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A methodology to improve the recyclability rate of Strategic/Critical Metals from car electronics

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European foreword

This CEN Workshop Agreement has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by a Workshop of representatives of interested parties on 2024-04-08, the constitution of which was supported by CEN following the public call for participation made on 2023-10-25. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

The TREASURE Workshop is driven by the need to address challenges in the automotive electronics sector, where car electronics are of significant value as sources of Strategic/Critical Metals (SCMs) such as copper, gold, silver, platinum group metals (PGMs) and tantalum. On average, modern cars contain between 5 kg to 8 kg of printed circuit boards (PCBs), depending on the trim and segment considered. These electronics have a substantial impact on the sector's economy, often accounting for over 30% of a vehicle's cost, rising to over 50% for luxury cars[1]. Despite the growth of the sector, the car recycling industry find it challenging to recover these valuable components from End-of-Life Vehicles (ELVs)[2].

This challenge is due to a complex web of barriers, including regulatory, governance, market, and technological, which are preventing the full adoption of Circular Economy (CE) principles and unveiling that a sectorial transition is far from being completed, despite significant investment in sustainable mobility approaches. In particular, the End-of-Life (EoL) phase poses specific challenges, preventing material recovery and the consequent reduction of natural resource dependence. Furthermore, the disconnection between Beginning-of-Life (BoL) and EoL stages, with data locked in protected databases, hinders the optimization of ELV processes. Thus, a systemic transformation requires a fundamental redesign of product lifecycles, integrating CE principles from the outset.

In this context, the TREASURE Workshop aims at providing a comprehensive and standardized framework for the recovery of electronic components from ELVs, with a specific focus on SCMs, and for the interconnection of actors along the automotive value chain, leveraging innovative technologies to overcome historical industrial limitations and propelling the automotive sector towards circularity.

ELVs represent a significant source of secondary raw materials, with annual volumes estimated at 7 million tons to 14 million tons in Europe alone. Carmakers have already been proactive in reusing approximately 30% of secondary materials to manufacture new vehicles. Various international directives and national laws have been introduced to promote sustainable practices, such as the European Directive 2000/53/EC [10] which sets a target of 95% recovery of the average mass of a generic ELV, with provisions for energy valorization and material recycling. The mass-based assessment approach of the Directive has mainly improved the recovery of basic materials, such as steel, aluminium, and copper. However, this does not incentivize the recovery of minor, but extremely valuable elements, such as rare-earth elements (REEs), precious metals, and other essential raw materials used in the manufacture of electric and electronic equipment, due to their low mass percentage within ELVs.

The ELV recovery process involves removing hazardous components, removal and potentially reusing valuable parts, and shredding the remaining hulk into small scraps. Ferrous metals (about 65%-70% of the average mass) are recycled to long steel applications (e.g. building sector) due to their high copper content (secondary steel contains 0,15% Cu and cars <0,06% Cu) [5]. The non-metals, approximately 25% of the average mass known as Automotive Shredder Residue (ASR), are often landfilled or used for energy generation. This fraction still contains metals and is further separated in post-shredding technology (PST) plants to recover non-ferrous metals, plastics, etc., from this fraction. The application of PST processing and the application thereof is different for different European countries. Non-ferrous metals (about 5%-10% of the average mass) are separated (e.g. by eddy current, density separation, colour sorting, etc.) to regain valuable materials like copper and aluminium or may become impurities in other fractions, depending on the equipment of the shredder company. The complex mixture of multi-materials and their strong interconnection however makes separation a challenging task. Liberation of materials in the shredding process is playing an important role. As SCMs are applied in very low/minor

[1] These statistics pertain to internal combustion engine vehicles and not battery electric vehicles where the content of electronic parts is even higher.

[2] The origin of the proposed activity is the H2020 TREASURE project (www.treasureproject.eu), GA 101003587. The objective of TREASURE is making automotive supply chains (with a specific focus in car electronics) more circular through the adoption of digital tools and improving the awareness of the different actors toward the presence of SCMs in specific car components.

quantities and connected in complex compounds and to other materials, their recovery is difficult and requires linking all stakeholders in the chain (from OEMs, dismantler, shredding/sorting plant to metallurgical recycling processing plants) to improve their recovery. Hence, despite recovery efforts, the shredding and sorting approach relies on traditional technologies. Data availability on use and location of strategic/critical materials in the design, linked to suitable recycling approaches could be the way to improve recycling of SCMs.

Although experts have proposed innovative procedures, which were developed by recyclers separately or together with automotive manufacturer, the primary focus remains on improving recovery rates, especially for ASR (e.g. manufacturer's process for plastics and copper). This limits the application of CE principles as it primarily targets materials contained in high percentages within ELVs.

The development and application of innovative and physics and industry-based recycling simulation models allow to both quantify industrial achievable recycling performance in detail for each different product design, disassembly approach, etc. and provide insights into optimisation and knowhow for Design for Recycling. This work has been published over the last 25 years in a long list of peer review journals and applied for example in the EU 6th framework project SuperLightCar, has been applied to assess and improve the recycling and Design for Recycling of the Fairphone as well as within the EU H2020 project in TREASURE (on the background of work over years on this topic) [6, 7, 12 to 16, 19]. This industry relevant and simulation based rigorous assessment of recyclability of products and parts is developed on an industrial and rigorous (physics and thermodynamics) basis. This is providing insight into recyclability of parts and products, achievable total recycling rates as well as individual material recycling rates and energy balances over recycling processing. It shows where losses occur and how recycling can be optimised either by redesign of products or by identification of most suitable and optimal combination of recycling processes (most optimal recycling flowsheet architecture based on a combination of disassembly and most optimal metallurgical recycling processing balanced with traditional options). This provides insights in how recycling can be optimised by application of modular recycling (through additional disassembly), optimal organisation and selection of recycling processes for the product/part and disassembled components from it and Design for Recycling and can at the same time provide insight into ambitious as well realistic and technologically feasible recycling target definition in regulation.

The ELV regulation draft [8] from the European Commission requires removal of several parts for assessment if the part can be reused, remanufactured or recycled. However, manual removal and disassembly for recycling is often not economical. At this moment this would mean that removed parts need to be sent to a WEEE recycling facility, where decision on reuse or recycling by shredding and subsequent sorting will be made. The removed parts could also be directly sent to a smelter for material recovery. This is determined by the size and composition of the removed part.

1 Scope

This document defines a method to support all the automotive actors in identifying the presence of SCMs in car electronics, particularly in ECUs, and disassembling/separating/recycling these components in a proper way. The final aim is improving the recyclability rate of SCMs from cars, create a market for secondary SCMs and reuse SCMs in new high-value applications.

