Tool by SUPSI. Specifically, the analysis has followed the standardized steps of LCA according to ISO 14040, i.e., the goal and scope definition, LCI, LCIA, and Interpretation of results.

The analysis has been performed with the final aim of testing the sustainability performance of IME as a competitive technology with respect to conventional car electronic production. The choice of the climate control module as product system of the analysis were based on both the availability of previous LCA studies by SEAT on that component for SEAT Leon car model, and the technical feasibility of replicating the same functionalities and size of the conventional part in an IME prototype through TNO pilot line.

Being the LCA aimed also at testing the adoption of GRETA Tool inside the TREASURE Platform, the IME component has been modeled to exploit the customization and comparison functionalities that GRETA offers in an eco-design perspective. The work done for the characterization of the IME prototype under the environmental sustainability perspective contains sensitive data from prototype owners for IME part and from SEAT for conventional one. For this reason, the analysis is not reported in the public part of this document D6.4. The assumptions of the goal and scope definition, the life cycle inventory, the life cycle impact assessment and the interpretation of results are described in detail in the confidential annex 1 of this document.

6.4. Comparison recycling performance of SEAT Air console with IME

The recycling process simulation model has 17 Tabs (each with a complete and relevant flowsheet) that cover all metallurgical processing infrastructures as depicted in the complete Metal Wheel (Reuter et al., 2013) as depicted in D3.3. and other deliverables), i.e. BAT industrially available processing routes. In order to compare the base case of the SEAT Air console with the IME part, two different flowsheet configurations are applied and assessed in the recycling simulation model.

- Recycling assessment of the Air console

  The complete Air console unit is processed in the copper refining route, , which includes 8 tabs of the complete route, starting with smelting and then passing through the many refining steps to process this unit. This process route is used to process the type of mix of materials as present in the part in order to recover a range of valuable elements/compounds as contained in this part from it. This route is also capable of using the complex mix of plastic/organics materials as present in this part in high percentages as energy source as well as reducing agent to split the console initially into phases that can be appropriately processed in appropriate metallurgical processes and obtain highest recycling performance as possible.

- Recycling assessment of the IME
  Due to the very large fraction of plastics (and small fraction of organics) as present in this part, an energy recovery route is selected to process this part. The valuable silver in the IME part is concentrated mainly into a flue dust that is then fed back into the copper processing route where it is recovered as electrolytic silver. The rest of the IME part is recovered as energy from the created off gas in waste heat boilers. This route basically then only applies 4 tabs of the complete flowsheet, thus much simpler processing and thus less silver losses in various sub-streams in the various unit operations.

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In Table 12 and Table 13 the most important results are summarized, noting that the IME part only has Ag as metal, the rest of the part consists mainly of a plastic and organics functional mixture. The main recycling results of the Air console are summarized in Table 12, while the main results of IME are summarized in Table 13. Note as well as that only the silver recoveries are presented in the Tables for comparison the two different part types.

It is clear from the tables that comparable results are achieved for the two routes processing the two modules, when comparing Ag recovery, energy recovery and Scope 1.

The Air console contains more elements that can be recovered through the assessed processing routes in comparison to the IME, which basically only contains silver as valuable metal. The recovery of the other elements from the Air console to high quality metal products (level 1 CE recycling) will bring the recovery of the Air console to 4.99% compared to the recovery rate of 0.10% for the IME. When the produced high quality slag of the processing of the Air console is also considered (level 3 CE recycling), the recycling rate of the Air console increases to around maximally 19.9%. It however is important to realise, that this is not a fully valid comparison, as only Ag is present as (recoverable) metal in the IME. The reduced use of metals of the IME can have positive impact during production (Harkema et al., 2024) and reduced resource dependency compared to that of the Air console. Whereas in the IME only Ag is used (excluding the plastics/organics), in the Air console around 50 different elements/compounds are applied (also excluding the plastics/organics). Part of these elements/compounds cannot be recovered from the Air console and will hence be lost from high quality products in the CE. For both devices, the high plastic/organic content is recovered as energy and/or applied as reducing agent in the processes (see Table 12 and Table 13 for energy recovery rates). Therefore Table 12 and Table 13 only show the comparison of Ag recovery from both devices.

Note as well as that industrial scale was used to ensure that there is enough flowrate to recover on an economy of scale valuable resources.

