D3.3: Recyclability analysis

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Technical References

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EXECUTIVE SUMMARY

The assessment of the recyclability of the various car parts as selected for disassembly in T3.1 and T3.2, as well as of their composing materials, elements and compounds is of importance to evaluate the performance of these parts and the effect of disassembling these parts in terms of Circular Economy. In this Deliverable, the calculation of recycling rates of the car parts for true circularity, i.e. into materials with a quality that can be applied in the same product (closed loop CE) and the assessment of the recycling system has been performed by the application of recycling flowsheet simulation modelling.

The following 7 car parts have been assessed in terms of recyclability:

- Infotainment unit – Leon II (level 1 disassembly)
- Infotainment unit – Leon III (level 1 disassembly)
- Combi-Instrument – Leon II (level 1 and level 2 disassembly)
- Combi-instrument – Leon III (level 1 disassembly)
- Combi-instrument – Ibiza IV (level 1 disassembly)
- Additional brake light – Leon II (level 1 disassembly)
- Additional brake light – Leon III (level 1 disassembly)

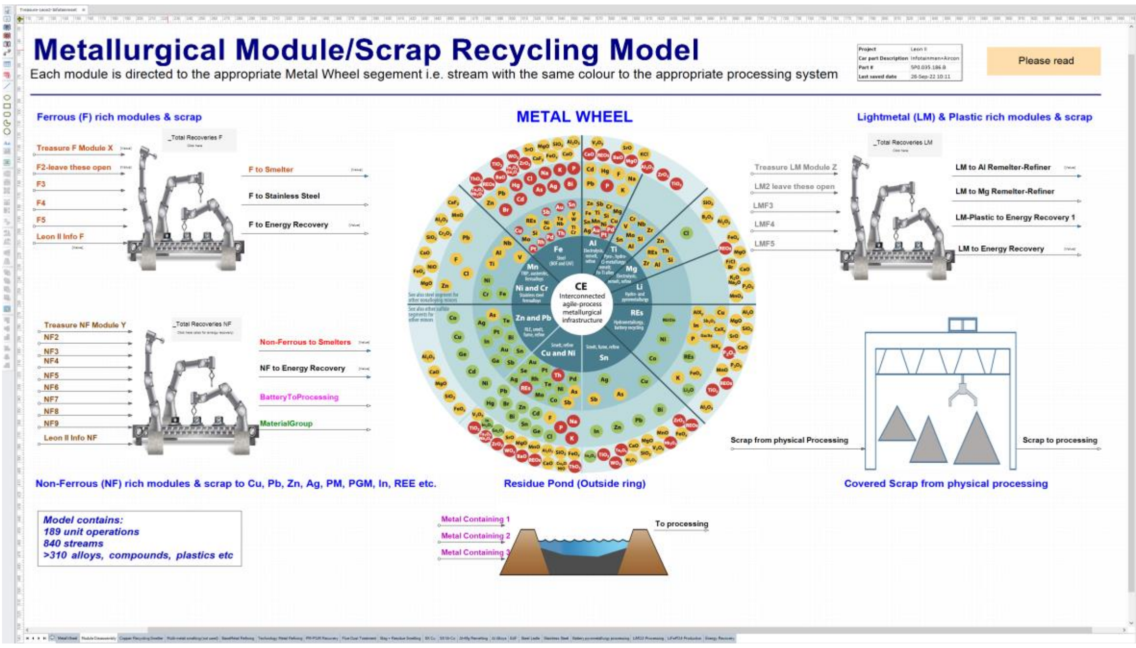
In T3.2 disassembly of the different car parts was explored and analysed. In order to assess the effect of additional disassembly on recycling performance also the level 2 disassembly was included in the recycling assessment. The assessment of level 2 disassembly of the Combi-instrument of the Leon II has been included in T3.3. This analyses also reveals the link between T3.2 and T3.3. This assessment will be expanded for more car parts as listed in Table 1 in the course of the project.

The assessment and underlying calculations as performed by the application of rigorous and physics-based process simulation model include the complex interlinkages of functional materials in the car parts as well as all chemical transformation processes in the reactors in the system model in versatile flowsheet simulation modules. These are provided in the report. This approach permits the rigorous evaluation of the recyclability of a product within the circular economy not simple cherry picking of elements, disregarding all other materials.

The figure below is a visual summary of the simulation-based approach used to determine the recycling rate of the different car parts. It shows that each car part is processed in a segment of the Metal Wheel for optimal recovery of materials and energy, where each segment in the Metal Wheel is representing a full metallurgical recycling infrastructure for the processing of the different (base and associated) metals. Detailed flowsheets for each of the processing routes are underlying this approach. Due to the complex mixture of materials in the car parts, it is not possible to define a most suitable processing option upfront, therefore, for each car part, based on its composing material composition, the two or three best options are selected based from the full metallurgical recycling infrastructures as available and depicted in the Feed sheet based on the expert knowledge within MARAS. By doing this, the most optimal recycling route can be selected based on the achieved recycling results.

The flowsheet model used for this simulation-based approach is based on industrial economically viable processing. It contains almost 190 unit operations for the ca. 310 materials and compounds in the car parts and produced by the flowsheet as well as over 840 streams for all phases including metals, molten flows, aqueous, dust, slimes, slags, calcine etc.

The recycling assessment, incorporating the full compositional detail of the car parts, recovered through metallurgical processing and energy recovery flowsheets and calculated recycling rates for the total car parts as well as all individual materials/elements provide the physics-based quantification to optimise Design for Recycling and make decisions and recommendations for more in depth disassembly.



The main conclusions from this study are:

Recycling simulation models for recyclability assessment

- The recycling simulation models provide a rigorous and physics based back bone for true industry based recycling assessment and forthcoming recycling system set up and DfR (Design for Recycling), design for modularity and disassembly recommendations.
- This can only be done, when the complex interlinkages of functional materials in the car parts as well as all chemical transformation processes in the reactors in the system model in versatile flowsheet simulation modules are included as is the case in this model and industry based method.

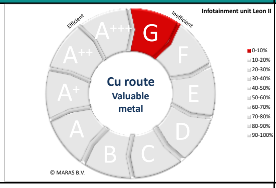
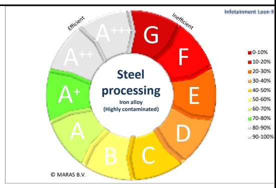
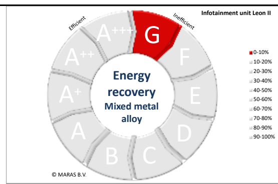
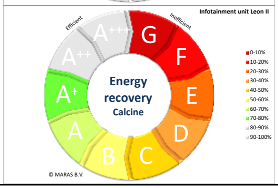
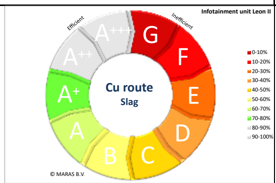
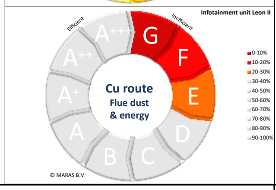
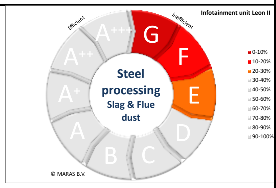
Recycling KPIs and Circular Economy

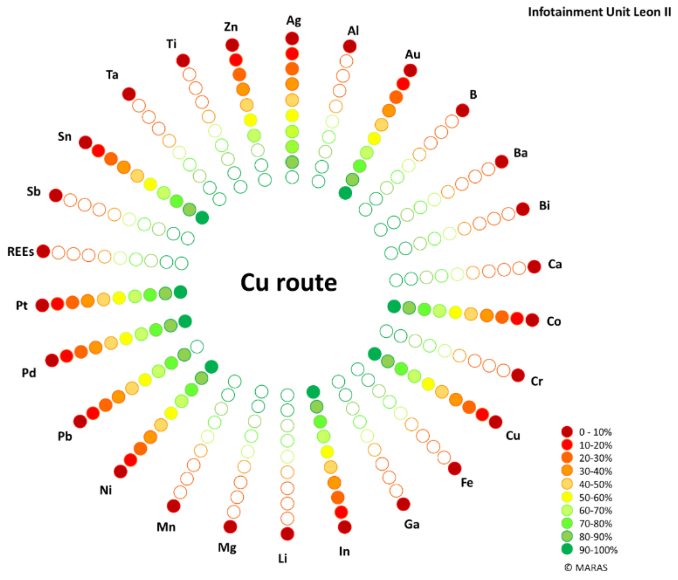
- The starting point of recycling (and simulations) is to create material and metal products, alloys, compounds etc. of a functional quality so that these can be used in the same product these have originated from. This would be true circularity. Three different levels of circularity have hence been defined to assess the recycling results (i.e. (1) closed loop CE recycling, (2) open loop CE to be processed into closed loop CE and (3) open loop CE recycling.
- Recycling KPIs are defined from the recycling simulation modelling approach
    - total Recycling Rate (%) of the product/part as depicted by the Recycling Index as developed by MARAS (see Figure below for the 3 levels of CE obtained for the Infotainment Unit of the Leon II level 1 disassembly)
    - Recycling Rates (%) for all individual materials/elements as present in the car parts. These are depicted by the Material Recycling Flowers (also developed by

MARAS) (see example of the Material Recycling Flower below for the recycling results of the Infotainment Unit of the Leon II level 1 disassembly)

- Energy recovery (MWh/t feed or per part)

- These KPIs can flow into Eco-Design tools, the Recycling and Eco-design module of the TREASURE platform, etc.

Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		No high quality CE products	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			 
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.15 MWh/t feed	No energy recovery (energy input required in the process)	1.77 MWh/t feed



Data processing and automation

- Successful accomplishment of recycling as well as environmental and exergetic assessment demands that the full 'mineralogy', i.e. the full chemical composition of all metals, materials, compounds (implying metals, metal oxides, organics, inorganics, etc) is available and applied for the analyses. Without this depth of data, recycling and linked EoL exergetic assessment is not realistic nor will lead to reliable results.
- The MISS files as provided by SEAT require, in spite of their relatively structured set up, extensive data analyses, processing and completion to define data into a consistent and detailed format, i.e. in a form that a thermochemically based simulator can recognise to provide the relevant thermochemical information and perform calculations. This implies that all materials/compounds/elements (including all organics) are described in full chemical composition and corresponding masses in the part.
- The data processing reveals that the car parts as included in the recycling assessment contain more than 320 different compounds (metals, alloys, oxides/sulphides, inorganics and organics), of which around 220 organics.
- Classification of the organics have been applied in view of the future step of moving the recycling simulation platform into the Recycling Module of the TREASURE platform and allow a more smooth transfer of data.
- The process of data classification can only be performed, the moment the full compositional detail of all organic compounds is known from the extensive data analyses and processing.
- The processing, completion and structurisation of the data is extremely time consuming, as for this moment, this can only be done manually. Automation/digitalisation of input data is essential so that it can link the product design easily to a digital twin of a metallurgical and energy recovery processing infrastructure for the development of the Recycling Module in the TREASURE platform. Recommendations are provided in this Deliverable for this.
- Classification of input composition is part of this process in view of preparation of data sets from the detailed simulation model to create surrogate functions that twin the simulation

model. These neural net – AI (Artificial Intelligence) based tools can then be trained and easily integrated into design tools.