The overall goal of the CEN Workshop is developing a CWA related to:

a) the identification of SCMs embedded ECUs (PCBs);

b) the information sharing among all the actors involved (for several reasons and with different roles) in automotive supply chains.

This document is intended to be used by car makers, car parts manufactures or suppliers and ELVs managers (e.g. car dismantlers and/or shredder companies which process ELVs). This document can support the policy makers in the development of a future digital product passport specific for PCBs and is based on the experience and results developed within TREASURE project. This activity is coherent with the new version of ELV regulation under development [8] and the current WEEE regulations [11].

Finally, the procedure could be adoptable by other sectors where the presence of electronics is relevant and SCMs can be recycled and reused.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
actuator
EED that performs movement functions with the help of components such as small electric motors, solenoid valves and the like, such as the window motor

3.2
control device
controller
EED that takes on control tasks in the vehicle, such as controlling the automatic climate control system

3.3
embedded electronic device (EED)
device in the vehicle that works with electrical power and is either connected to the central energy supply or has its own battery supply (such as for tire pressure sensors)

3.4
in-mold electronics (IME)
variant of printed electronics where devices, assemblies or products are realized by combining in-mold decoration or in-mold labelling with functional elements based on printed electronics

3.5
sensor
EED that detect or measure a physical property and records, indicates, or otherwise responds to it

4 List of acronyms

The list of acronyms used in this document is given in Table 1

Table 1 — Acronyms

ASR	Automotive shredder residue
BAT	Best available technique
BoL	Beginning-of-Life
CAGR	Compound annual growth rate
CE	Circular economy
ECU	Electronic control unit
EED	Embedded electronic device
ELVs	End-of-Life Vehicles
EoL	End-of-Life
IMDS	International material data system
IME	In-mould electronics
IMSE®	In-mould structural electronics
MDS	Material data sheet
OEM	Original equipment manufacturer
PCB	Printed circuit board
PGMs	Platinum group metals
PST	Post-shredding technology
SCMs	Strategic/Critical Metals
SSNA	Social semantic network analysis
WEEE	Waste from Electrical and Electronic Equipment

5 TREASURE project vision

Car electronics is one of the most valuable sources of SCMs in cars. On average, modern cars contain between 5 kg to 8 kg of PCBs, depending on the trim and segment considered. A scientific article that has cited a manufacturer's statistic [9] has shown that these systems can account for more than 30 % of total vehicle cost (and more than 50 % in luxury cars). From 2000 onwards, electronics saw an increased penetration in the automotive sector. A Markets and Markets research report quantified the automotive microcontrollers market in about $989.2 million in 2017, with a projection to $1,886.4 million by 2022, at a CAGR of 13.78 %. The car recycling industry finds it challenging to recover these valuable components from ELVs. Arguably, the complex set of barriers (e.g. regulatory, governance-based, market, technological, cultural, societal, gender, etc.) result in difficulties for companies to implement CE by limiting potential benefits. All these data show that the sectorial transition towards CE seems to be far from its completion, even if car manufacturers are investing big capitals trying to shift their business towards more sustainable mobility concepts. Especially at EoL stage, there are still many issues to be solved to functionally recover materials from cars (e.g. reuse recovered materials for the same purpose they were exploited originally) and the dependence from natural resources when producing new cars (even if electric/hybrid/fuel cell-powered) is still too high. This mandatory systemic transformation requires all companies/sectors to redefine products lifecycles since the beginning, by considering CE already before designing them. Considering together the wide number of barriers impacting on the automotive sector and the limited collaboration among actors involved in traditional automotive value chains, the transition towards CE cannot be reached so easily. This issue is related (especially) to two elements. From one side, BoL and EoL stages are still unconnected from an information sharing perspective. Data about materials embedded in cars are spread on a plethora of strictly protected databases accessible only by authorized actors. This way, even if data on SCMs embedded in cars are known since many years, no one can exploit them (e.g. to optimize ELV management processes). From another side, even if ELV management processes are active in Europe since the sixties, none of the actors involved in these processes is available to share their knowledge with car makers or car part suppliers. So, both car makers and car part suppliers cannot improve their design practices to make cars easier to disassemble and recycle. In this context, TREASURE can offer a good opportunity for testing innovative technologies to make the automotive sector more circular, by going beyond some of these historical limitations characterizing this industry.

In order to make better-informed decisions in design practices, understand consumers holistically, and discern and anticipate potential concerns, the cultural aspect of the CE ought to be considered. TREASURE created an online platform where industry stakeholders (i.e. consumers, experts, and industry enthusiasts) can hold discussions, exchange experiences, and explore solutions for adopting circular practices in every aspect of the automotive industry. Community-driven activities and events were organized to explore and discuss various dimensions of awareness, choices, and behaviours related to car use, ownership, disposal, and circularity. Collected data from events, interviews and discussions was coded and analysed using social semantic network analysis (SSNA) which visualizes the relationships between users, published content, topics discussed on the platform and interviews, providing insight into cultural associations and domains of meaning involved in circularity practices. By identifying connections, SSNA provided valuable insights and helped to understand the different opinions, concerns, and priorities of various stakeholders. This approach starts with the premise that all the different areas of expertise involved in the automotive industry and sustainable practices are situated in a shared cultural space, and aims to bridge the “silos” between differently specialized stakeholders. This approach also encourages collaboration towards shared goals.

6 Identification of electronic components

6.1 Variables

Typically, EEDs were grouped into different device types. EEDs that fulfil a similar function, contain similar components and have a similar composition are assigned to a specific type of device. [1]

The electronic content depends on the vehicle class and version, the brand and, above all, the year of manufacture. For example, in the past the car radio and the GPS were two separate devices. Today, however, there is usually a large multimedia module that combines the functions of the car radio and GPS. [1]

According to a study promoted by the German government [2] 47 % of the EEDs are in the front and the engine compartment with adjoining areas having a mass proportion of 65 %. Large heavy components, like starter, generator, fan engine, engine power steering are the reason for the high weight proportion. Further 45 % of the components are located in the interior with a mass proportion of 29 %. These are light electronic components, like controls, small electric motors, operating elements or screens. The rear space of the vehicle contains 9 % of components with a mass proportion of 5 %, like back lights, parking sensors, a small windshield wiper engine and some controls [3].

The EEDs can be classified in different types of device categories:

— the “control device” category (also called controller);

— the “actuator” category;

— the “sensor” category.