For more information regarding this analysis, check the Annex 2 of this document

Table 12. The processing of the Air console following the copper processing route and main Scope 1 impact of recycling and recovery of Ag.

20 tph Module – MOD	Amount	Unit
Total feed rate of MOD	20.00	t/h
Copper alloy (Oxidative melting) collector of valuable metals	1.41	t/h
Multi-Metal (pyrolysed – energy recovery)	0.00	t/h
Total valuable metal recovered per kg of feed	0.07	Kg/kg MOD
Energy recovery from offtake (30% efficient)	33,001.04	kW
Energy recovery (if 30% efficient) Ox WHB	15,011.91	kW
Energy recovery (if 30% efficient) Red WHB	2,924.08	kW
Energy recovery/tonne of feed Cu smelting	2.55	MWh/t MOD
Cleaned slag (building material) Non-ferrous (fluxes are added)	0.87	Kg/kg MOD
Scope 1 GWP	2.21	Kg CO2/kg MOD
Scope 1 AP (SOx + NOx)	Low	Kg SOx-eq/Kg MOD
Ag recovery (99.999% purity electrolytic)	99.26	%

Table 13. The processing of the IME presenting the main Scope 1 impact of recycling as well as recovery of Ag from the IME module. Note that this is indicative, as the flowsheet, while including best available technology is generic. However, it clearly shows what preferred options may be and how technology must be linked to optimally recover metals, alloys, materials and energy (among others).

40 tph Module – MOD	Amount	Unit
Total feed rate of MOD	40.00	t/h
Metal phase (recycled to other units flowsheet)	0.03	t/h
Energy (if 30% efficient boiler)	83,770.34	kW
Per tonne of feed	2.09	MWh/t MOD
Total kg CO2	116,922.05	Kg
Scope 1 GWP	2.92	Kg CO2/kg MOD
Scope 1 AP (SOx + NOx)	Low	Kg SOx-eq/Kg MOD
Calcine (low grade oxidic material-costly to recycle)	0.00	t/h
Ag recovery (99.999% purity electrolytic)	98.95	%

7. Conclusions

The conclusions drawn from the analyses conducted reveal significant findings regarding the feasibility, sustainability, and efficiency of the technologies evaluated in the automotive industry context. From the validation of pilot plants to the comparison of traditional components with emerging technologies, several areas for improvement and opportunities to advance towards a more sustainable and circular model have been identified.

The application of indices such as thermodynamic rarity has provided deeper insights into material criticality and facilitated comparisons between traditional components and emerging technologies. This methodology has underscored the importance of considering not only the quantity of materials but also their quality and impact on the product life cycle.

The predictive nature of simulation models allows for the physics-based estimation of how life-cycle systems respond to changes in, among others, feed material compositions, process configurations, operating conditions, and the technology used and thereby enables DfR. The system-wide effects of product design changes on resource consumption and sustainability can be evaluated as early as during the product design phase so as to maximize recyclability.

The disassemblability, assessed with the coordinated robot (cobot), is essential as shredding the car leads to low mineral capital recovery due to critical metal mixing during the process. The cobot's integration provides significant improvements, particularly in tantalum recovery, enhancing recyclability and representing notable advancements. Economic value calculations underline differences in economic benefits among recycling scenarios, while decreasing disassembly time and increasing metal recovery value with each subsequent step indicate tantalum recovery potential with the cobot. Depending on tantalum content, this could notably increase both the price of recovered metals and the sustainability and circularity of tantalum, making it feasible for reuse in new manufacturing processes. These findings underscore the multifaceted considerations necessary for advancing sustainability and circularity in metal recycling within the automotive industry.

On the other hand, the recyclability of ITO glass and in-mold electronics (IME) have been undertaken through a hydrometallurgical pilot plant. With the results obtained, it has been observed a high efficiency recovery for the products analysed.

The focus on indium extraction from ITO glass, has been successful, with the hydrometallurgical method facilitating the recovery of over 98% of the total metal content in terms of mass. This process also recover a significant amount of reusable glass as a secondary product, enhancing sustainability and circularity. Similarly, the IME recovery process demonstrates efficiency, with a high mass recovery rate. The recovery of polycarbonate as a secondary product further underscores the value-added nature of the process, enhancing material circularity and overall technology efficiency. These advancements represent significant progress compared to traditional PCB metallurgical processing methods, which often leave behind challenging-to-valorize solid residues. With the indicators calculated for both pilot plants, it has been included Table 14, where all the results obtained in terms of circularity are collected. As it is seen, the circularity increases by 92% for the thermodynamic rarity and by 93% for the intrinsic economic value for the case of collaborative robot. In the case of the hydrometallurgy, these values are even higher since the base case only focuses to recover copper, while the pilot plant has been developed to recover indium and silver.