Results of the recycling assessment

For the assessment of the total car parts, the following can be concluded:

- The composition of the Infotainment Unit is characterised by a low valuable metal content (low in Cu and related valuable metals), a relatively high Fe content (however with the presence of many contamination metals) and high content of organics. Both the Combi-instrument as well as additional Brake Light for all car models show a very low Fe content, a very low valuable metal content and a very high organics content.
- Three different recycling routes have been tested in the recycling assessment of the Infotainment Unit, i.e. the Cu processing route, the steel processing route and the Energy recovery route (see figure above). For the other two car part types, only the Cu processing route and the energy route would, due to the very low Fe content of these parts, be suitable and have been tested for recycling assessment.
- In general, it can be concluded that depending on the selected recycling processing route, the valuable metals which are compatible with the Cu segment of the Metal Wheel can be recovered. No closed loop recycling can be achieved for Fe and organics. The overall recycling rate for all 7 car parts as assessed in this Deliverable is low, due to the composition of these parts.
    - Due to the very low valuable metal content, the recovery of the car parts into high quality closed loop CE products is very low. Cu processing route can recover these materials into closed loop CE applications.
    - No closed loop recycling can be achieved for the Fe. Due to the presence of many contaminating metals for steel recycling such as , Pb, Cr, Co, Au, Cu, Mn, Mo, Ni, Ag, V, Sn, Sb, As, Bi, Ga, In, Pd, Ru, Ta, Nb, W, Ge, Pt, C, Be, S, Zn, the recovery of the Fe results in a highly contaminated iron alloy, hence no closed loop CE recycling. To render this alloy to a closed loop CE product, this alloy has to be diluted by pig iron or Direct Reduced Iron (DRI), but this may not achieve the tight specifications of steel alloys and carries with it the carbon footprint of the primary pig iron production, with a negative environmental as a consequence, while nevertheless the many harmful elements will also then have a negative impact as mentioned due to steel alloy specifications.
    - In the energy recovery route, the energy content of the organics is recovered (however never with an efficiency far below 100%). No closed loop recycling is achieved in this process. The calcine and metal phase as also produced in this process are open loop CE fractions, which needs further upgrading to render this to a closed loop recycling.

The assessment to determine the effect of additional (level 2) disassembly shows the following:

- Recyclability of the car part increases, as sub-parts are created, with a more comparable composition, matching with the different segments in the Metal Wheel allowing a separate processing of the different sub-parts/modules in the most suitable recycling route (rather than having to select a sub-optimal (most acceptable) processing route for the entire part)

- Increase in total recovery can be achieved, although this depends much on the mass contribution in the total part of each the separated 'leading' materials (e.g. Fe content, Cu content, etc.)
- Increase in the recovery of the individual elements/materials of product into closed loop CE high quality products
- Mitigation of creation of open loop CE products (such as slags/flue dust)
- Recovery of (in)compatible materials separated over different sub-parts is now possible in different processing routes
- Ability of recovering both (valuable) metals and energy content with minimisation of losses of valuable metals e.g. to open loop CE products (to be processed into closed loop CE) such as mix metal alloys and/or calcine

Selection of most optimal recycling processing routes

- Based on the outcomes of the recycling assessment and the calculated recycling KPIs, the most suitable recycling route(s) can be defined. Comparing individual material recycling rates is crucial in this discussion.
- As a consequence of the complex and heterogenous mix of materials in the car parts, there is no one best option to process these different parts, as each of the processing options, will lead to recovery of certain elements, and losses of other, as depicted qualitatively by the Metal Wheel.
- When the focus is to recover as much (valuable and critical) metals from the car part, the most preferred route from a closed loop CE point of view, would be to process this part in the Cu route. In spite of low recovery rate, in the Cu processing route high quality closed loop CE products can be realised, while at the same time (part of the) energy contained in the organics fraction is recovered. The incompatible materials will either report to the slag or flue dust, which can be applied as open loop CE products. It has to be considered, that due to the low Cu content, recycling of this car part requires a significant input of heat and primary resources to obtain the correct operation point. This can be considered as a negative point for this processing route.
- Due to the very high organics content, the energy processing route would be the best option to recover the energy as contained in these organics. In this process, also a metal phase and calcine are produced, however these are both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading, e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE.
- For the processing of the sub-parts created through additional disassembly, a combination of the different recycling routes can be applied, resulting in a more optimised recycling of the part under consideration.

Recommendations for additional disassembly and Eco-design/Design for Recycling

Additional disassembly

- Additional disassembly of the car parts into sub-parts or components is recommended to optimise the recyclability due to the complex combination of materials, low valuable metal content and high concentration of organics/plastics in these parts

- The composition of the sub-parts created by additional disassembly should be aligned (as far as possible) based on the (in)compatibility of materials as reflected by the Metal Wheel, implying that for compatible materials there is no need to further separate and for incompatible materials (which either get lost or are harmful to the material product being recovered) should be separated by additional disassembly (within limits of possibility)
- The effect of additional disassembly (level 2) is clearly visible on the recycling results and leads to increased recycling performance. Results of this assessment can be applied to guide and assess level 2 and level 3 disassembly for other car parts
- (Further) recommendations for additional disassembly are to separate the organics containing sub-parts from the Cu (and related metals) based (sub)parts to increase the concentration of valuable elements in the Cu based part, while the metal content of the organic-based fraction for energy recovery can be decreased recovery of plastics and organics are recovered in their original quality can be increased.

Eco-design/Design for Recycling

- DfR should be focussed, within the limits of product functionality, on designing sub-parts/modules in which their composition is harmonized with the compatibility of the metals in the different sections in the Metal Wheel. The individual recycling rates as calculated in the recycling assessment quantitatively support and guide, which options in both additional disassembly and/or DfR will have the highest impact in improvement of recyclability. Additionally, rarity based % as defined in D3.1 could be used as a driver to select materials/elements and disassembly and DfR options. Physics-based DfR as part of Eco-design will be further expanded and detailed in Task 3.4.

The modelling, data processing and full recyclability analyses and interpretation of the results have been performed by MARAS. The MISS data has been provided by SEAT. UNIZAR selected, in consultation with SEAT the car parts for disassembly and was committed to test the data processing based on MARAS' instructions, to create a common understanding in view of future activities on Eco-Design in T3.4 and WP4 and the automation of the data processing for the TREASURE platform. This work provides input and links to various other deliverables within the TREASURE project related to recycling and Design for Recycling, such as the development of the TREASURE platform, Recycling Module, AI modelling and recycling assessment and Recycling Module development and application in the use-cases as well as within WP5 and WP6. The work as described int D3.3 provides the rigorous basis for all activities and advice related to recycling assessment and quantification, recycling optimisation and Design for Recycling within this project.

TABLE OF CONTENTS

1. Introduction

1.1 Goals and purpose of the Recyclability Analyses

Task 3.3 will set up an innovative recycling system model to assess the recycling/recovery of the car parts, selected in T3.1 for disassembly based on the rarity indicators, and of which disassembly was analysed in T3.2. The recyclability assessment has been performed by the application of recycling flowsheet simulation modelling. The recycling performance of different disassembled car parts, as selected in Task 3.2 have been assessed to determine the recycling rates within the context of circular economy into a quality that can be applied in the same product. This can be achieved by application of Best Available Techniques (BAT) in metallurgical recycling processing as well as to determine best recycling flowsheet architecture to process the different cars parts.

The different disassembly levels and approaches defined in T3.2 are hence tested on optimised results from recycling and circularity (e.g. including primaries required for dilution to produce alloys from recyclates) from an End of Life (EoL) perspective. This information will allow to establish general as well as specific quantification and recommendations regarding recyclability of the car parts. Results of the recyclability analyses will hence provide technology based, quantified feedback to support and guide disassembly decisions, but will at the same time provide input to define the most optimal depth of disassembly, when combining recycling parameters with e.g. cost of disassembly (of which the latter is no part of this Task 3.3). Most optimal recycling flowsheet architectures, based on industrial Best Available Techniques (BAT), will be advised based on the assessment as derived from the recycling simulation models.

The assessment and underlying calculations as performed by the application of rigorous and physics-based process simulation model include the complex interlinkages of functional materials in the car parts as well as all chemical transformation processes in the reactors in the system model in versatile flowsheet simulation modules. This approach permits the rigorous evaluation of the recyclability of a product within the circular economy, not simple cherry picking of elements, disregarding all other materials.

In the assessment by the application of the developed recycling system model, all mass flows, recoveries and losses for all metals/materials and elements/compounds (both on physical as well as chemical level) will be revealed. The research is following a Product Centric approach towards recycling as defined by Reuter and Van Schaik (Reuter and Van Schaik, 2013). This implies that the focus goes beyond only representing Critical Raw Materials (CRMs), as the combination of all materials/compounds/elements present interact during chemical and physical recycling and determine the recyclability and are crucial to quantify Circular Economy in the EoL stage of a product. Only selecting CRMs or any other metal/material under consideration, while ignoring all other materials/elements/compounds, will lead to erroneous results.

The process simulation model has been developed in the industrial software platform HSC Chemistry Sim® 10 (www.mogroup.com), providing a professional and industrial platform for process simulation tools and recycling as well as environmental impact calculations (please note that environmental impact calculations are not part of T3.3 but are implicitly included in the models).

The recyclability analyses hence comprise of the following the activities:

- Development and application of recycling simulation models for recyclability analysis
    - Recycling/recovery assessment based on disassembly linked to most suitable industrially available BAT carrier metallurgical recycling infrastructures
    - Assessment based on full mass (& energy/exergy) balance for all materials/metals/elements/compounds of selected car parts
    - Definition of link between design data and chemical/metallurgical recycling: data interaction within TREASURE project of crucial importance (digitalization)
- Assessment of results of modular (disassembly driven) recycling and assessment of and recommendations for most optimal disassembly depth
    - Assessment of modular (metallurgical) recycling for the different disassembly levels, i.e. improved disassembly strategies to optimise recycling/recovery during chemical recycling that produces the required high-quality materials that can return to the same part of larger product, i.e. cars
- Definition of most optimal recycling system architecture
    - Definition of the most optimal recycling system architecture (flowsheet configuration) for the processing of the different disassembled car parts for optimal recycling/recovery
- Calculation of Recycling/recovery rates to quantify the recyclability of the various car parts
    - KPI's on recycling/recovery for whole parts/product as well as for individual elements/materials
    - Presentation of recycling assessment results in terms of the Recycling Index, which present the total recycling rate of the car part (or product) as well as in terms of the Recycling Material Flower (Reuter & van Schaik, 2018), which shows the individual recycling rates for all elements included in the car parts.

1.2 Background of the work

A selection of references from high impact journals as well as industry applications of the recycling simulation models for recycling assessment, recycling rate calculations and Design for Recycling and Eco-design recommendations are the basis for this work. The simulation model has evolved over the years as developed and explained in these publications (see various references by Van Schaik/Reuter/Ballester).

The recycling simulation models provide a rigorous and physics based back bone for true industry based recycling assessment and forthcoming recycling system set up and DfR, design for modularity and disassembly recommendations.

The starting point of the recycling (and simulations) has always been to create material and metal products, alloys, compounds etc. of a functional quality so that these can be used in the same product these have originated from. This would be true circularity.

The guiding light has always been to maintain material quality, thus minimize exergy dissipation through low energy quality or dilution. The unit for this is kW, the same as energy flow. This therefore harmonises the circular and recycling performance in one unit, i.e. kW (Reuter et al. 2019). This goes beyond simpler foot printing methodologies, that lack rigour.

2. Data analysis and processing of car part data, completion and consistency check of data, mass balancing and transformation to data format suitable for simulation

Successful accomplishment of recycling assessment on a rigorous simulation basis requires that detailed product data of the product/car parts for which the recycling assessment is being performed, is available, i.e. in this case for the different car parts and their structural build-up. This implies in other words, that the complete “mineralogy” of the product must be available as is usual when simulating and optimizing metallurgical processes and flowsheets (see Reuter and Van Schaik, 2013; Van Schaik and Reuter, 2014 a & b; Ballester et al, 2017).

Figure **1** gives an overview (obtained from Task 3.2) of the different car parts (to be) selected for disassembly. This figure reveals the focus on metals, which is applied in the rarity assessment (% given in figure). As indicated, successful accomplishment of recycling as well as environmental and exergetic assessment demands that the full ‘mineralogy’, i.e. the full chemical composition of all metals, materials, compounds (implying metals, metal oxides, organics, inorganics, etc) is available and applied for the analyses. Without this depth of data, recycling and linked EoL exergetic assessment is not realistic nor will lead to reliable results. The data as presented in Figure 1 is hence processed in this Task 3.3 to a much more detailed compositional build-up based on the data processing as described in this Chapter.