The highest amount of precious metals (especially gold, silver and palladium) is allocated in PCBs in numerous applications. The concentration ranges are partially very wide (up to one order of magnitude) which illustrates the heterogeneity of metal contents in the PCBs in vehicles of different ages, producers and applications. The most valuable PCBs in vehicles containing the highest amount of precious metals can be found [4] within the ECUs for the engine and infotainment, display and control unit, control panel, airbag control and auxiliary stop light. [3] On the other hand, it is important to mention that the miniaturization of electronic components has progressed further over the last decade. During the same period, content of precious metals had decreased significantly. Therefore, of the mentioned device categories this document only considers the controllers and ECUs, in which most of the PCBs are located.

The type and version of a car have a strict impact on the number and type of ECUs. Content of precious metals in an ECU depends on the function of that ECU and doesn’t depend on the size or weight. It relies on the components mounted on the PCB. Relevant are, for example, high computing power, multilayer circuit boards, but it is not possible to make a generalisation.

Information on the SCMs in electronics are not always available to car manufacturers. Suppliers can change the material composition due to cost efficiency, availability or technical changes. In addition, the information in the International Material Data System (IMDS) data base content is not publicly available, because it belongs to the car suppliers, and cannot be shared by car manufacturers. Moreover, information on material amount is not sufficient if the specific place within the considered electronic part is not known.

Update and tuning of hardware during lifetime will be done in workshops which can be independent or OEM-related. Therefore, an update has to be done by the respective workshop.

On the other hand, the future development of car electronics shows a trend to combine ECUs and to group them in 3-4 places in the car if the needed installation space is available, which could ease the disassembly process. Nonetheless, autonomous driving requires redundant ECUs for several applications for safety reasons and therefore the amount of ECUs will increase, making it difficult to locate the ECUs in few certain places. In this line, the car electronics architecture of the modern generation of electric vehicles is undergoing a profound transformation, moving away from the many individual control units of current cars and towards a small number of high-performance computers. In the future, they will provide the computing power for the functional domains in the vehicle.

7 Systemic analysis of disassembly using a value chain perspective

The increasing use of electronics and contained critical and other raw materials demands a different approach to EoL recycling, to allow for a better recovery of these materials from car electronic parts. Current traditional recycling processing of ELVs is still mainly based on the recovery of bulk materials from ELVs as driven by the traditional design and composition of cars. Removal is driven by either environmental requirements, enforcing the save removal of car liquids, tires, batteries, etc., by depollution and by economic potential of selling removed car parts for reuse to the market. Shredding and subsequent physical separation are applied to liberate the materials from the dismantled/depolluted car wreck and to separate the most predominant materials (from a mass based perspective) into recyclate fractions, such as ferrous, aluminium, copper, plastic, etc., fractions, which are subsequently sent to further final treatment processing (such as metallurgical processing infrastructures, plastic processing, energy recovery operations, etc.) to recover materials and energy from these.

In current shredding-based recycling of ELVs (and other products), valuable, minor and critical materials disperse over the various recyclate fractions, from which they cannot be recovered at all or cannot be recovered most optimally. These materials also go lost during this processing scheme, to dust and other residue fractions, from which they cannot be recovered (economically).

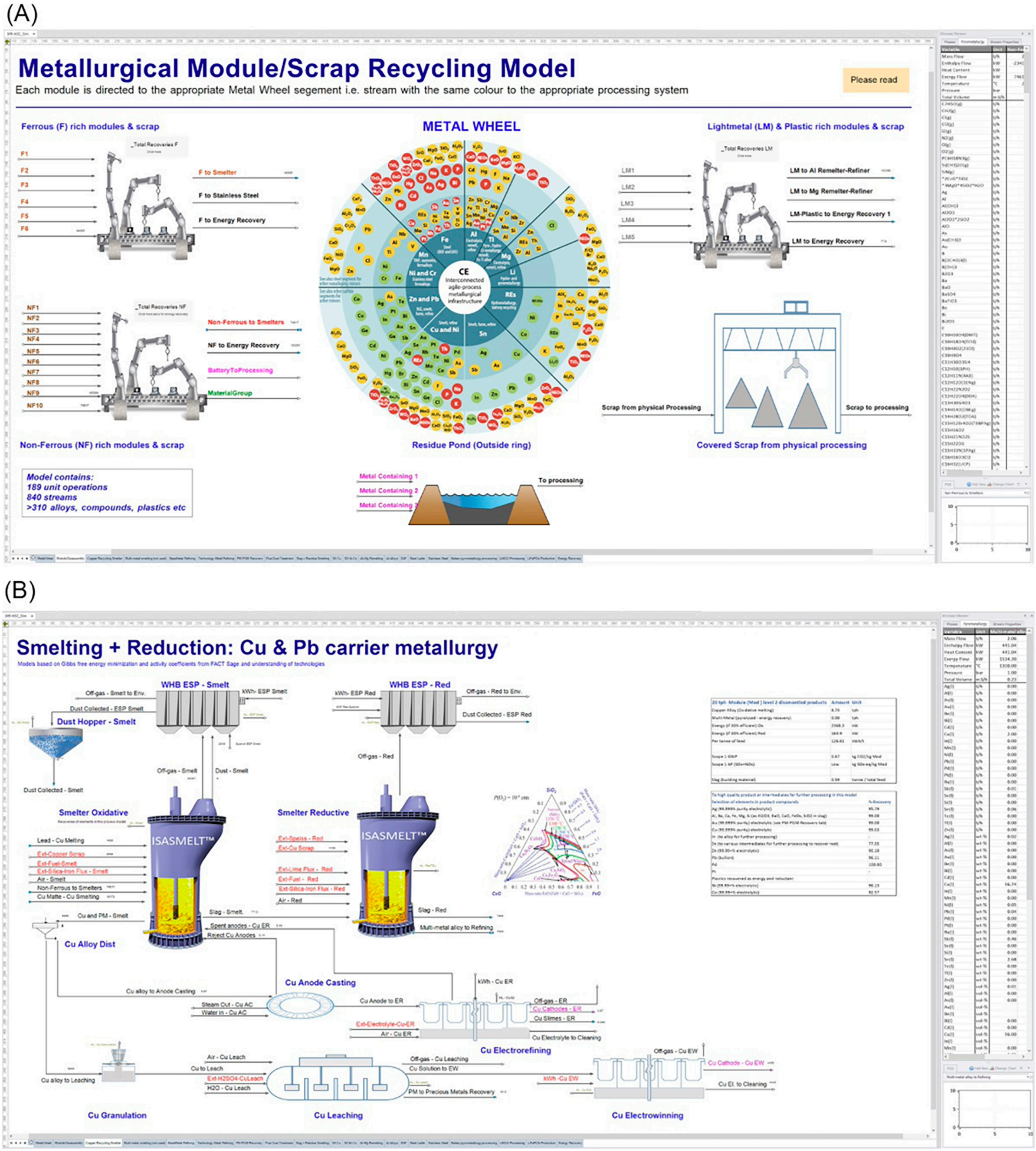
Previous research on recycling of complex EoL products such as mobile phones [6, 12] and work performed in the TREASURE project, made very clear that a novel modular, hence selective disassembly driven approach to recycling, supported by a physics knowledge based recycling assessment methodology allows for a better recyclability of materials and compounds, since modularity allows for a better ‘separation’, i.e. by (automated or manual) removal and selection of recyclates, modules or parts for subsequent focussed metallurgical and other final treatment processing. When disassembled parts are being directed to the most suitable final treatment processing infrastructures, this can result in optimized recovery, not only of SCM, but also of other material contained in e.g. car electronics, reduction of losses and emissions, and higher quality levels of recovered materials. The latter is essential in view of realizing true CE.