Table 14. Circularity assessment according to the indicators calculated.

	IEV	Thermodynamic Rarity
Collaborative robot		
Base case	1%	3%
Cobot pilot plant	94%	95%
Hydrometallurgy		
Base case	0.48%	1%
Pilot plant	ITO 89% - IME 78%	ITO 99% - IME 83%

One of the highlights is the significant reduction in the use of metals and the simplification of compositions in new technologies, such as In-Mold Electronics (IME). These advancements not only promote resource efficiency but also contribute to reducing material criticality and enhancing product circularity.

Comparison of IME versus base case recycling shows comparable results, however the less material intensive design of the IME has considerable advantages in the entire life cycle. Attention should be paid for both designs to the high plastics/organics content. Design for Recycling and disassembly advisory has been defined for these cases in order to further improve their recovery potential. Exergetic assessment of EoL emphasis the crucial role of material quality in achievement of true CE and is an important parameter to be included in future CE assessment (applied already today in other studies) as this allows for minimization the creation of entropy, across whole value chains of the CE in addition to closing material loops through EoL recycling.

Furthermore, it has been demonstrated that ease of disassembly and metal recovery at the end of their life cycle are key elements for the sustainability of the evaluated technologies. The ability to easily remove power LEDs during recycling and to send only the foil containing silver and PC to hydrometallurgical processes highlights efficiency in metal recovery and strengthens sustainability and circularity objectives.

To evaluate the sustainability, Table 15 has been added to compare the different indicators for both components. It has been also calculated a life cycle assessment, however, due to sensitive content, it will be included in a confidential annex.

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Table 15. Comparison for sustainability for the both components.

	IEV	Thermodynamic Rarity
Traditional part	0.43€	Total 12,902 – Metal 7,478
IME	0.03€	Total 2,968 – Metal 417

In summary, the analyses conducted provide a comprehensive understanding of the evaluated technologies and their implications for the automotive industry. The findings highlight the importance of advancing towards more sustainable and circular production models, where resource efficiency, material recovery, and collaboration among different stakeholders play a key role in building a more sustainable and resilient future.

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Annex 1

Provided internally in a confidential way.

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Annex 2

1. Comparison recycling performance of SEAT Air console with IME (MARAS)

The recycling performance for the pilot demo, in which the recycling of the SEAT Air console is compared with the recycling of an alternative design as IME, has been assessed by MARAS by the application of the recycling simulation model as defined and discussed in D3.3 and D5.4. In the recycling process simulation model, the processing flowsheets for these two pilot demo parts have been defined and modelled.

1.1 Data processing of Air console and IME data

The data on the Air console as provided by SEAT in the format of a MISS file as well as the IME data as provided by TNO have been processed according to the procedure as described in detail in D3.3 and D5.4. This step is crucial in order to have the parts compositional data in a format that matches the thermodynamic process simulator in HSC being the basis for the recycling simulation models (see Table 1).

Table 1 Input definition of Airconsole and IME defined through data processing from MISS data file and TNO data – full compositional input to HSC Sim recycling simulation model (after classification of organics) (only a section of the complete composition/table is shown in this table in view of confidentiality of the compositional data)