Figure 1 Overview of car parts selected for disassembly (figures and figure obtained from Task 3.2) and general approach to data specification, which reveals the focus on just the CRMs/metals contained in the different car parts in view of determination of rarity% (organics, inorganics and oxides are not shown)

Car part		Leon II	Leon III	Ibiza IV
		Main critical metals from Rarity point of view and share over the car part Rarity (%)	Main critical metals from Rarity point of view and share over the car part Rarity (%)	Main critical metals from Rarity point of view and share over the car part Rarity (%)
	Infotainment	Ta (57%); Pd (26%); Au (7%)	Ta (64%); Au (18%); Pd (5%)	Ta (64%); Au (18%); Pd (5%)
	Combi instrument	Au (53%); Ta (36%); Pt (6%)	Ta (76%); Au (8%); Pd (6%)	Au (45%); Ta (31%); Pt (16%)
	Exterior mirrors	Zn (60%); Cu (34%); Ni (2%)	Cu (44%); Ta (21%); Zn (15%)	Cu (77%); Mg (5%); Zn (5%)
	Additional brake lighting	Au (53%); Ta (37%); Pt (6%)	Ta (73%); Au (8%); Pd (6%)	Cu (79%); Cr (18%); Mn (1%)
	Speed sensor	Au (91%); Cu (4%); Pd (4%)	Au (91%); Cu (4%); Pd (4%)	Au (91%); Cu (4%); Pd (4%)
	Rain sensor	Au (53%); Ta (37%); Pt (6%)	Ta (73%); Cu (7%); Au (7%)	Non available in this model
	Air quality sensor	Non available in this model	Ta (76%); Au (7%); Pd (6%)	Non available in this model

The selected car parts belong to SEAT models Ibiza and Leon and correspond to the most critical ones according to the assessment carried out in Deliverable 3.1. SEAT Ibiza and SEAT

Leon models have been chosen, given that they are the most representative models in terms of sales of SEAT brand. From 2005 to 2019, more than 2 million cars of these models have been sold worldwide. In addition, both models Ibiza and Leon are hatchback compact cars, based on Volkswagen (VW) Group platforms (A0 and A respectively). Therefore, most of the contained car parts are shared among many vehicles from the Volkswagen Group. That is, Ibiza shares VW Group platform with VW Polo, Audi A1 and Skôda Fabia, whereas Leon with VW Golf, Audi A3 and Skôda Octavia. Overall, such vehicles represent different generations of cars covering as many different car parts and configurations as possible. Further, the high trimmed version has been selected, due to the higher proportion of electronic car parts. In addition, considering that more than 2 million cars have been sold in the last years, it becomes clear that enough volume of such cars will be arriving at Authorised Treatment Centres (information from ILSSA).

2.1 Data analyses and processing

Data on the composition of the car parts identified for disassembly has been made available in the format of MISS data files as provided by SEAT. The MISS data files have been set up to comply to ELV directive requirements. Hence, although the data in the MISS files is provided in a relatively well structured and detailed format, the MISS files require extensive data analyses, processing, structuring and completion to prepare and structure this in a consistent and detailed format, from which the input to the recycling simulation models can be defined i.e. must be available in a form that a thermochemically based simulator can recognise to provide the relevant thermochemical information (see Figures and Tables below). The material information is mainly only detailed for the metals, and structure and consistency requires improvement. This means the full compositional information of all materials must be made available from the MISS data files, as well as their distribution over the sub-parts to provide the input to the recycling process simulation models to calculate the recycling performance into high quality products.

These data as provided by SEAT have been analysed and processed by MARAS to define the input data for the recycling assessment per car part. This involves the following activities:

- Data have been analysed on completeness, consistency, unclarities and possible errors in data as detailed in this list below
- Identified data inconsistencies or errors have been identified and corrected when present (e.g. mass balance inconsistencies, missing material/compound data, etc. – also see below)
- Data (gaps) have been completed where required and if possible (missing material/compound data, chemical formulas, CAS numbers, etc)
- Mass and compositional data have been verified, completed and calculated. The data is defined in terms of complete composition of the product/part and sub-parts, thus all compounds, functional materials, alloys, plastics etc. and their spatial position on the car parts and sub-parts. This means aluminium in Al, an alloy of aluminium, Al_2O_3 as an oxidized/anodized layer on the aluminium, or a filler etc.
- All data have been transferred from material descriptions, names and/or CAS numbers to stoichiometric chemical formulas that are recognisable by a thermochemically based flowsheeting simulator. This has been done based on a very extensive consultation of material and compositional databases.
- Data description of organic compounds, which are in general only provided in a descriptive manner in the MISS data, have been added to the data file in terms of CAS numbers and

stoichiometric formulas/composition. This is important as this determines the enthalpy and entropy of the compounds.

- The product data is moved from a mainly metal and element-based approach to a full compositional analyses.
- In order to support the data processing and improvement, a database is being built up containing material compositions and chemical/molecular formulas to ease upcoming data-analyses on other parts.
- Masses for all materials and compounds related to their distribution in the part are calculated.
- A full mass and compositional analyses in terms of chemical formulas have been defined and derived for each of the different car parts and sub-parts as listed in the MISS. Excluded are confidential material and compound data.
- A consistent and detailed data structure has been defined representing all compounds in their chemical/stoichiometric formula and corresponding masses and distribution over the car part as required for recycling assessment

2.2 Car parts included in the Recyclability Assessment

Figure **1** and Table **1** give an overview of the car parts (to be) selected for disassembly (obtained from Task 3.2). In consultation with SEAT and UNIZAR, a selection has been made from below Table, which car parts are within Task 3.3. included for the recycling assessment. It was decided that a selection of car parts would be made for the Leon II and Leon III models, also to be able to compare the difference in recycling behaviour of these subsequent version of this model. As also data processing was performed on data of the Combi-Instrument from the Ibiza IV (this data file was the first MISS file as provided by SEAT to MARAS), this part is also included in the recycling assessment within T3.3. The following car parts have been assessed in terms of recyclability:

- Infotainment unit – Leon II
- Infotainment unit – Leon III
- Combi-Instrument – Leon II
- Combi-instrument – Leon III
- Combi-instrument – Ibiza IV
- Additional brake light – Leon II
- Additional brake light – Leon III

The above list reveals that not all car parts as included in T3.2 are included yet in the recycling assessment. As the data processing and completion from the MISS data files was extremely time-consuming (different than was foreseen/expected due to the structure and scope of the MISS data files), a representative set of parts was selected to perform the recyclability assessment. This selection includes the most complex car parts from the list (i.e. the infotainment unit and combi-instrument). The parts which are included are selected to be representative to demonstrate the methodology applied, assessment of different recycling routes and results achieved from the recycling assessment and how these could be applied to define disassembly recommendations and Design for Recycling input. The other car parts as listed in Table **1** will be assessed in terms of the different use cases within the TREASURE project, the set up and testing of the Platform and for Eco-design purposes.

The data processing and analyses have been performed for the above 7 car parts.

Table 1 Car parts selected for disassembly in Task 3.2

Car part name	Group	Leon II	Leon III
Infotainment unit	Infotainment-Combi Instrument - Air conditioning unit	x	x
Combi-Instrument*	Infotainment-Combi Instrument - Air conditioning unit	x	x
Exterior mirror	Mirror / lighting	x	x
Additional brake light	Mirror / lighting	x	x
Speed sensor	Sensors	x	x
Rain sensor	Sensors	x	x
Air quality sensor	Sensors	x	x

* for the Combi-instrument of the Leon II, the recycling assessment is also performed for disassembly level 2 (see D3.2)

In T3.2 disassembly of the different car parts was explored and analysed. In order to assess the effect of additional disassembly on recycling performance, also the level 2 disassembly was included in the recycling assessment. This was done for one of the car parts, i.e. the Combi-instrument of the Leon II. This analyses provides a demonstration of how T3.2 and T3.3 can be linked and allows the assessment of the effect additional disassembly on recycling performance of the car part. This assessment will be expanded for more car parts as listed in Table 1 in the course of the project. Also disassembly level 3 will be included in these assessments in the use cases in this project. Combining the results of the recycling analyses for level 2 (or even level 3) with costs for additional disassembly (provided from disassembly analyses) will allow to determine the trade-off between disassembly costs for improved disassembly and increased recycling performance as a consequence. This will allow to define the most optimal balance between disassembly depth, recycling performance and costs.

2.3 Results of data analyses and processing

Figure **2** gives an impression of the data in the MISS file and the data format as included through the data processing as described above (only a snapshot is given, as for some car parts, the data file contains over 2300 rows).

2.3.1 Classification of organic compounds

The car parts as included in the recycling assessment contain more than 320 different compounds (metals, alloys, oxides/sulphides, inorganics and organics), of which around 220 compounds are organics.

All compounds are defined and included in the process simulation platform. To make the processing of the data more efficient and avoid over-detailing when this is not of use, also in view of the future step of including and transferring the recycling simulation platform into the Recycling Module of the TREASURE platform, we have classified the organics into different categories, to reduce the number of different organic compounds to be included into the model and platform.

Organics can be classified into different groups/classes, based on their main compositional components (e.g. presence of Br, Cl, Si, F, etc) and their ratio of C, H and O. Organics can either be present as plastics or as organic compounds within the different structures of the car part.

It must be noted that depending on the application of the plastics, these are often functionally linked to other materials (e.g. containing fillers, coatings, etc.) from which they can be separated only with difficulty, whereas the additives of the plastics often limit their material recycling as this will lower the quality of the final recycled material produced from the recyclate. The non-plastic organics in the car parts are part of compounds and combinations in complex parts of the car parts and therefore non-recyclable in terms of material recycling as from these generally no high-quality materials can be produced after recycling. Therefore, the use of organic materials in the smelting process(es) both as reductant as well as energy carrier in the process, replacing the addition of (part) of the primary resources is usual industrial practice to the process to achieve the required thermodynamic and operation conditions for processing. It often also makes no sense to recycle such complex mixtures into plastics again as often the same material quality cannot be achieved (this can make sense for a plastic-rich or purely plastic module in which the plastic can easily be fully liberated/separated from other materials).

As organics present as plastics could potentially be recovered, when selective dismantling is possible from the car part structure/design, the compound compositional definition of the plastic organics are maintained in the classification. The remainder of the organics have been classified based on their C-H-O ratio and other elements as present within the organics structure (Br, Cl, F, Si, etc). By application of this approach, the 220 different organic compounds have been classified into 65 classes covering the composition of the organic compounds present, including the various additives and fillers. In total 181 different compounds/elements/materials are included in the model.

It is crucial to be aware that the process of data classification can only be performed, the moment the full compositional detail of all organic compounds is known from the extensive data analyses and processing as has been performed on the MISS data files. Without insight into the full range of organics present including the applied additives/fillers/etc, classification is not possible and would lead to baseless and erroneous decisions, which would render the recycling assessment and related exergy/environmental assessment unreliable.