It is proven that additional, selective disassembly can contribute significantly to improve the recycling rate of elements and materials of interest such as SCMs as well as of connected materials and elements in a specific module or part by reducing the multi-material complexity of parts, which complicates and limits recycling due to physics and process thermodynamic reasons (nature laws). Disassembly facilitates parts and modules to be processed in the most suitable routes, leading to a higher recycling for more than just one material or element. Additional removal, however, will not always contribute drastically to the overall recycling performance in case the material and/or elements selected for additional removal have a low mass contribution relative to the total weight of the product, but is crucial from a CE point of view.

In the overall recycling performance, the materials and/or elements that have a low mass contribution relative to the total weight of the product are not well presented and do not contribute significantly to the overall recycling rate. Their recyclability cannot be deduced from the overall recycling rate, making overall recycling rate calculations based on average product data not sufficient to optimize the recycling of car electronics. Quantifying individual material recycling rates, in particular of materials/elements, which are present in low percentages as is the case for most valuable and critical materials, requires detailed product compositional data, reflecting not only the presence of the elements/materials of interest (and all others), but also their location/spatial distribution in the product tree. Comparing individual material/elemental recycling rates is crucial when selecting the most optimal disassembly and recycling options and will differ for the different car electronic parts and is depending on the materials or elements defined as critical to recover, hence on the objective of recycling optimization.

Optimization of recycling also requires rigorous methodologies and know-how on best technologies and how to most optimally link different stakeholders in the recycling system, such as disassemblers, shredding/sorters, final treatment processing to guide the flow of components/modules in the system. As the different stakeholders are optimizing their own step, this will not always necessarily lead to optimal performance of the recycling system. Only a true systemic approach can capture this. This implies that a fundamental understanding of recycling is required to assess and define most optimal levels of disassembly linked to best available techniques (BATs) recycling processing infrastructures. This can best be done based on innovative recycling system model based methodology, which provide the physics and industry based framework/tool to assess the recycling/recovery of disassembled car parts. Such approach allows to assess and quantify the recycling performance of different disassembly levels for different car parts and determine the recycling rates within the context of CE into a quality that can be applied in the same product. This can be achieved by combination of disassembly with most suitable/optimal BATs in metallurgical recycling processing as well as to determine best recycling flowsheet architecture to process the different cars parts, including most optimal level/depth of disassembly.

The figure below is a visual summary of this simulation-based approach used to determine the recycling rate of the different car parts and define the most optimal disassembly depth and combination with most suitable subsequent processing infrastructure. It shows that each car part is processed in a segment of the Metal Wheel for optimal recovery of materials and energy, where each segment in the Metal Wheel is representing a full metallurgical recycling infrastructure for the processing of the different (base and associated) metals. Detailed flowsheets for each of the processing routes are underlying this approach (B) representing the copper processing flowsheet being one of the very many processing flowsheets included in the models). The bullets in the Metal Wheel show the interaction and recovery and losses of different materials in the different recycling routes, hence directly indicating that the full compositional build-up of a car part determines the recycling rate as all materials/elements/compounds are interacting. This illustrates the need for this detail in data.



Key[3]**:**

A) The robotic (or manual) disassembly

B) Copper processing

Figure 1 — A complete model for the recycling of complex consumer products (applied to e.g. mobile phones, WEEE goods, laptops, LED lamps, and car electronics) made in process simulation software

[3] The tabs show all the involved technologies to realize the CE recycling. The many linked tabs can be observed at the bottom of the windows. In total, there are close to 200 metallurgical reactors, 1000 species (i.e. compounds, plastics, alloys, elements etc. in the various streams of the system), and 1000 streams linking them in this model.

On such rigorous basis, different disassembly levels and approaches can be tested on optimized results from recycling and circularity (e.g. including primaries required for dilution to produce alloys from recyclates) from an EoL perspective. This information will allow to establish general as well as specific quantification and recommendations regarding recyclability of the car parts. This type of recyclability analyses allows to provide technology based, quantified feedback to support and guide disassembly decisions, and provide at the same time guidelines to define the most optimal depth of disassembly, when combining quantified benefits of disassembly such as recycling parameters for all materials/compounds/elements with e.g. cost and time of disassembly combined with most optimal recycling flowsheet architectures (both from a recycling rate as well as from an environmental and circular point of view), linked to most optimal architecture of industrial BATs for recycling processing.

8 Disassembly

8.1 Identification of the level of disassembly to reach

To be able to address and understand the balance between disassembly and metallurgical and plastics processing as well as energy recovery and optimize this, detailed product and part compositional data are required, as well as a rigorous understanding of the entire recycling system flowsheet (from disassembly up to and including final treatment processing routes) linked to design considerations.

The flowsheets should cover the complete metallurgical (and other final treatment) recycling processing infrastructures present in industry for the processing and recovery of all materials and compounds of the ELV car parts linked to disassembly options. The figure above shows the cover disassembly sheet of the model that directs the modules into the different sections of the complete flowsheet to maximize recovery into the highest quality products. The recycling simulation models cover the entire recycling processing flowsheet for the optimal recycling of car (electronic) parts. These flowsheets are industrially realistic and economically viable for different processing routes. Recycling/recovery rates are calculated, different recycling processing options have been evaluated, including the energy flows within the recycling system. The work provides recycling KPI’s, disassembly recommendations and BAT flowsheet architecture for recycling of each of the parts.