Airconsole		IME	
Compounds (chemical formulas)	Mass % in part	Compounds (chemical formulas)	Mass % in part
*2CoO*TiO2		*2CoO*TiO2	
*3MgO*4SiO2*H2O		*3MgO*4SiO2*H2O	
Ag	0.002620179	Ag	0.103237796
Al	0.000341733	Al	
Al(OH)3		Al(OH)3	
Al2O3	0.1831859	Al2O3	
Al2O3*2SiO2	0.097764526	Al2O3*2SiO2	
AlO		AlO	
As	3.11149E-05	As	
As(CH3)3		As(CH3)3	
Au	0.005856415	Au	
B		B	
B(OH)3		B(OH)3	
B2O3		B2O3	
Ba		Ba	
BaO	0.00425689	BaO	
BaSO4	0.01809244	BaSO4	
BaTiO3		BaTiO3	
Be	5.55285E-08	Be	
Bi	6.29909E-07	Bi	
Bi2O3		Bi2O3	
C	0.606383195	C	
CaCO3		CaCO3	
CaMg(CO3)2		CaMg(CO3)2	
CaHPO4*2H2O		CaHPO4*2H2O	
CaO	0.000204604	CaO	…
..	…	..	
…	…	…	…
…	…	…	…
C12H11N(4AB)	2.06344252	C12H11N(4AB)	2.263191694
C12H12O(1ENg)		C12H12O(1ENg)	4.91634E-06
C12H22N2O2		C12H22N2O2	
C12H22O4(DDA)		C12H22O4(DDA)	
C13H30Si4O3	1.73266129	C13H30Si4O3	
C14H14O(DBEg)		C14H14O(DBEg)	93.29951373
C14H28O2(TDA)	70.4517911	C14H28O2(TDA)	0.261825294
C15H12Br4O2(TBBPAg)	2.09791393	C15H12Br4O2(TBBPAg)	
…	…	…	…
..	…	..	…
SUM	100.000	**SUM**	100.000

1.2 Recycling assessment of Airconsole and IME

The recycling process simulation model has 17 Tabs (each with a complete and relevant flowsheet) that cover all metallurgical processing infrastructures as depicted in the complete Metal Wheel (Reuter et al., 2013) as depicted in D3.3. and other deliverables), i.e. BAT industrially available processing routes. A Tab refers to a complete flowsheet in the versatile and multi-level recycling flowsheet structure in the model. In order to compare the SEAT Air console with the IME part, two different flowsheet configurations are applied and assessed in the recycling simulation model as developed by MARAS in HSC Chemistry Sim® 10 (www.mogroup.com) (development and working of simulation model is described in D3.3/D5.4/D4.8 etc and not repeated here, see list of references by Reuter, Van Schaik, Ballester).

- Recycling assessment of the Air console

  The complete Airconsole unit is processed in the **copper refining route**, which includes 8 tabs of the complete route, starting with smelting and then passing through the many refining steps to process this unit. This results in the recycling performance as summarized in Table 2. This process route is used to process the type of mix of materials as present in the part in order to recover a range of valuable elements/compounds as contained in this part from it (range of recoverable metals/elements depicted in the Metal Wheel for this route). This route is also capable of using the complex mix of plastic/organics materials as present in this part in high percentages as energy source as well as reducing agent to split the console initially into phases that can be appropriately processed in appropriate metallurgical processes and obtain highest recycling performance as possible.

- Recycling assessment of the IME
  Due to the very large fraction of plastics (and small fraction of organics) as present in this part, an **energy recovery route** is selected to process this part (similar to the recycling route/flowsheet as described in D5.4 for the IME type as assessed for comparison of existing with newly developed processes) i.e. Energy Recovery. The valuable silver in the IME part is concentrated mainly into a flue dust that is then fed back into the **copper processing route** where it is recovered as electrolytic silver. The rest of the IME part is recovered as energy from the created off gas in waste heat boilers as shown in Table 3. This route basically then only applies 4 tabs of the complete flowsheet, thus much simpler processing and thus less silver losses in various sub-streams in the various unit operations.

In both cases the silver for example is processed in the precious metal flowsheet show in Figure 1 below.