Figure 2 Snapshot/screen caption of data format in MISS file (left side) and data derived through data processing in red box (right side)

Baum-Ebene	Typ	Name	Teilnummer / Sachnummer/ Werkstoffn	Menge	Gewicht [g]	Mengenanteil [%]	Mengenanteil [%] (von - bis)	Mass per compound [g]	Substance/compound
1				1	1973				
|—2		Case/Gehäuse	-	1	1098				
|—3		Metall	-	1	880				
|—4		Screw-Material (Torx)	-		7.91				
|—5		Material for Fasteners Property Class <=12.9 (Flat	-			100			
|—6		Kohlenstoff	7440-44-0			0.275	0.0 - 0.55	0.021677671	C
|—6		Phosphor	7723-14-0			0.0125	0.0 - 0.025	0.000985349	P
|—6		Schwefel	7704-34-9			0.0125	0.0 - 0.025	0.000985349	S
|—6		Silicium	7440-21-3			0.175	0.0 - 0.35	0.013794882	Si
|—6		Mangan	7439-96-5			0.65	0.0 - 1.3	0.051238132	Mn
|—6		Chrom	7440-47-3			0.85	0.0 - 1.7	0.067003712	Cr
|—6		Molybdän	7439-98-7			0.4	0.0 - 0.8	0.031531158	Mo
|—6		Nickel	7440-02-0			0.85	0.0 - 1.7	0.067003712	Ni
|—6		Vanadium	7440-62-2			0.175	0.0 - 0.35	0.013794882	V
|—6		PCB-epoxy for PCB laminate, High Component Load	-			21.649573	19.0 - 24.0		
|—7		Epoxidharz	Acrylharz			86.7		39.86669871	C15H22O6
|—7		Acrylate	79-10-7			0.25	0.0 - 0.5	0.114955879	C3H4O2
|—7		Bariumsulfat	7727-43-7			0.1	0.0 - 0.2	0.045982351	BaSO4
|—7		TBBA	79-94-7			7.5	5.0 - 10.0	3.448676359	C15H12Br4O2
|—7		Titandioxid	13463-67-7			0.5	0.0 - 1.0	0.229911757	TiO2
|—7		Talk	14807-96-6			0.2	0.0 - 0.4	0.091964703	Mg3Si4O10(OH)2
|—7		Sonstiges, nicht zu deklarieren	system			2	1.0 - 3.0	0.919647029	#N/B
|—7		Pigmentanteil, nicht zu deklarieren	system			1.75	0.5 - 3.0	0.80469115	#N/B
|—7		Siliciumdioxid,	60676-86-0			1	0.0 - 2.0	0.459823515	SiO2
|—6		PCB-epoxy for components, High Component Load	-			6.589744	5.0 - 8.0		
|—7		Bismut	7440-69-9			0.05	0.0 - 0.1	0.006998104	Bi
|—7		Biphenyl	92-52-4			0.15	0.0 - 0.3	0.020994312	$C_6H_5C_6H_5$
|—7		Ruß	1333-86-4			0.25	0.2 - 0.3	0.03499052	C
|—7		Epoxidharz	Acrylharz			19.5	17.0 - 22.0	2.72926054	C15H22O6
|—7		Bromiert Epoxy	68928-70-1			0.1	0.0 - 0.2	0.013996208	C36H32Br8O6
|—7		Formaldehyd, polymer mit (chlormethyl)oxiran	29690-82-2			0.55	0.0 - 1.1	0.076979143	C33H42O9X2
|—7		Glaskugeln	7631-86-9			0.55	0.4 - 0.7	0.076979143	SiO2

2.3.2 Full compositional build-up of the car parts – results of the data processing

The data processing results in a full compositional analysis for the different car parts. To be able to compare the composition of the different car parts, as well as to structure the input to HSC Sim recycling simulation models and to smoothen the integration of this data into HSC Sim, for each car part, an identical list of materials/elements/compounds is defined. This list of compounds has been defined based on the full composition of all different car parts, as well as including all compounds and phases that are created in the recycling processing of these car parts in the different processing routes as included in the model (see Chapter 3 for a detailed overview of the complete recycling infrastructure as captured in the models). Table **2** shows for the Infotainment Unit of the Leon II how the input composition derived from the MISS data file after the performed data processing and completion looks like. It shows that all materials are defined based on their full chemical composition and corresponding mass in the car part. The list shows the mass normalised to 100%, as the input to the model. This mass distribution has been defined from all individual masses of each of the compounds in each part/sub part and component of the car part. This data is now available for all assessed car parts. The composition as defined in Table **2** is provided for a section of the complete composition/table in view of confidentiality of the car part compositional data. Car parts compositional data has been derived based on the data processing for all car parts and sub-parts assessed. This full compositional data is however not provided in this report due to data confidentiality. In order to be able to get an overview of the compositional similarities and differences for the different car parts as well as to reveal the link to the compositional requirements and suitability of the various (metallurgical) recycling processing infrastructures as assessed, the composition of all car parts is given in this report in classified form in various pie-charts. However, it is important to be aware, that in order to assess the compatibility with the processing routes and assess the recyclability, the full compositional detail, of which a section is illustrated in Table 2, is required and included in this work.

This data processing provides the input data in a format suitable to recycling and recovery rate calculations using a process simulation platform.

For the case in which disassembly level 2 has been included in the assessment, the different parts have been grouped/indicated in the MISS file. Compositional data is then grouped with their corresponding composition for each of the different disassembled sub-parts, resulting in a similar table as presented by Table 2, listing the compounds and masses for each individual sub-part (e.g. PCB parts, plastic containing parts, ferrous parts, etc).

Table 2 Input definition of car part derived through data processing from MISS data file – full compositional input to HSC Sim recycling simulation model (after classification of organics) for the Infotainment Unit of the Leon II (only a section of the complete composition/table is shown in this table in view of confidentiality of the car part compositional data)

Infotainment-Combi Instrument - Air conditioning unit			
Leon II			
Compounds (chemical formulas)	**Mass % in car part**	**Compounds (chemical formulas)**	**Mass % in car part**
*2CoO*TiO2		Si	0.038089945
*3MgO*4SiO2*H2O		Si(CH3)2O(g)	0.081145506
Ag	0.050879254	Si(OC2H5)4(l)	8.91422E-05
Al	3.324194317	SiN(g)	
Al(OH)3	0.000221513	SiO	0.017611932
Al2O3	0.010980374	SiO2	6.120841659
Al2O3*2SiO2	0.000735423	Sn	0.330726024
AlO		SnO2	
As	6.25873E-05	SrFe12O19	0.369481684
As(CH3)3	0.000389997	SrO	0.002444903
Au	0.003174198	Ta	0.034698979
B	0.011693839	Tb	
B(OH)3		Te	
B2O3	0.000159093	Ti	0.000190354
Ba	0.026569005	TiO2	0.05595244
BaO	0.004543896	Ti(OC3H7)4(TTIPg)	0.003168093
BaSO4	0.006158511	V	0.000866525
BaTiO3		W	
Be	7.60241E-06	Zn	0.273005216
Bi	0.001581435	Zn(OH)2	7.19722E-06
Bi2O3	7.22426E-06	Zn5(OH)6(CO3)2	
C	0.079298357	ZnC2O4*H2O*CH3OH	
CaCO3		ZnO	0.000238977
CaMg(CO3)2		ZnSO4	
CaHPO4*2H2O	5.2456E-05	ZrO2	
…	…	…	…
…	…	…	…
…	…	…	…
Pb	0.147341834	C6H12O6(ADG)	3.332776712
PbO	0.000165707	C6H18OSi2(HMDI)	0.08860842
PbO*TiO2	0.000809446	C6H4O2(QUIg)	0.307403945
PbO*ZrO2	0.000668399	C6H5F(FBZg)	
PbSiO3		C6H6S(BTHg)	0.158417758
PC6H18N3(g)		C6H6S(BTHI)	
Pd	0.002698819	C7H4F3NO2(3NIBg)	0.014802409
Pt	1.92979E-05	C2H6O12Zn5 - C36H70O4Zn	4.74074E-05
Ru	9.73492E-05	C7H6O2(BAC)	
RuO2	1.07967E-05	C8H18O2S(DBSg)	0.00169436
S	0.01450747	C8H18OSi2	
Sb	0.002978447	C8H24O4Si4	0.000222076
Sb2O3	0.008691691	C8H8(COTI)	0.00615385
Sb2O5	3.36309E-05	C9H16(2NOg)	0.422591563
Se		**SUM**	100.000

Figure 3 Screen capture of recycling model input definition in HSC Sim showing the car part compositional input of Table 2 integrated in HSC Sim (left column). The figure also reveals all other parameters (next to mass % of input) such as flow rates (kg/h) and energy thermodynamic parameters (in kW) (the input to the model has been simulated for 20 ton/h in order to render the process industrially realistic)

	A	C	D	E	F	G	H	I	J	K	L	U	V	W	X	Y	AB	
1		Input																
2																		
3																		
4	**Flags**	**Input streams**	**Value**	**Units**	**Flow Rates**			**Thermal E Flow**	**Total H Flow**	**Thermal E**	**Tot H**	**Chem Ex Flow**	**Phy Ex Flow**	**Tot Exergy Flow**	**ELEMENTS**		**Ag**	
5	MIXER				kg/h	Nm³/h	kmol/h	kW	kW	kWh/kmol	kWh/kmol	kW	kW	kW	Total - Inerts	kmol/h	0.25	
6		Total Gas Flow	0.00	Nm3/h											Total - Inerts	kg/h	26.65	11
7		Total Condensed Flow	120.14	t/h	120 135.20	#DIV/0!	1 285.75	- 2.42	-243 325.10			235 540.37	- 11.32	235 529.05	Total	kg/h	26.65	11
837																		
838		**Leon III Infotainment NF**	40.00	t/h	Flow Rates			Thermal E Flow	Total H Flow	Thermal E	Tot H	Chem Ex Flow	Phy Ex Flow	Tot Exergy Flow	ELEMENTS		Ag	
839		Temperature	25.00	°C	kg/h	Nm³/h	kmol/h	kW	kW	kWh/kmol	kWh/kmol	kW	kW	kW				
840		Pressure	1.00	bar											Total	wt-%	0.04	
841	Fix	Total	100.00	wt-%	39 999.97	#DIV/0!	677.99	- 1.36	-27 446.40			96 207.43	- 10.66	96 196.76	Total	kg/h	16.79	1
842		*2CoO*TiO2	0.00		0.54	#DIV/0!	0.00	0.00	- 0.96	0.00	- 407.00	0.12	0.00	0.12				
843		*3MgO*4SiO2*H2O			0.00	0.00	0.00	0.00	0.00	0.00	-1 638.03	0.00	0.00	0.00				
844		Ag	0.04		16.79	0.00	0.16	0.00	0.00	0.00	0.00	4.29	0.00	4.29			16.79	
845		Al	4.00		1 599.13	0.59	59.27	0.00	0.00	0.00	0.00	13 099.81	0.00	13 099.81				1
846		Al(OH)3	0.11		43.03	0.02	0.55	0.00	- 195.56	0.00	- 354.48	2.08	0.00	2.08				
847		Al2O3	0.25		99.34	0.03	0.97	0.00	- 453.51	0.00	- 465.47	4.06	0.00	4.06				
848		Al2O3*2SiO2	0.00		0.04	0.00	0.00	0.00	- 0.18	0.00	- 928.10	0.01	0.00	0.01				
849		AlO			0.00	0.00	0.00	0.00	0.00	0.00	24.17	0.00	0.00	0.00				
850		As	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01				
851		As(CH3)3			0.00	0.00	0.00	0.00	0.00	0.00	- 4.72	0.00	0.00	0.00				
852		Au	0.01		4.37	0.00	0.02	0.00	0.00	0.00	0.00	0.31	0.00	0.31				
853		B	0.00		0.45	0.00	0.04	0.00	0.00	0.00	0.00	7.21	0.00	7.21				
854		B(OH)3			0.00	0.00	0.00	0.00	0.00	0.00	- 304.11	0.00	0.00	0.00				
855		B2O3	0.00		0.01	0.00	0.00	0.00	- 0.07	0.00	- 353.78	0.00	0.00	0.00				
856		Ba	0.05		18.42	0.01	0.13	0.00	0.00	0.00	0.00	28.89	0.00	28.89				
857		BaO	0.00		0.26	0.00	0.00	0.00	- 0.26	0.00	- 153.82	0.12	0.00	0.12				
858		BaSO4	0.01		4.13	0.00	0.02	0.00	- 7.20	0.00	- 406.82	0.19	0.00	0.19				
859		BaTiO3			0.00	0.00	0.00	0.00	0.00	0.00	- 444.65	0.00	0.00	0.00				
860		Be			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
861		Bi	0.00		0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.20				
862		Bi2O3			0.00	0.00	0.00	0.00	0.00	0.00	- 157.59	0.00	0.00	0.00				
863		C	0.16		63.37	0.03	5.28	0.00	0.00	0.00	0.00	601.31	0.00	601.31				
864		CaCO3			0.00	0.00	0.00	0.00	0.00	0.00	- 335.17	0.00	0.00	0.00				
865		CaMg(CO3)2	0.00		0.07	0.00	0.00	0.00	- 0.23	0.00	- 646.04	0.00	0.00	0.00				
866		CaHPO4*2H2O			0.00	0.00	0.00	0.00	0.00	0.00	- 672.55	0.00	0.00	0.00				
867		CaO	0.48		193.75	0.06	3.46	0.00	- 609.35	0.00	- 176.37	122.62	0.00	122.62				
868		CaSO3	0.00		0.03	#DIV/0!	0.00	0.00	- 0.08	0.00	- 322.05	0.02	0.00	0.02				
869		CaZrO3			0.00	0.00	0.00	0.00	0.00	0.00	- 490.34	0.00	0.00	0.00				
870		Cd	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
871		Cl(g)			0.00	0.00	0.00	0.00	0.00	0.00	33.70	0.00	0.00	0.00				
872		Cl2(g)			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
873		Co	0.00		0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.32				