The recycling assessment does not only provide recycling rates for the total car part and its materials and compounds, but also provides insight and knowhow on the industrially BAT for the metallurgical recycling processing options. This supports the recommendation and feedback on the best suitable recycling flowsheet system architecture combined with disassembly to most optimally process the different car parts.

All compositional data of the disassembled car parts and their composing modules/sub-parts should be made available be integrated into rigorous recycling assessment methods for all materials and compounds included in the car parts, allowing not only recycling rate calculations, but at the same time environmental analysis including exergy assessment (not part of this deliverable). This quantifies therefore also each stream not only in kg/h units but also in MJ/h or kW. This is rather important to analyse the true losses also in terms of thermodynamics of all materials, i.e. in terms of exergetic dissipation or losses in line with the second law of thermodynamics. In fact, this is the only correct way to fully understand the CE of products and their recyclability.

8.2 Identification of the different electronics components inside PCBs

8.2.1 General

Within TREASURE, systematic procedures have been explored and established for the extraction of pertinent data from WEEE. A specific methodology was crafted to facilitate the recognition of diverse electronic components on PCBs.

The impetus for creating this methodology was borne out of a comprehensive review of the recyclability and composition of electronic boards. This review underscored the concentration of SCMs within the components affixed to PCBs. Furthermore, it was ascertained that SCMs are not uniformly distributed across all components but are confined to certain ones. This underscores the imperative to accurately identify these components to map the distribution of SCMs on the PCB. The proposed methodology is bifurcated into two distinct phases to ensure the meticulous extraction of valuable material-related information from the PCBs. Clauses 8.2.2 and 8.2.3 elucidate the specifics of each phase.

8.2.2 Image-acquisition

At this juncture, the protocol necessitates the careful preparation of the setup to enable the image acquisition of PCBs in the specified manner. A rigorous inspection process should be established to ensure PCBs are free from contaminants such as dust, dirt, or extraneous substances that could impair the boards' visual clarity. Any contamination could lead to the exclusion of critical data during analysis, thereby impacting the integrity of the process outcomes. The environment for capturing images should be meticulously configured to manage variables, including but not limited to illumination and the placement surface for the PCBs. Considering the propensity for electronic boards to feature reflective surfaces, it is crucial to mitigate potential disruptions in image clarity. If the application of anti-reflective matte sprays is not preferred, alternative measures should be considered to address the reflection issue. Upon completion of these preparatory actions, the image capture may commence. The choice of sensor whether an RGB sensor or a standard camera is dependent on its ability to deliver an optimum pixel density per inch. This metric is critical as it influences the granularity of the data captured and varies according to the camera's specifications, including focal length and the distance from the object. Therefore, it is imperative to determine the optimal camera placement relative to the PCB to ensure the highest resolution of information is obtained during the acquisition phase. It is incumbent on the process to define the camera setup parameters clearly, ensuring repeatability and consistency in image acquisition, which are pivotal for subsequent analysis accuracy.

8.2.3 Image processing

The image acquisition phase is followed by the initiation of the analysis protocol. This protocol is governed by a systematic approach to information extraction from the captured image data set. The selection of a suitable analysis instrument is paramount, and it necessitates the deployment of advanced machine vision algorithms. These algorithms are adept at discerning and extracting the necessary features from the data set. Given the complexity of component identification as established in existing academic literature, reliance on conventional vision algorithms alone is deemed inadequate. The protocols thus mandate the integration of artificial intelligence-enhanced machine vision algorithms, which offer superior abstraction capabilities. When electing an appropriate algorithmic model, the decision matrix extends beyond the model's performance to encompass the availability and quality of the data set required for its training. Machine vision models are intrinsically dependent on comprehensive data sets, which necessitate high-resolution data and a substantial volume of labelled instances. The preparation of such data sets is resource-intensive, requiring significant data procurement and meticulous labelling a process that can be both complex and laborious. A preliminary requirement is the exhaustive evaluation of available data sets to ascertain their adequacy for training the selected machine vision model. Post-evaluation, the chosen model is to be implemented, adhering to the criteria of data accessibility and algorithmic suitability. Post-training, the model's efficacy is demonstrated through its ability to accurately categorize electronic components on circuit boards. In the context of the TREASURE project, a thorough examination of data availability revealed the insufficiency of data for the development of a model with the desired level of identification accuracy. Consequently, an alternative strategy was formulated, adopting an open-source model [18]. This model was enhanced via transfer learning methodologies to offset the data limitations, ultimately enabling the precise identification of integrated circuits on PCBs.

8.3 Disassembly procedure and equipments (function of car)

The disassembly of electronic boards is conducted in accordance with the protocol outlined in Clause 8.2. This stage is meticulously engineered to facilitate the removal of electronic components from the PCBs. The disassembly is a critical precursor to segregate material streams before initiating the recycling process. This segregation is pivotal to enhance the recovery efficiency of specific materials, particularly SCMs. To ensure the disassembly phase is both economically viable and efficient, optimization of the process is required. Within the scope of the TREASURE project, the implementation of collaborative robots (cobots) to support human operators in the disassembly task was piloted. The cobots are outfitted with a precision air desoldering tool. Upon identification of the target components for removal, the cobot proceeds to desolder these elements from the PCB. Subsequently, the operator will assist in the retrieval of these components. This approach aims to streamline the disassembly process, thereby rendering it not only feasible but also cost-effective, aligning with the broader objectives of material recovery and recycling within the project.

9 How to recycle

9.1 Define requirements of material declaration

Material declaration for recycling car electronic parts involves providing detailed information about the composition of a material to facilitate its efficient and safe recycling process. The requirements can vary depending on the recycling facility, jurisdictional regulations, and the specific material being recycled. Here are some common requirements:

— identification of electronic components in different electronic car parts;

— toxic or hazardous substances: disclose the presence of toxic or hazardous substances in components and materials, including heavy metals, brominated flame retardants, etc.;

— disassembly instructions: develop disassembly instructions or guidelines for dismantling cars at the end of their lifecycle, ensuring safe handling of hazardous components and efficient separation of recyclable materials.

Successful accomplishment of recycling, environmental and exergetic assessment requires that detailed product data of the different electronic car parts for which the recycling assessment is being performed, is available and their structural build-up. This implies in other words, that the full ‘mineralogy’, i.e. the full chemical composition of all metals, materials, compounds (implying metals, metal oxides, organics, inorganics, etc.) of the product should be available as is usual when simulating and optimizing metallurgical processes and flowsheets [6, 12, 14, 15]. In view of CE, quantification and, if possible, increase of recovery rates of individual materials, even when low in weight, is of high importance. The calculation and understanding of individual material recycling rates, puts demands on the type and detail of data available from products and parts.