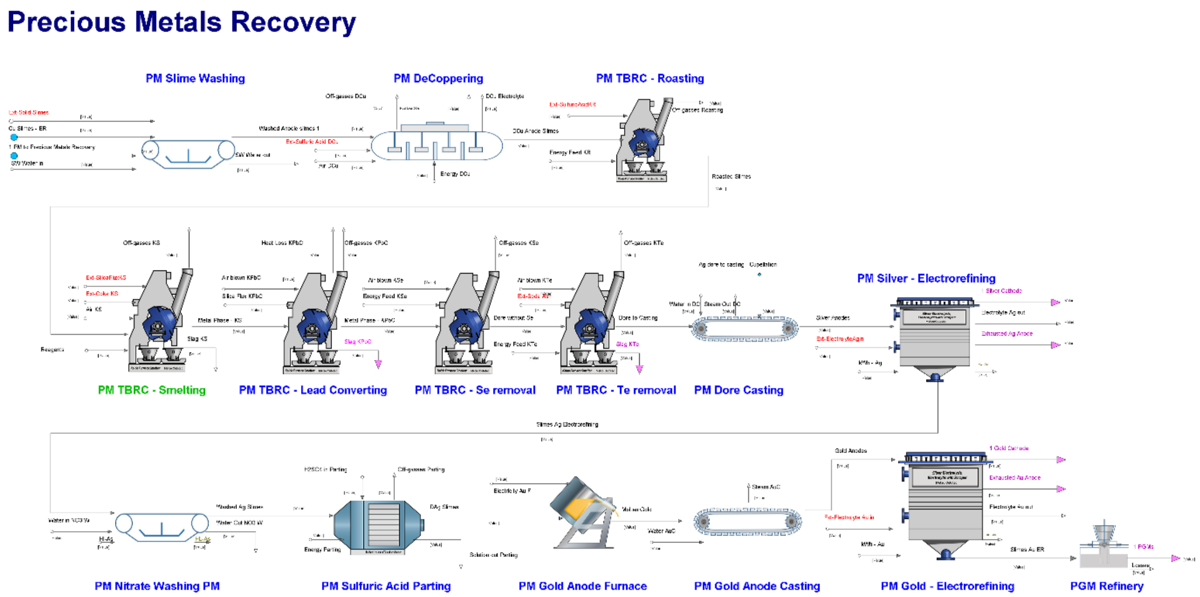

Figure 1: The refining of silver to a high-grade silver metal product as used in both cases.

1.3 Results and discussion of recycling assessment and Scope 1 results

In Table 2 and Table 3 the most important results are summarized, noting that the IME part only has Ag as metal, the rest of the part consists mainly of a plastic and organics functional mixture. The main recycling results of the Air console are summarized in Table 2, while the main results of IME are summarized in Table 3. Note as well as that only the silver recoveries are presented in the Tables for comparison the two different part types.

It is clear from the above tables that comparable results are achieved for the two routes processing the two modules, when comparing Ag recovery, energy recovery and Scope 1.

The Air console contains more elements that can be recovered through the assessed processing routes in comparison to the IME, which basically only contains silver as valuable metal. The recovery of the other elements from the Air console to high quality metal products (level 1 CE recycling) (as far as thermodynamically and economically possible in BAT processing routes as assessed) will bring the recovery of the Air console to 4.99% compared to the recovery rate of 0.10% for the IME. When the produced high quality slag of the processing of the Air console is also considered (level 3 CE recycling), the recycling rate of the Air console increases to around maximally 19.9%. It however is important to realise, that this is not a fully valid comparison, as only Ag is present as (recoverable) metal in the IME. The reduced use of metals of the IME can have positive impact during production (Harkema et al., 2024) and reduced resource dependency compared to that of the Air console. Whereas in the IME only Ag is used (excluding the plastics/organics), in the Air console around 50 different elements/compounds are applied (also excluding the plastics/organics). Part of these elements/compounds can not be recovered from the Air console and will hence be lost from high quality products in the CE. For both devices, the high plastic/organic content is recovered as energy and/or applied as reducing agent in the processes (see Tables 2 and 3 for energy recovery rates). Therefore Tables 2 and 3 only show the comparison of Ag recovery from both devices.

Note as well as that industrial scale was used to ensure that there is enough flowrate to recover on an economy of scale valuable resources.

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Table 2 The processing of the Airconsole following the copper processing route and main Scope 1 impact of recycling and recovery of Ag

20 tph Module - MOD	Amount	Unit
Total feedrate of MOD	**20.00**	**t/h**
Copper Alloy (Oxidative melting) collector of valuable metals	1.41	t/h
Multi-Metal (pyrolysed - energy recovery)	0.00	t/h
Total valuable metal recovered per kg of feed	0.07	kg/ kg MOD
Energy recovery from offtake (30% efficient)	33001.04	kW
Energy recovered (if 30% efficient) Ox WHB	15011.91	kW
Energy recovered (if 30% efficient) Red WHB	2924.08	kW
Energy recovered / tonne of feed Cu smelting	2.55	MWh / t MOD
Cleaned slag (building material) Non-ferrous (fluxes are added)	0.87	kg / kg MOD
Scope 1 GWP	2.21	kg CO2 / kg MOD
Scope 1 AP (SOx+NOx)	Low	kg SOx-eq / kg MOD
Ag recovery (99.999% purity electrolytic)	**99.26**	**%**

Table 3 The processing of the IME presenting the main Scope 1 impact of recycling as well as recovery of Ag from the IME module. Note that this is indicative, as the flowsheet, while including best available technology is generic. However, it clearly shows what preferred options may be and how technology must be linked to optimally recover metals, alloys, materials and energy (among others).