Input / Output / Dist / Controls / Model / Mixer / Weight per subcomponent

2.4 Automation of data processing for TREASURE platform

The processing, completion and structurisation of the data is extremely time consuming, as for this moment, this can only be done manually. In view of the development of the TREASURE platform and the integration of the Recycling Module into this, automation of the data processing needs to be part of this process. Automation is required in the platform facilitating a smooth data conversion between OEM data (MISS files) and recycling rate predictions. Based on the performed data processing in this Task 3.3, the data structure, and points of attention for automation of the data processing can be defined. This provides input to future developments and activities to be performed in this project on data processing and integration within the TREASURE platform and the required format of the data lakes provided and applied within the platform. Task 3.3 also allows to give feedback to the OEMs in terms of improvement of data definition, detail and set-up of the MISS data files to facilitate the automation of data processing. Some points which should be accounted for in view of automation of the data are listed below:

- Data should be provided in xlsx or comparable format (not in pdf as is the case now)
- All material data/descriptions (now defined under name in the MISS data files) should be defined in a clear manner, which leaves no room for uncertainty (e.g. abbreviations should be written in full) and for all material names the corresponding CAS numbers should be included in the MISS file, as this would allow for an easy lookup of stoichiometric/chemical formula
- A database containing all CAS numbers of applied materials/substances in the car parts and their corresponding full chemical/stoichiometric formulas should be set up
- All masses/weight percentages should be given in point separated format (for decimal definition)

- Masses of individual materials/parts should add up to full mass of component/100% (this is not always the case in current data files), the same applies for all masses within the subparts/components
- The structure of the data file (masses and weight percentages) should be defined in such manner that an easy calculation of mass per material/compound/substance is possible in an automated manner from the data file – this demands a thoroughly thought through set up of the data file (another option is to calculate/define masses already in the MISS data file based on the masses (‘Gewicht’) and weight % per sub-part/component (‘Mengenanteil’) instead of providing these separately
- The number of times a part occurs (defined under ‘Menge’) should be defined in an equal manner for all sub-parts. This is required for a proper calculation of the mass per compound within a sub-part or component.

The required structure and detail of the data format is given in Table **2**. Details on manual data processing to be transferred into automated data processing are available from the data processing as performed within this Task by MARAS.

3. Set up of recycling system flowsheet simulation model for recycling assessment

The recycling of the various disassembled car parts as defined in T3.2 has been assessed in T3.3 by the application of innovative recycling flowsheet simulation models. This chapter will describe the further development and set up of the recycling system flowsheet simulation model, which has been evolved from past work to include the materials in the parts.

It is important to keep in mind that recycling in the context of the circular economy is understood to produce the same quality of materials so that they can function at the same quality in the same product again. The recycling rates of a product and its composing materials and compounds are determined by:

- the design, structure, materials and compounds used in a product, part or module,
- their functional connections and full composition of each (multi-) material, as well as,
- the recycling route(s) and combination of processes, which are applied to recycle the complete product and/or different modules or parts.

Previous research by MARAS on recycling of complex EoL products such as mobile phones (Ballester et al, 2017; Reuter et al, 2018) made very clear that a modular, physics knowledge based recycling allows for a better recyclability of materials and compounds, since modularity allows for a better 'separation', i.e. by (automated or manual) dismantling and selection of recyclates, modules or parts for subsequent focussed metallurgical and other final treatment processing. The approach within TREASURE by assessment of the recyclability of selectively disassembled parts, follows this 'modular' based approach to recycling.

The recycling flowsheet simulation models have been applied to assess and calculate the recycling/recovery rate of the car parts and sub-parts for the level 2 disassembly assessment, under consideration. This has been done by linking car part compositional and structural data as derived from the MISS data as obtained from SEAT to the HSC Sim models and the performance of simulations as described in Chapter 2.

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.

3.1 Development of recycling simulation model and processing flowsheets in model

The recycling processing flowsheet, including all (industrial) available processing routes for the recycling of the car parts, provides the basis for the calculation of the recycling rates. This processing flowsheet has been developed and extensively updated and expanded within TREASURE project, investigating and including best suitable technologies for the processing of the selected car parts for disassembly and adopting and processing all materials/compounds/elements as present in the car parts as disassembled from the ELVs.

This has been done based on existing background within MARAS (Reuter et al, 2018; Van Schaik and Reuter; 2016; Reuter et al; 2015; Van Schaik and Reuter, 2014). To allow for the assessment of recycling and the optimization of the industrial feasibility of the metallurgical recycling processing options, all modules and hence all materials and compounds present in the disassembled car parts are included in the recycling assessment. Including all materials, elements and compounds in recycling assessment is crucial, as material combinations are affecting the mutual recovery rates in processing. Only including a selection of materials/compounds would lead to unreliable and erroneous recycling rate calculations, as all materials/compounds in the input are affecting each other and affect the recycling rate and losses resulting from the recycling processing of the car parts or any other product under consideration.

We therefore follow the Product Centric approach (addressing all materials and compounds in a product and not just a selection of elements) as defined by Reuter and Van Schaik (Reuter and Van Schaik, 2013). When desired, materials of special interest (e.g. CRMs) can be given special focus where required, e.g. when selecting the most optimal or most suitable recycling route(s) for processing the different disassembled car parts or additionally selected parts for further disassembly of the car parts.

To be able to address and understand the balance between disassembly and metallurgical and plastics processing as well as energy recovery, a complete particle and thermochemistry-based flowsheet simulation model was developed as depicted by Figure 4 for the ELV parts and was expanded to the expansive flowsheets depicted e.g. in Figure 6, Figure 8 and Figure 9. Each flowsheet is connected appropriately.

The flowsheets as shown here 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. **Figure 5** is 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 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 to most optimally process the different car parts. To accomplish this, the recycling and processing flowsheets have been extensively integrated in the model within this project in order to facilitate this and reflect state of the art industrial processing options for recycling.

Hence, the assessment cases generate insight on the Best Available Technique (BAT) industrial (and hence economic viable) recycling processing routes and hence plants to be applied to derive the most optimal treatment for the different car parts and objectives of recycling (either focussing on optimal total recovery or optimal recovery of specific elements).

All compositional data of the disassembled car parts and their composing modules/sub-parts is integrated into the simulation models as described in Chapter 2. HSC Chemistry Sim 10 calculation modules automatically utilize extensive thermochemical databases, which contains enthalpy (H), entropy (S) and heat capacity (C) data for all materials and compounds included, 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 circular economy of products and their recyclability. Mass-based approaches, such as material flow analysis (MFA), do not include thermodynamics and therefore give erroneous results.

3.2 Recycling assessment of car parts and selection of most suitable processing routes

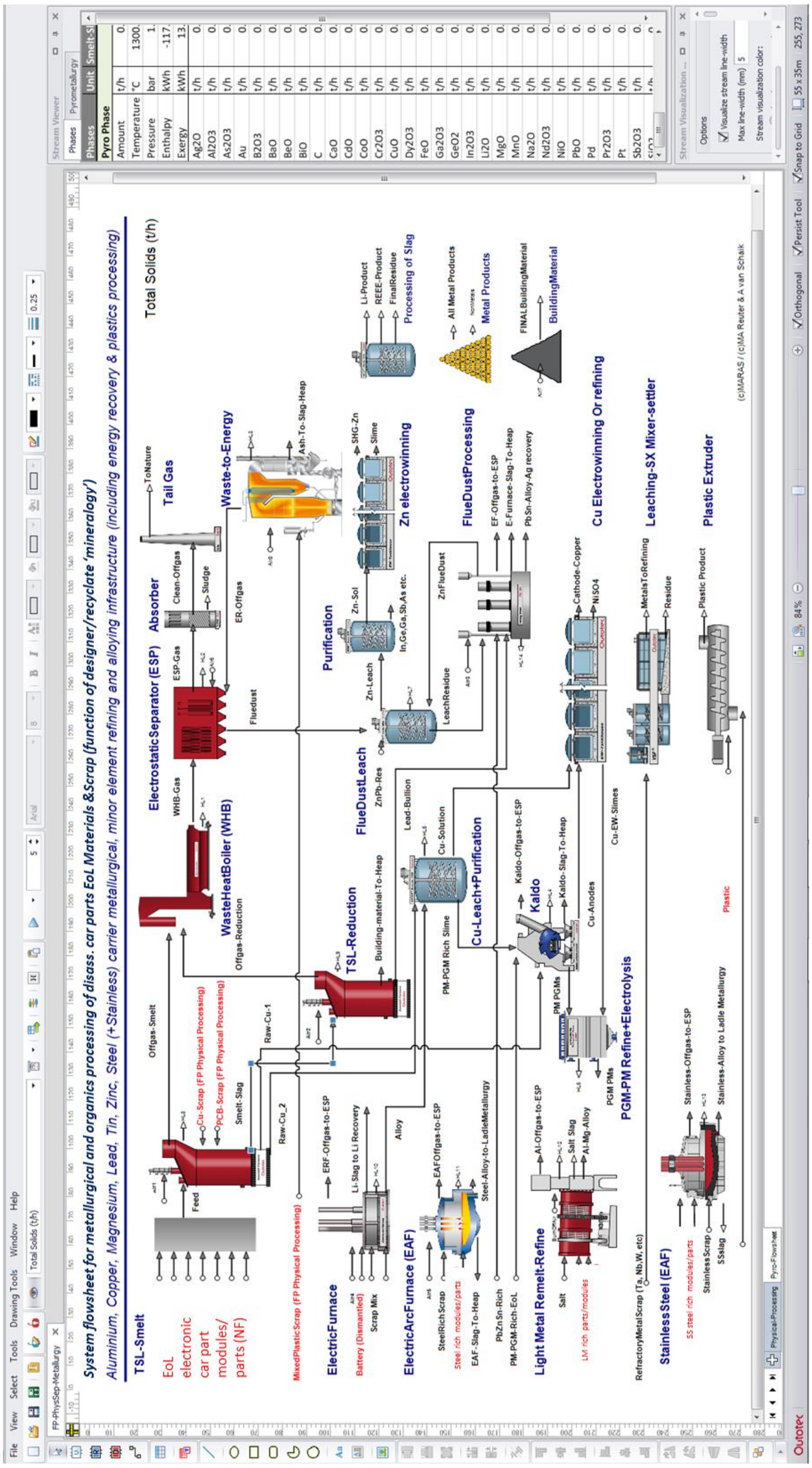
The Metal Wheel (Figure **7**) depicts the basic metallurgical infrastructure in the centre band, that makes the recovery of elements in each segment possible due to the refining and alloying infrastructure and compatible chemistry and material physics (Reuter and Van Schaik, 2013). To assess the recyclability of the different car parts, the different disassembled car parts and possible disassembled sub-parts are directed into the recycling flowsheet simulation model following the segments in the Metal Wheel, which is covered in the simulation models by the complete flowsheets and range of reactors composing the different (metallurgical) processing infrastructures (as displayed in the 'Feeds' sheet of **Figure 5**). On this basis, the effect of the different recycling processing routes on the recyclability can be determined and the most optimal/suitable recycling processing flowsheet for the part under consideration can be determined. In order to render the simulations viable and realistic, the selection of the most suitable range of metal and plastic processing routes (from the entire range of infrastructures available to process the different car parts (or modules)) is based on the expert knowledge within MARAS. Most suitable routes imply the recycling processing infrastructure in which the compounds of the module are most optimally recycled with a minimum of losses and emissions. This will differ per module, due to its specific material composition as defined in the design. For some modules, different options in processing might be considered, depending on which of the materials is preferred to recycle from the car part's material content.