The data should be available in the following format and depth:

— mass and compositional data of the different electronic car parts and sub-parts, thus all compounds, functional materials, alloys, plastics, etc. and their spatial position on these parts should be available as well as the masses for all materials and compounds related to their distribution in the part. This means aluminium in Al, an alloy of aluminium, Al_2O_3 as an oxidized/anodized layer on the aluminium, or a filler etc.;

— data should be available or convertible to stoichiometric chemical formulas that are recognizable by a thermochemically based flowsheeting simulator;

— the product data should be available based on full compositional analyses and not mainly metal and element-based approach;

— a consistent and detailed data structure should support this allowing to represent all compounds in their chemical/stoichiometric formula and corresponding masses and distribution over the car parts.

Very important is that the above list of data requirements also provides the basis to collect data from 2nd, 3rd, 4th tiers/suppliers to ensure and enforce that producers/suppliers of (car) electronic parts and components will make this data available to car producers in order to be provided to recyclers. Aggregated data or average data could be generated in order to overcome and/or capture compositional variations for different suppliers of similar electronic parts as well as to deal with confidentiality.

9.2 Additional useful information for recycling

Here below are listed some additional useful information for recycling:

— physical properties: a description of the properties of materials used in cars, such as conductivity for metals, tensile strength for plastics and thermal conductivity for cooling systems. Provide information on the durability and fatigue resistance of materials, especially those subjected to high stress or temperature variation;

— recyclability: evaluate the recyclability of the materials based on factors like ease of disassembly, material purity and compatibility with recycling processes. Assess the potential for materials recovery from components such as ECUs.

9.3 Data collection and role of data in CE

Data collection on SCMs (e.g. precious metals) for electronic components will be a challenge as only the original manufacturer of the respective electronic component on the PCB has the knowledge on the exact material composition. Vehicle manufacturers are located at the other end of the supply with several tiers in between. The automotive industry established in 2000 the IMDS to monitor compliance with global material restrictions. Nevertheless, information on the SCMs in electronics are not always available to car manufacturers.

One reason is that at the beginning of IMDS only restricted substances had to be declared and moreover the original electronic component manufacturers cannot be forced to use IMDS. For this reason, the IMDS steering committee developed Material data sheets (MDS) for “high level” and “low level” PCBs with and without Lead (Pb) on the basis of laboratory analysis from 2009 regarding the amount of contained substances. These MDS were and are still used by electronic suppliers. Regarding the content of precious metals for example these MDS are very outdated and show amounts of e.g. gold which are much higher than newer laboratory analysis show.

The second reason is, that the IMDS database content is not publicly available, belonging to the intellectual property of the original manufacturer and cannot be shared by vehicle manufacturers. Thus, there are strict terms of use for checking the chemical conformity the car part data. For this reason, car manufacturers cannot share this confidential information with the recycling industry. Therefore, if the exact composition of electronic components is essential for the recycling industry to find the correct recycling process then the electronic industry should be part of any project with regard to recycling of SCMs from electronics. Perhaps all these challenges can be tackled within the development of the Digital Product Passport (DPP). Nonetheless, it is fundamental to know which actors along the supply chain have access and to which information in order to avoid confidential and competitive issues. Thus, the development of passports should be carefully followed.

Annex A
(informative)

Identification of future electronics based on in-mould electronics

A.1 Introduction

This informative annex aims to provide initial recommendations for the treatment of automotive electronics based on In-mould Electronics (IME).

IME is an attractive alternative for conventional electronics based on PCBs for aerospace, domestic appliances and automotive due its form-factor, light weight, seamless design, high level of integration and recently also its reduced environmental impact. In printed electronics, the electronic circuitry is manufactured by printing and curing of conductive inks. The circuitry may consist of conductive tracks for external contacting and internal wiring, but also to create sensors, antennas and other electrical features or functionalities. The circuitry can be combined with elements from traditional electronics, such as semiconducting components that include capacitors, resistors, light-emitting diodes, driving chips, sensors and so forth, but also other type of electronics, such as solar cells, external sensors, external PCB driving boards, and so on. IME is currently being developed for aerospace, domestic appliances and automotive. Unique to IME is the combination of printed electronics on 2D thermoplastic substrates with a glass transition temperature (Tg) well above room temperature and shaping of the substrate a 2 1/2 or 3D shape by a process called thermoforming. Thermoforming occurs at high pressures and a temperature at or just above Tg. Subsequent injection moulding of additional plastic onto the printed circuitry provides strength, stability, rigidity and encapsulation of printed electronics from external influences.

The IME market for automotive is growing rapidly and mass manufacturing of IME parts is expected to boom following favourable assessments by OEMs. Due to the novelty of this technology in comparison to conventional electronics based on PCBs, additional measures for disassembly and recycling may be beneficial to increase recycling yields. After a more detailed description of IME, including an overview of a typical composition, this annex elaborates on disassembly and recycling scenarios.

A.2 Example state-of-the-art IME parts for automotive

For visual reference, exemplary state-of-the-art IME and IMSE® prototype parts are provided in Figures A.1 and A.2.

a) **b)**

Key

a) climate control unit

b) automotive front grill demonstrator

NOTE Automotive front grill demonstrator: 5D film insert moulding (FIM) combines rear 3D structures with colour and decoration due to the design freedom enabled by printed polycarbonate films. Integrated metal lines can be used for example for deicing to keep sensor areas clear or provide brand differentiation through integrated LED lighting powered by printed electronics.

Figure A.1 — IME prototype part

a) **b)**

Key:

a) IMSE® automotive panel

b) example layout showing buildup

i functional substrate

ii printed metal circuitry

iii semiconductor components

iv injected thermoplastic resin

v front thermoplastic decorative foil

Figure A.2 — IMSE® prototype part

Like other electronics and electronic devices, IME combines plastics with metals, semiconductor technology and carbon-based coatings that improve aesthetics or provide a function within the layer stacking as protective, adhesion or otherwise supporting layer. The coatings and bulk plastics are chosen and tuned to provide a highly reliable part that can last for years. Metals and components are largely fully embedded within the plastics. While this is highly favourable for protecting the electronic functionalities, this is less than favourable for recycling at EoL. This annex further describes a general composition of IME parts and hereafter possible steps to improve recyclability of IME parts.