40 tph Module (Mod) to energy recovery due to many mixed plastics	Amount	Unit
Total feedrate of MOD	**40.00**	**t/h**
Metal phase (recycled to other units in flowsheet)	0.03	t/h
Energy (if 30% efficient boiler)	83770.34	kW
Per tonne of feed	2.09	MWh / t MOD
Total kg CO2	116922.05	kg
Scope 1 GWP	2.92	kg CO2/kg MOD
Scope 1 AP (SOx+NOx)	Low	kg SOx-eq/kg MOD
Calcine (low grade oxidic material - costly to recycle)	0.00	t/h
Ag recovery (99.999% purity electrolytic)	**98.95**	**%**

The results for Scope 1 are indicative only, as the GWP refers only to the main processing unit i.e. Top Submerged Lance (TSL) Oxidative Melting unit for the copper route, and for the energy unit it is the energy recovery unit. Furthermore, due to for instance matte recycling in the complete flow sheet as one of the intermediate phases created, the GWP for the smelting unit will be less than that of calcination as it is also an energy carrier. Furthermore, the Airconsole has less carbon i.e. less plastics/organic material (around 13% less). This means that any result must always be considered in the full context of the flowsheet. Also, note that the economy of scale, the energy balance considerations etc. will all affect the GWP and other footprints. Also, note that, while the model can produce a complete impact assessment as it is linked via openLCA to Ecoinvent, this is outside the scope of this work package (see Reuter et al, 2015 and Handbook of Recycling, 2024).

An important aspect to be considered that energy recovery processing normally creates a dirty calcine, while the copper route produces slag as a product. In this case, the IME product has no inorganic materials other than silver, therefore no calcine is formed. Obviously, in reality, the word no does not exist, as there are always contaminants that will affect the process. All of the contaminants have to be processed and recovered and therefore affect the economics of recovery. As only the recycling of IME and its composition are considered here, this is not further addressed.

1.4 Advisory for disassembly and Design for Recycling resulting from recycling assessment

The IME part has over 10 plastic/organic functional materials linked, which then brings up the point that when applying physical recycling to remove these, it is important to consider how cleanly these can be separated during physical separation for reuse with the same quality in the

IME part. The contained PC however holds for more than 93% of the total mass and hence is the main part in the contained plastics/organics, which is beneficial from a recycling point of view. This coincides with activities as explored by TNO to investigate different options to remove/separate and recover the PC (Harkema et al, 2024). The same argument on recycling of plastics/organics holds for the Airconsole part, that has over 15 plastics/organics functional materials, which is however very challenging to separate, also compared to the IME, as these are contained and spread out over many different sub-parts and connected to many different other materials.

It is clear from the results of the recycling assessment, that removal of plastics/organics to recover these materials either through physical recycling (for the case of the IME) or application of additional disassembly for the Airconsole unit to separate plastic parts from the Cu/PG(M) based parts, is advised to improve recovery and mitigation of loss of materials due to incompatible material combinations. This could provide an alternative for recovery of plastics/organics as energy and/or use as reducing agent as is the case in the current assessment. Important in this is that the physical recycling can produce a plastic recyclate with high enough purity to be reapplied in comparable quality as used in the original part.

Eco-design in terms of Design for Recycling (DfR) advisory can be deduced from the recycling assessment results referring to specific 'hot-spots' in the design due to which losses occur or which lower the CE level of recycling and/or by pinpointing design aspects which are complicating recycling. For the case of the IME, DfR should focus on the ease of removal of PC from the metal (Ag) containing part(s) as already explored by TNO. In case of the Airconsole, DfR should focus on the separation of plastic/organics in the sub-parts from recoverable metals. Also should the combination of incompatible materials/compounds, in particular with respect to the Cu processing route, in which the critical and valuable materials (including Ag) can be recovered, be avoided (see Metal Wheel Cu section for specific guidelines on (in)compatibility). It will be evident that Eco-design and Design for Recycling is also constraint by the functional specification of the part and sub-components.

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