All technologies as included in the recycling assessment are industrial operations running at economy of scale. In the simulations/calculations, only the selected car parts under consideration are assessed in terms of their recyclability and are fed as the only secondary input to the simulations in order to be able to assess the true recyclability of the specific car part. In normal operation conditions, different input types will be mixed and integrated on site by the operator, to create the most optimal input to the furnace. This is creating the economy of scale to also feed different car part types (as part of the other input flows) to these industrial plants. In the simulations, the effects of only simulating the recycling performance of the car part is included in the setting of the processing conditions and input, in order to address the normal operation conditions and input integration. For example, due to the low copper grade in (most of) the car parts, the copper routes require additional heat to heat slag for a specific operating point, i.e. these parts are processed on a backbone of copper metallurgy. Usually processing of these parts will be integrated and mixed with other copper and valuable materials and processed together to render processing economic. This is the basis of the HSC Sim simulations of the recycling assessment for all car parts and processing routes assessed. This allows simulating normal operating conditions, while still being able to address the specific recycling rate, losses and emissions of the car part under consideration.

In the recycling assessment as discussed in this Task, it is included that all fractions/parts lie within the acceptable ranges of the selected processing route/plant and all materials are taken care of technologically as well as economically in the selected and/or most suitable processing route(s). This implies that the car parts would be acceptable within the range of integration and mixing with other (primary and/or secondary) metal sources as is normal practice in the metallurgical plants as are included in the recycling simulations models. It will be discussed per case, if or where problems can occur due to the composition of the parts. Hence where needed, constraints to the recycling specific car parts are included in the discussion of the results when applicable. On this basis, also DfR and disassembly recommendations are based.

The simulations are performed for each of the car parts separately to assess the individual recycling rate per part (and its composing materials) as well as to determine the effect of additional dismantling on recycling performance and recovery of individual materials. By discussing the various cases, the critical issues in composition of the car parts are intrinsically addressed. This illustrates and reveals at the same time, if and in what manner similar car part types from different models can or cannot be best processed in the same route. Although not part of this Task, however, simulations and calculations could also be similarly be performed for a mix of different car parts (from similar or other car models) by taking into account their individual compositions and masses.

Figure 4 The metallurgical, energy and plastics processing flowsheet for (electronic) car parts and complex EoL products as industrially available to process the multitude of metals, alloys, functional materials and plastics in an end-of-life product. It covers steel, stainless steel, copper, lead, tin zinc, aluminium and magnesium as carrier metal metallurgical infrastructure as well as plastics recycling and energy recovery



NB The separate flowsheets in this report show the further expansion and details of the processing infrastructure flowsheet included in the model to cover all materials/elements/compounds as present in all the different car parts selected for disassembly.

Figure 5 In the process model, the “Feeds” sheet is of importance as it shows in which metallurgical processing infrastructure (according to the segments of the Metal Wheel in the middle) the car parts and possible disassembled sub-parts are processed

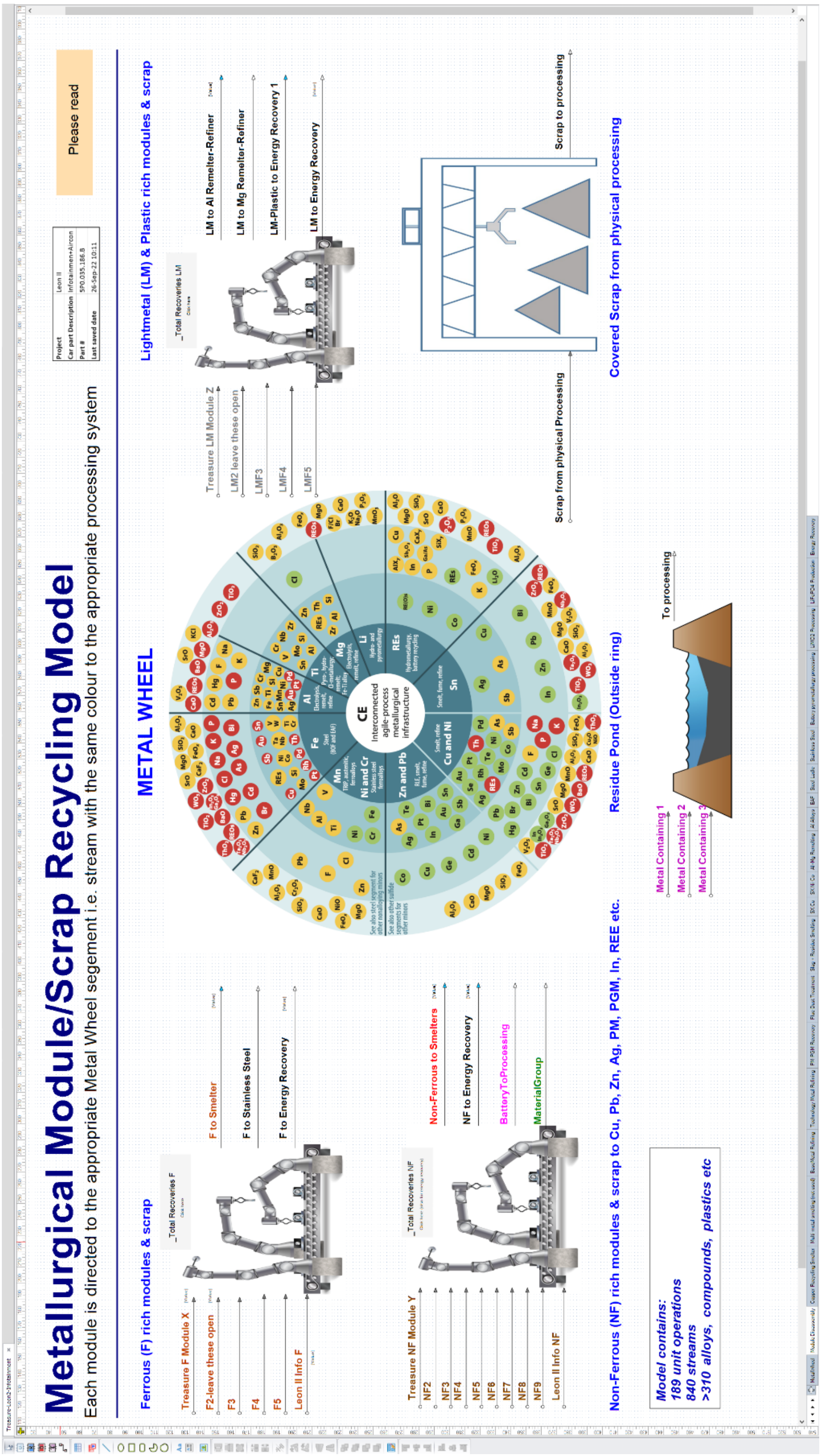


Figure 6 'Cu processing route ' – Oxidative smelter (Cu Isasmelt™)), reduction of Pb bullion (Pb Isasmelt™ Reductive smelter) and Cu refining. The Isasmelt™ reactor (a Top Submerged Lance (TSL) reactor) can also be a proxy for a TBRC (Top Blown Rotary Convertor) type reactor, the metallurgy is determined by the partial oxygen pressure and temperature in the reactor. Also shown is the oxidative leach of raw copper and subsequent electrowinning of the copper

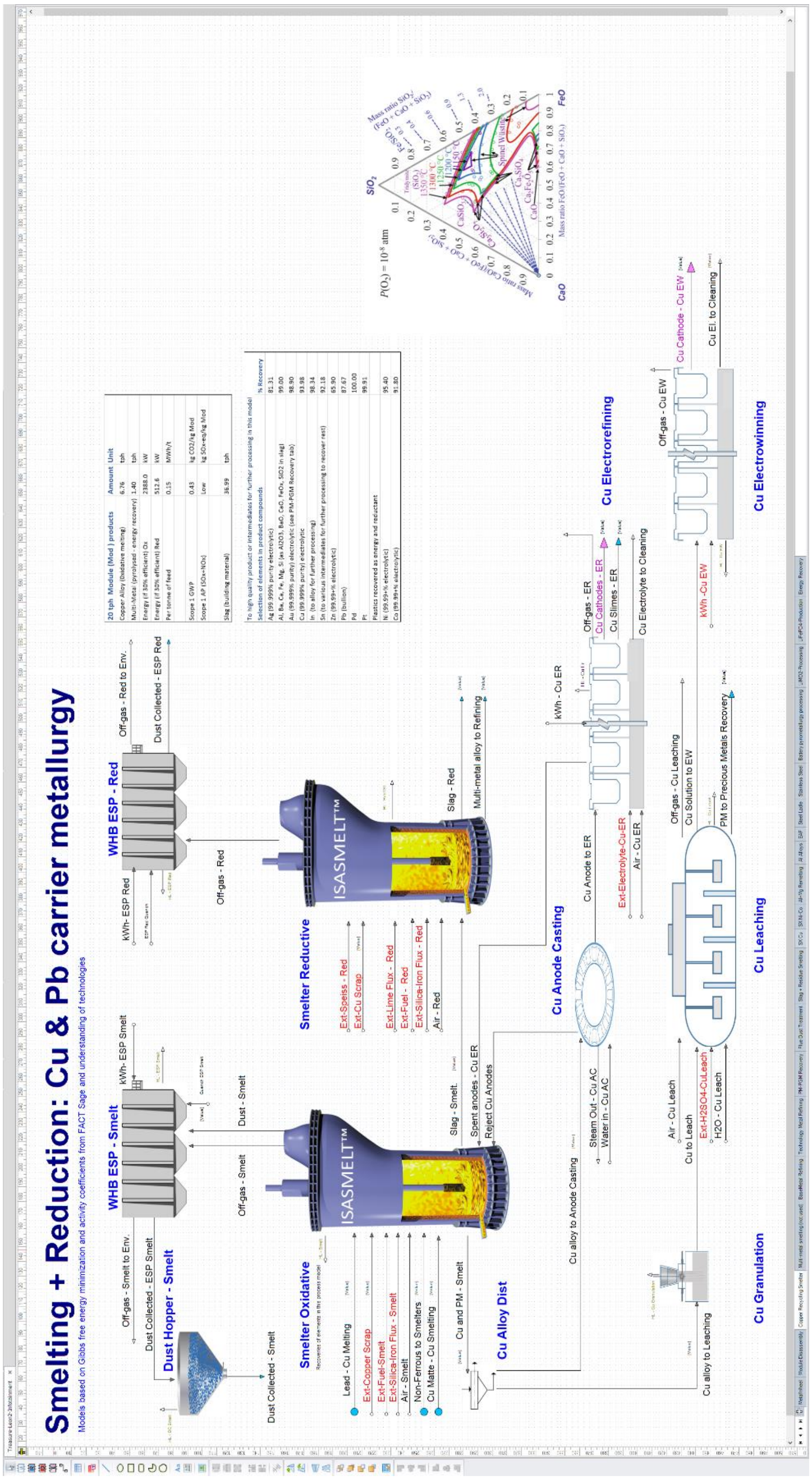
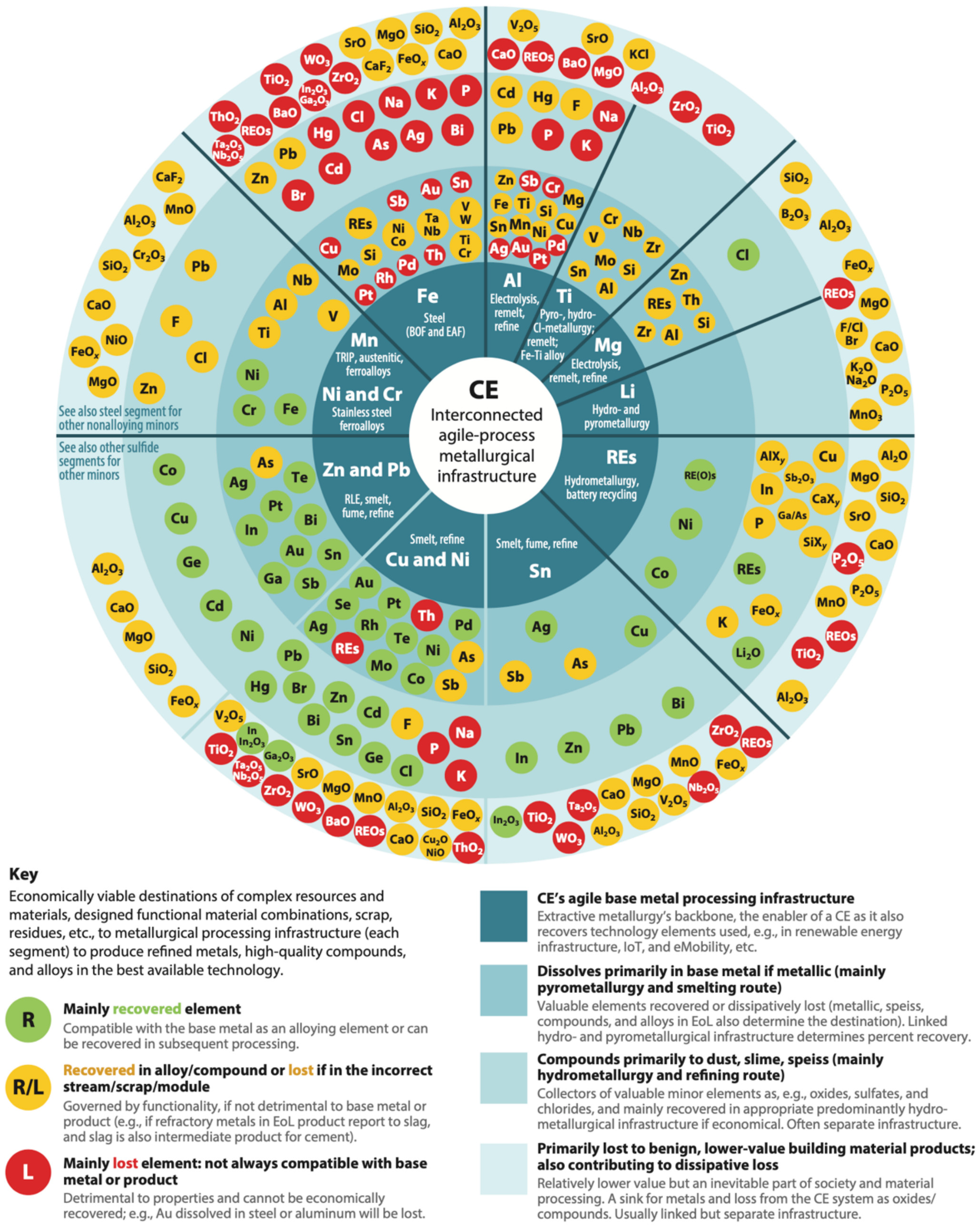