A.3 Material composition

IME parts, as shown in Figure A.3, may be comprised of:

— thermoplastic bulk material as substrates and resins: 70 %–99 % by weight, depending on the design of the part, and concerns pure or a combination of e.g. polycarbonate, acrylonitrile butadiene styrene, polymethyl methacrylate, polyamide, either from petrochemical, bio-based or recycled origins;

— thermoplastic coatings: 1 %–10 % by weight and concern e.g. polyurethanes, polybutylene terephthalate and acrylates, either from petrochemical, bio-based or recycled origins. When serving as external anti-scratch coatings on the front side (the viewer side), the plastics may have been cross-linked;

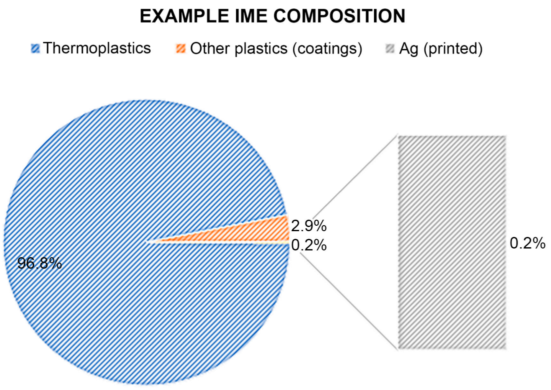
— thermoset adhesives: 0 %–1 % by weight and concern e.g. structural adhesives e.g. based on epoxy-resins;

— printed conductive tracks, 1 %–5 % or more typically 0 %–1 % by weight, are typically applied as pastes, containing 20 %–40 % solvent. Metals may be virgin Ag or Cu or preferably obtained from recycled sources. The solid weight of printed conductive material is predominantly metallic, but may be contained in a polymer matrix in the concentration range of 50 %–80 %;

— additional engineering plastics, e.g. thermoset polyimide for external contacting as flexible PCB (flex-PCB) connectors, metallized polyimide with copper (Cu).

— potentially additional plastic carriers for functional coatings or functional devices, e.g. sensors, organic photovoltaic devices, organic light-emitting diodes or even thin film displays;

— semiconductor components may be present in IME automotive electronics in < 1 % in weight as heterogenous elements that have been separately encapsulated in black epoxy moulding compound before being embedded in IME parts. The composition of these components varies heavily on the provided functionality and generally may consist of various elements, including silicon, copper, gold, silver, germanium, phosphorus, boron, indium and gallium, to name a few. SCMs are present in semiconducting components in low to very low amounts (in the order of 10^1-10^3 g/ton for e.g. Ga, In, Ag, Pd, Au).



a)

b)

Key

a) Composition of IME part shown in b) consisting of 96.8 % polycarbonate, 2.9 % other plastics (coatings, adhesives) and 0.2 % by weight Ag.

b) IME part developed in the Treasure project for automotive application as climate control unit.

NOTE Semiconductor components and external PCB driver excluded.

Figure A.3 — Example composition for a polycarbonate-based IME device

A.4 Automotive IMSE and assemblies

IME parts may be assembled in the interior as well as the exterior of vehicles, with a larger variety of products within the interior. IME may be included in seamless car parts assembled into the car body to provide some form of vehicle-to-pedestrian communication using lighting, signaling and signage. One example may be a front grill in electrical vehicles (see Figure A.1 b). Furthermore, IME may be used in e.g. small plastic emblems to provide automotive branding purposes. In the interior, IME parts may be used as door trims, mid-consoles, overhead control units, dashboard sections or potentially the entire dashboard.

Similarly to exterior or interior parts based on conventional electronics, the IME parts will be connected to main car electronics, drivers and computational units using round or potentially flat cables.

A.5 Potential recycling schemes

In ELVs, IME parts are likely to be readily accessible for removal due to their usage as part of the human machine interface. After removing the IME parts either with or without cables, these may be sold and re-used, or collected as a separate waste stream if these are not deemed valuable or re-usable. Without correct identification, the panel may instead be shredded as part of the car and end up in different recycling fractions, depending on the sorting processes applied in the plant, such as density separation and eddy-current separation, and the properties (composition) of the IME, including, if not foremost, the ratio of metal and non-metal. It is advised to include by design digital or analogue means to identify/recognize this type of automotive electronics, similarly to what is useful/desirable for future IME-based WEEE, such as control panels in household appliances. Furthermore, it is advised to contribute to the total information provided with the ELVs an overview of the amounts and locations of the IME car parts and how to remove these from the ELVs. Figure A.4 provides two scenarios for either removable or non-removable IME automotive electronics after removing these from ELVs.

The right side of the graph depicts the current treatment of IME automotive electronics if treated similarly to conventional PCB-based electronics. Such electronics are removed from the car if required by law (current ELV regulation draft), if deemed valuable because of its high SCMs content, or to sell as reusable part. If such an IME component is recycled, it may be treated similarly to household waste comprised of plastic and metallic content: parts are shredded, sorted and sold for further processing at other facilities for the further recovery of metals and/or plastics. The IME panel may rightfully be recognized as metallized plastic, similar to a PCB, but this depends on the type of metal used and the concentration of that metal. Due to the currently low concentrations of metals in IME in comparison to separate PCBs, recyclers may struggle to merge IME waste into a PCB-rich waste flow: the average metal content, and thus also the value of the waste, will drop. If treated as a contaminated plastic, incineration is the likely outcome of the recycling process.

Note that Figure A.4 is not meant to be all inclusive, but as a simplification to illustrate various different routes. Depollution, for example, such as the removal of batteries, is not included as IME parts in automotive are linked to power units in the vehicle. For further information on potential recycling routes, see bibliography. [15, 16]

Treating the IME panel as metallized plastic or as a metal component contaminated with plastics, such as a PCB, is bound to cause high losses in plastics and metals. The recycling route for removable IME (left part of Figure A.4) provides considerably more options to liberate the plastics, the metals and the semiconductor components. Irrespective of the exact details of the removal and recycling methodologies and their recycling efficiencies, more than a single recycling methodology may be applied, leading to potentially higher yields and purities with a more likely outcome that materials can be contained in a closed loop. These alternative recycling scenarios assume a full separation of the functional substrate and the bulk thermoplastic material. The functional substrate should contain most, if not all of the printed metal and most, if not all of the semiconductor components. One method to accomplish this separation is described in bibliography. [17] Recycling routes may depend on the preferred metallurgic method and the preferred plastic recycling method and may prioritize either the metals or the plastics first. Which is most cost-effective, sustainable and best supported by current industry processes is still a topic for further research.