Figure 7 The Metal Wheel, based on primary metallurgy but equally valid for metals recycling reflects the destination and hence recoverability or losses of different elements in a product/component for different interlinked metallurgical processes (Reuter and Van Schaik, 2013)



4. Results of recycling assessment

This chapter will present and discuss the results of the recycling assessment as performed on the basis of the process and methodology as described in the previous Chapter.

The following 7 car parts have been assessed in terms of recyclability. The results of the recycling assessment for each of these parts, is presented and discussed in this chapter.

- Infotainment unit – Leon II (level 1 disassembly)
- Infotainment unit – Leon III (level 1 disassembly)
- Combi-Instrument – Leon II (level 1 and level 2 disassembly)
- Combi-instrument – Leon III (level 1 disassembly)
- Combi-instrument – Ibiza IV (level 1 disassembly)
- Additional brake light – Leon II (level 1 disassembly)
- Additional brake light – Leon III (level 1 disassembly)

4.1 Model definitions and set up for recycling assessment of car parts selected for disassembly

As pointed out in Chapter 2, the data of the different car parts as provided by SEAT and analysed and processed by MARAS, have been integrated as input into the HSC Sim 10.0 simulation models. This has been done by including the required detailed description of materials in terms of needs to functionally describe metallurgical processing using a thermochemical based process simulator.

The HSC Sim simulation model as applied for the assessment of the recycling of the car parts has (see Figure **5**):

- 189 reactors/unit operations
- 840 streams
- over 310 alloys, compounds, organics, etc being processed

From the 310 alloys, organic and inorganic compounds, elements, etc. originate 180 compounds/elements/materials from the car part as input to the recycling processes (see Table **2**) after classification of the organics as described in Chapter 2). The other compounds, alloys, etc are the phases created during the processing of the car parts, either as intermediate and/or end products. It is a globally unique model to assess recyclability and at the same time analyse design changes and improvements in complete detail.

4.2 Assessment of different recycling routes for recycling of car parts and sub-parts

Figure **5** in Chapter 2 shows a screen capture of (and a section of) the “Feeds” pane of the simulation model. In the right-hand table a small excerpt of the input compositional (and material combinational) data is shown as included in the models as described in detail in Chapter 2. This ‘sheet’ directs all flows of the modules to the correct and most suitable (i.e. with the highest recovery and lowest amount of losses/emissions) metallurgical processing infrastructure (segments in Metal Wheel in Figure **7**) based on the composition of the car part and the expert know-how of MARAS.

As discussed in Chapter 2, the composition of the car parts as selected for disassembly is highly distributed and very inhomogeneous due to among others functionality reasons. The car parts are composed of a complex mix of metals, materials and compounds and complex combination of the materials/metals within the different segments of the Metal Wheel, of which the processing cannot, therefore, be covered by one single metallurgical recycling infrastructure as depicted by the Metal Wheel. As this complex mixture of materials/elements/compounds is connected and combined within one car part, there is no one best option to process these different parts, as each of the processing options, will lead to recovery of certain elements, and losses of other, as depicted qualitatively by the Metal Wheel. This implies that the most suitable processing option cannot be defined upfront, therefore, for each car part, based on its composing material composition, the two or three best options are selected based from the full metallurgical recycling infrastructures as available and depicted in the Feed sheet of Figure **5** and recycling system flowsheet of Figure 4 on the expert knowledge within MARAS, rather than preselecting one best options upfront. The following processing routes have been assessed to be the most suitable options for the different car parts, unless the composition directly indicates for one or two options out of the options given below:

- Cu processing route (see Figure 6 in Chapter 3, which gives an overview of the processing in terms of reduction and oxidative processing, as well as cleaning of the slag to create a building material quality product)
- Steel processing (see Figure 8) – simplified but with sufficient detail to create a complex iron alloy
- Energy recovery (Figure 9) – simplified and operating to create a calcine and energy

The additional disassembly (level 2) of car parts reduces the complexity of the composition (although the sub-parts are still a complex mixture of materials). Based on careful study of the part compositional analyses as derived from the data processing (see example in Table 2) the sub-parts of the Combi-instrument have been directed to the most suitable processing route depending on the sub-part composition.

Figure 8 Steel scrap smelting to create a dirty iron-rich alloy from the part as there is sufficient Fe in the part as major alloying element – PGMs could make the processing of alloy profitable, but creates significant residues during hydrometallurgical processing

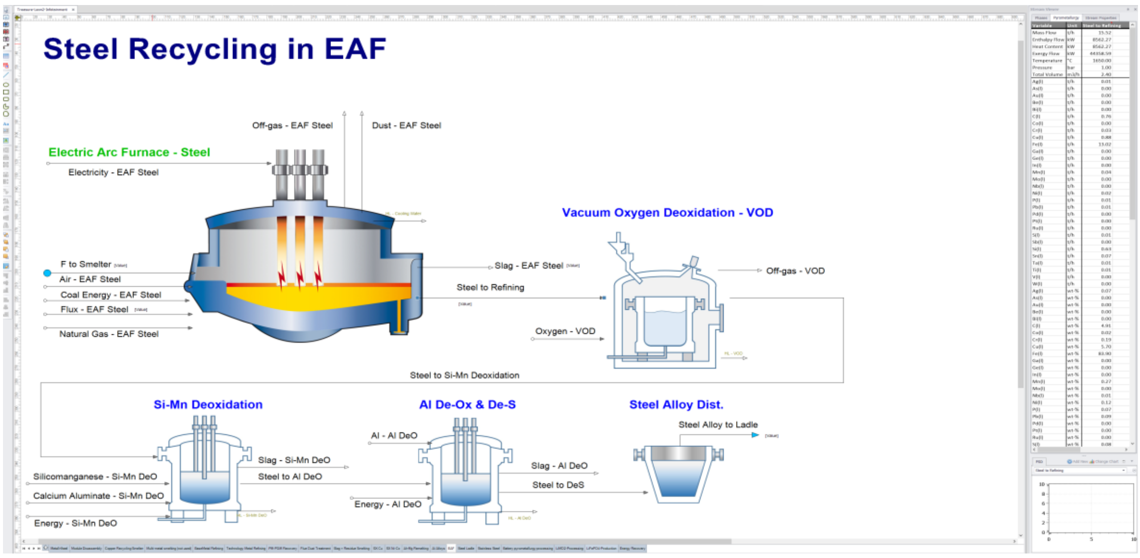
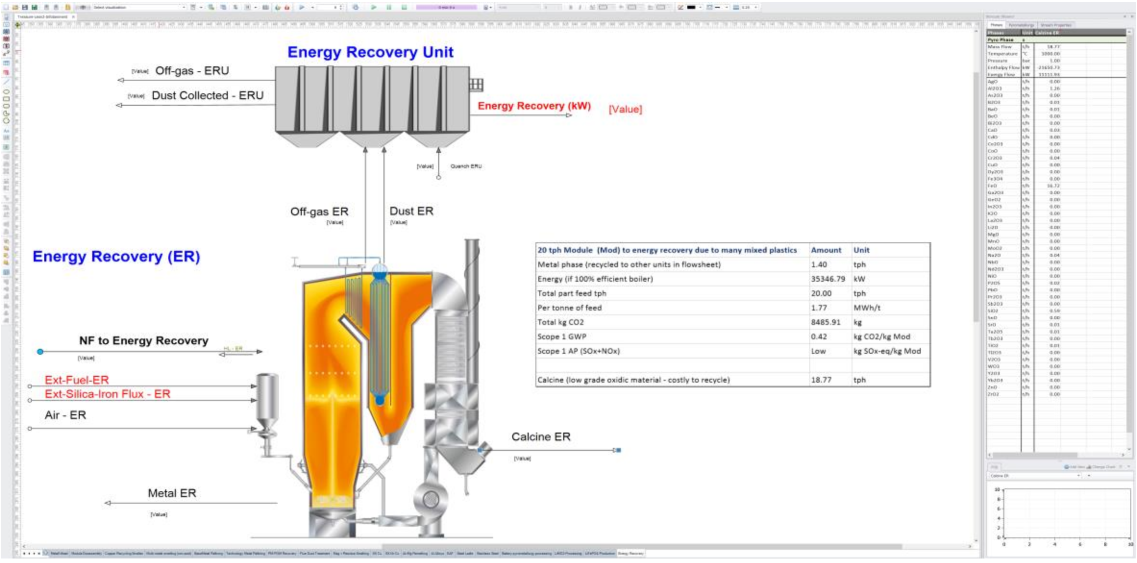


Figure 9 Energy recovery processing to create calcine (oxidized elements as well as some highly alloyed and low value metal alloy and energy from all car parts



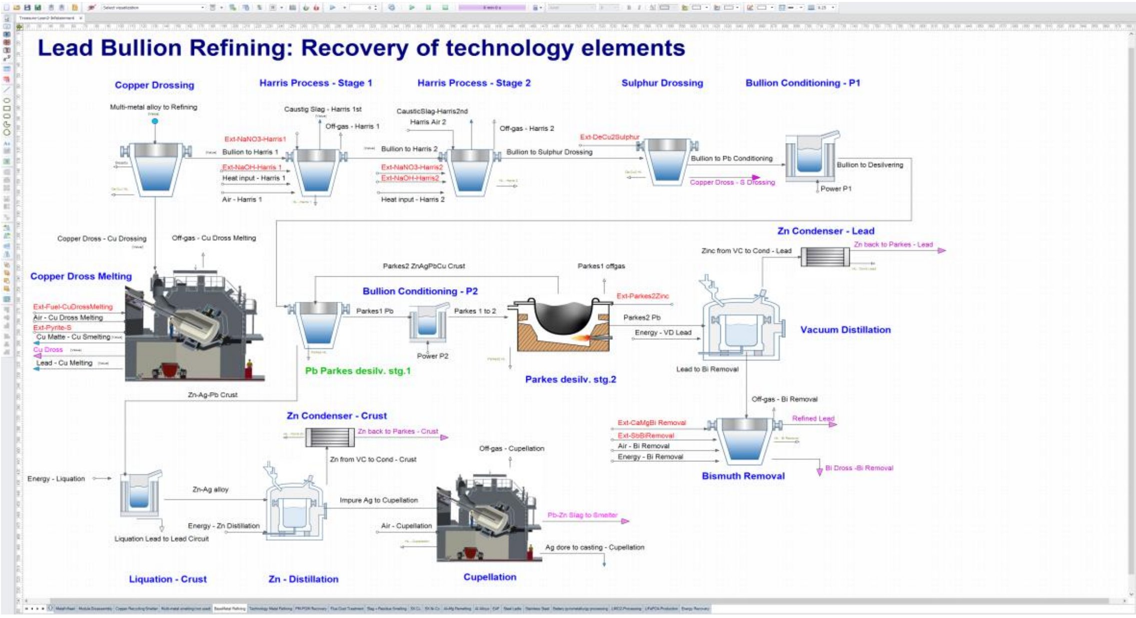
In the next sections, the results of the recycling assessment for the different car parts will be discussed and elaborated on, based on the processing of the car parts in the recycling routes as listed above, which have been selected from the entire range of processing infrastructures represented in the different segments of the Metal Wheel (Figure **7**) as most suitable options for the processing of the car parts.