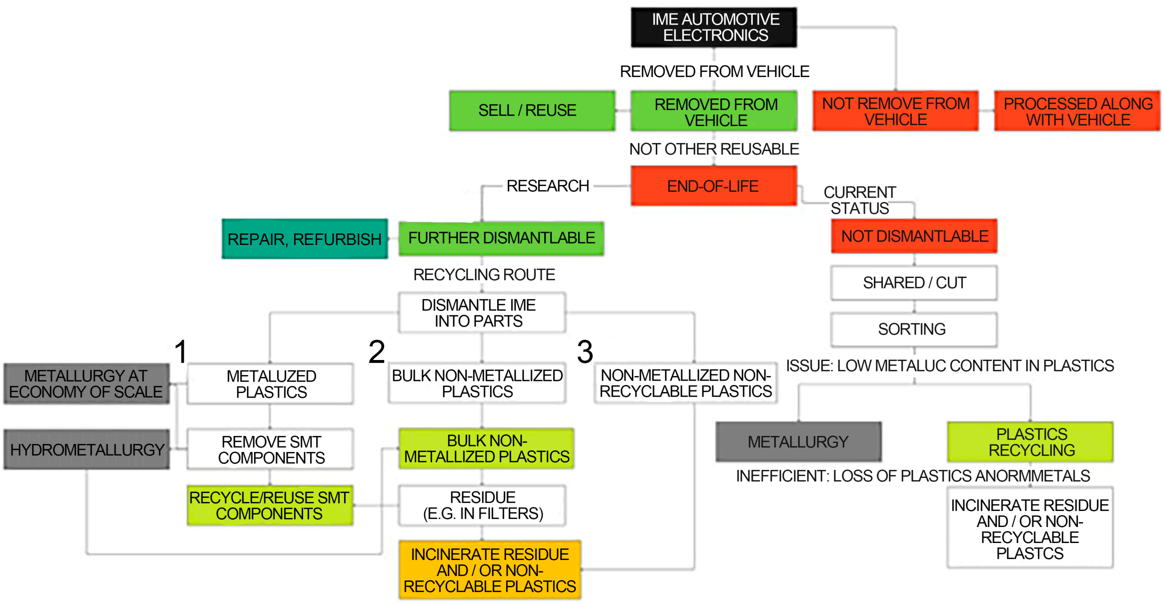


Figure A.4 — possible removal and recycling schemes for IME automotive electronics enabled by sustainable developments [17]

A.6 Advice

To prevent materials from IME automotive electronics to be lost, we advise:

1) removing IME automotive electronics from ELVs, following recommendations by the manufacturer of the part and/or the vehicle;

2) to treat IME automotive electronics in accordance to information/recommendations from suppliers/manufacturers (3. and further);

3) to label IME products in vehicles using analogue or digital means to improve processing at EoL using information captured in a database in the cloud or a digital passport (when available/applicable);

4) to capture within such information (in 3.) a description on how to efficiently remove IME automotive electronics from an ELV;

5) to capture within such information (in 3.) a description on how to further disassemble such parts, thereby making use of the design-to-recycling;

6) to contain within such information (in 3.) a description of the composition:

   i. plastics;

   ii. metals;

   iii. SCMs;

   iv. semiconducting components yes/no, preferably including type, manufacturing, serial code, etc.

   v. please consult the main text of this document for data requirement and other recommendations.

Annex B
(informative)

Connection among data sets outside the TREASURE project

Concerning the data collected by the platform, different data sources that contribute to populate the TREASURE Data Lake. In the scope of this project, several kinds of data sources have been taken into account, ranging from the output of different tools constituting the TREASURE Platform, knowledge provided by involved technical partners and additional information coming from industry-standard external data sources. The complete set of information contained in the TREASURE Data Lake are the following:

— technological information concerning car part material composition coming from external data source, i.e. IMDS database;

— augmented reality procedures, execution logs and user feedback, coming from the WEAVR Platform;

— semantic information, ethnographic data and user sentiment analysis, coming from the SSNA Platform;

— information about car parts, components, materials and removal instructions, coming from BoL actors (cars/components manufacturers) and EoL actors (car parts/components disassemblers and dismantlers);

— environmental KPIs, materials life cycle information and recycling best-practices, coming from the Recycling simulation Tool;

— socio-economic KPIs coming from a sustainability assessment tool.

As for the database used, within TREASURE the access to confidential data sources is focused on the IMDS database because for the project scope it contains the most applicable and valuable information. A mapping of the available databases has been previously performed and some data sources have been tested (IDIS and Quattroruote). Given the analysis to be performed for the project objectives, the IMDS database includes the wider range of data concerning material composition of car parts belonging to SEAT use case. In the Table B.1, the full list of selected data sources is presented with the explanation of pros and cons in using the specific database.

Table B.1 — Data sources mapping

Database name	Database Owner	Use/relevance in Treasure	Data provided	Data type	Strategy to access data	Platform module involved	Assessment on suitability	Notes
RMIS	EU	High	ELV volumes, embedded materials - average	n.d.	Free	All	Relevant, no restrictions	No compositional data is provided. The RMIS only uses a single material approach by indicating which elements are used (per country) or which elements are put on market (for some cases related to parts/products). However no data is available on part or product composition.
IDIS	TEC4U	High	ELV disassembly procedures	PDF	Private access	Disassemblability	Relevant, private access, read-only option	The information provided is too generic and broad to be used for the TREASURE platform. Some data is missing for older car models
IMDS	DXC	High	Materials embedded in ELVs - details	EXCEL	Private access	All	Relevant, private access, read/write options	Closed data base
SCIP	EU	Low	Hazardous materials	n.d.	Free	Eco-design	Convenient, no restrictions	The database doesn't include detailed data

Database name	Database Owner	Use/relevance in Treasure	Data provided	Data type	Strategy to access data	Platform module involved	Assessment on suitability	Notes
Eurostat	EU	Medium	ELV volumes	EXCEL	Free	Recyclability	Convenient, no restrictions	Data provided is too generic to be used for the project use case
audatex	solera	low	Insurance, for economic assessment of disassembly	nd	private	disassemblability	Restricted	Databased focused only on car model identification for part repair; thus it's not relevant for the project
Infocar data	Quattroruote	medium	disassembly	pdf	private	disassemblability	restricted	Provided data refers to some models and it's not always complete; the information doesn't include electronics components
raupe	offis	low	Assessment of reusability of used car part components	nd	private	recyclability	restricted	Data is partial related to specific use cases so it's not relevant enough for the project
azeler	Azeler Automoción SL	low	Car part repair data base to sell and buy used car components	nd	private	disassembly	restricted	No relevant information provided

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