It is important to understand in the context of this project that the recycling of a product within the circular economy implies creating the same material quality after recycling so that it can be applied in the same product. This definition is taken into account in the definition of the recycling results. **Three levels of CE have been defined** in order to present the results of recycling. Energy recovery is added to this list as fourth option.

1. **Closed loop CE** – recycling into high quality products with material properties equal to original product/material.
2. **Open loop CE to be processed into closed loop CE** – recycling into intermediate products, such as low grade alloys, calcine, etc which require further physical sorting and/or chemical upgrading to achieve the required high quality material properties/alloy quality to render closed loop CE. At the same time, open loop CE products suitable for repurposing could also be produced as product from sorting/upgrading of the intermediate products to render closed loop CE. The possibilities of processing of open loop intermediate into closed loop CE products is subject to economic, thermodynamic and environmental constraints.
3. **Open loop CE** – recycling into (intermediate) products such as slag and flue dust for repurposing e.g. as building/construction material etc. - requires significant energy and thus exergy dissipation and thence costs to convert to level 1 closed loop CE materials
4. **Energy recovery** from feed is included in the summary of the recycling results, as organic content will be used in some of the processing routes as an energy carrier from which the energy content is (partially) recovered (in the Cu processing route, organics are also used as reductant). 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.

The three different levels of closed and open loop CE in recycling, correspond to the three outer circles in the Metal Wheel (with closed loop CE in the most inner circle (after the dark blue base metal circle) to the Open loop CE as reflected by the most outer circle. Thus, detail for recovery of all elements are required as shown by the figure below (see Figure **10**).

Figure 10 Detailed flowsheet of processes required for recovery of all recoverable (technology) elements (green bullets in the Cu segment of the Metal Wheel)



The RIs are hence provided for the three defined levels of CE in recycling. Energy recovery from feed is also included in the presentation of the results, as use of organic materials in the smelting process(es) both as reductant as well as energy carrier, replacing the addition of (part) of the primary resources is usual industrial practice to achieve the required thermodynamic, kinetic and processing conditions for processing. This differs however per type of recycling route as is shown in the presentation of the results below.

4.3 Results recycling assessment different car parts (level 1 disassembly)

In this section, the results of the performed recycling assessment of the assessed car parts are given and described. The major findings and results are included in this section.

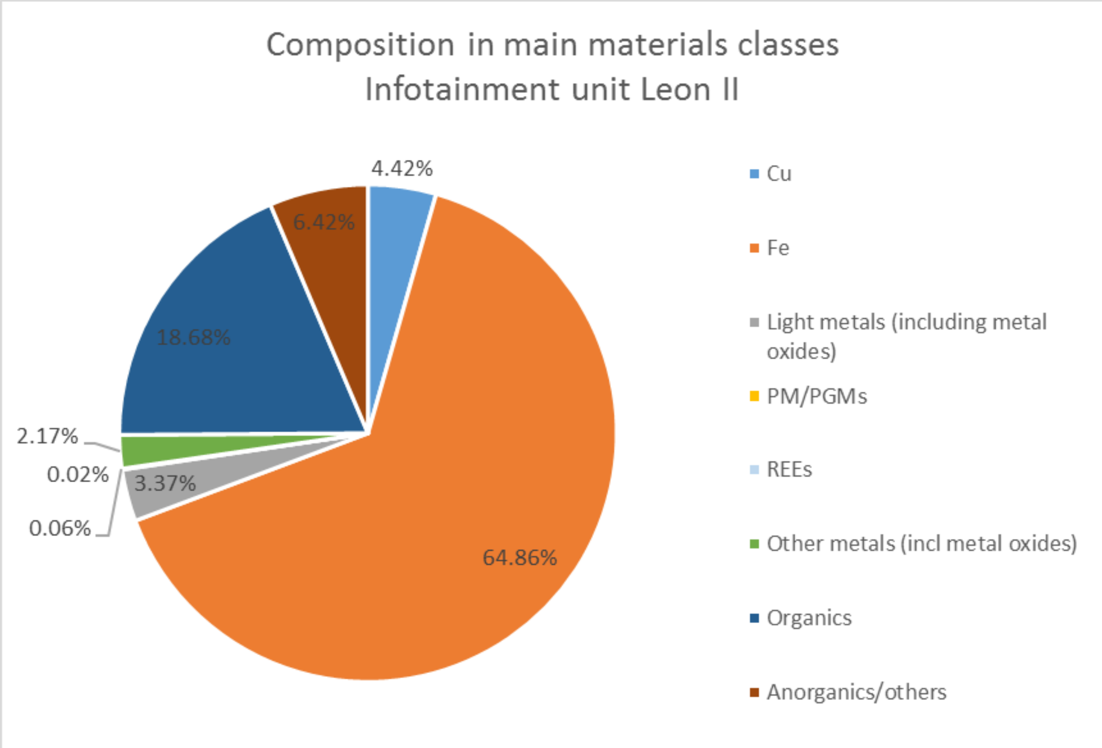
4.3.1 Results recycling assessment Infotainment unit Leon II

4.3.1.1 Composition of car part

Figure 11 shows the major composing materials/compounds of the Infotainment unit of the Leon II. What immediately becomes clear is the low (mass) based content of Cu and related valuable (incl. part of the CRM) materials. The Fe content is very high, however many other elements/materials/compounds are present. The percentage of organics is also relatively high (close to 20%). Due to the high Fe content (close to 65%), the presence of Cu (over 4%) and associated metals as depicted in the Cu segment of the Metal Wheel and the relative high content of organic compounds (close to 20%), the following three possible processing routes for the recycling of the Infotainment unit have been assessed:

- Cu processing route (see Figure 6)
- Steel processing (see Figure 8)
- Energy recovery (Figure 9)

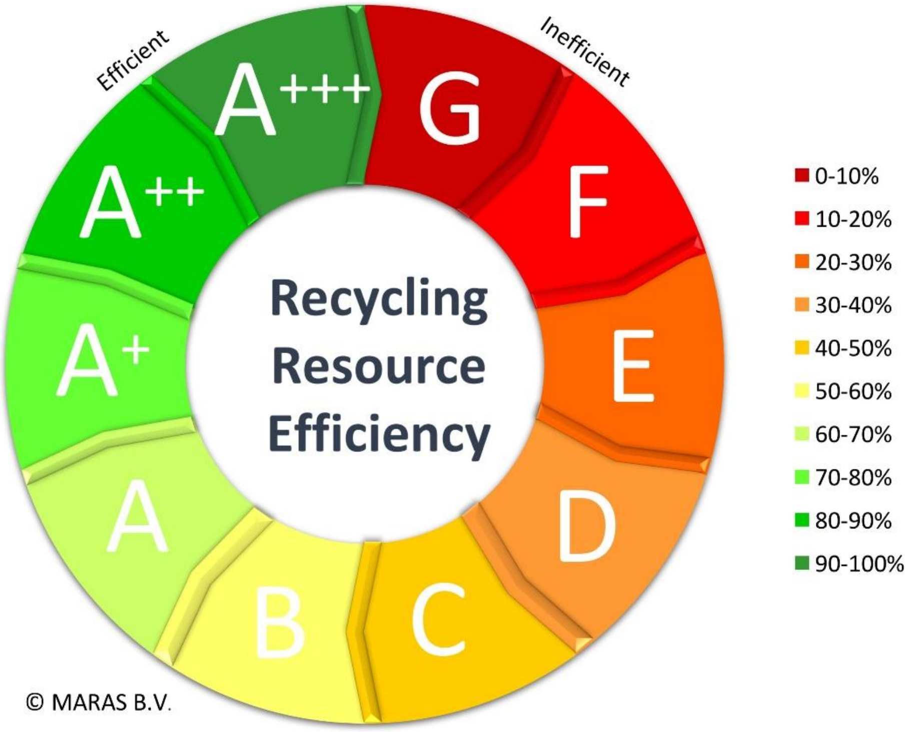
Figure 11 Major composing materials of the Infotainment Unit of the Leon II (classified)



4.3.1.2 Overall/total recycling rates

The overall recycling rate of a product can be visualised by the application of the Recycling Index (RI) as developed by Van Schaik and Reuter (Van Schaik and Reuter, 2016). It visualizes the overall recycling rate of a product, part or module in a clear and easy to understand manner (see Figure 12). Figure 12 is presented to render the legend of the figure readable in view of the use of the Recycling Index in the figures (starting with Figure 13) presenting the recycling performance of the different processing routes for the different level of Circular Economy as defined above.

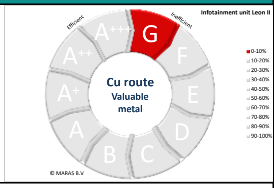
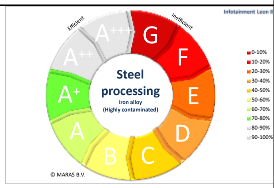
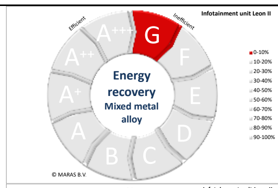
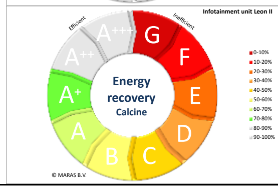
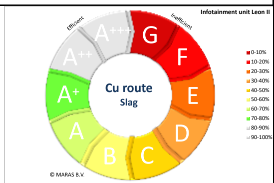
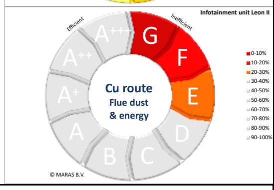
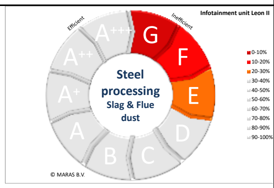
Figure 12 Recycling Index visualising the total recycling rate



The overall recycling rate for the Infotainment Unit of the Leon II for the three assessed routes is given in Figure **13**. Please note that the recycling rate is presented relative to the total weight of the product or part. As an example, this implies that e.g. when only 5% of copper is present in the part and Cu is fully recovered, that the overall recycling rate will only be 5%, in spite of the high recycling rate of Cu itself (which is presented in the Material Recycling Flower below). The Recycling Index shows the sum of all recovered materials relative to the total product.

Figure 13 present the overall recycling results for the Infotainment Unit for the different recycling routes and different levels of Circularity.

Figure 13 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route, Steel processing and Energy recovery) – Infotainment unit Leon II

Recycling in terms of CE recycling products	**Cu processing route**	**Steel processing**	**Energy recovery**
1. Closed loop CE – high quality products which can go straight back into part or product		No high quality CE products	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			 
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.15 MWh/t feed	No energy recovery (energy input required in the process)	1.77 MWh/t feed

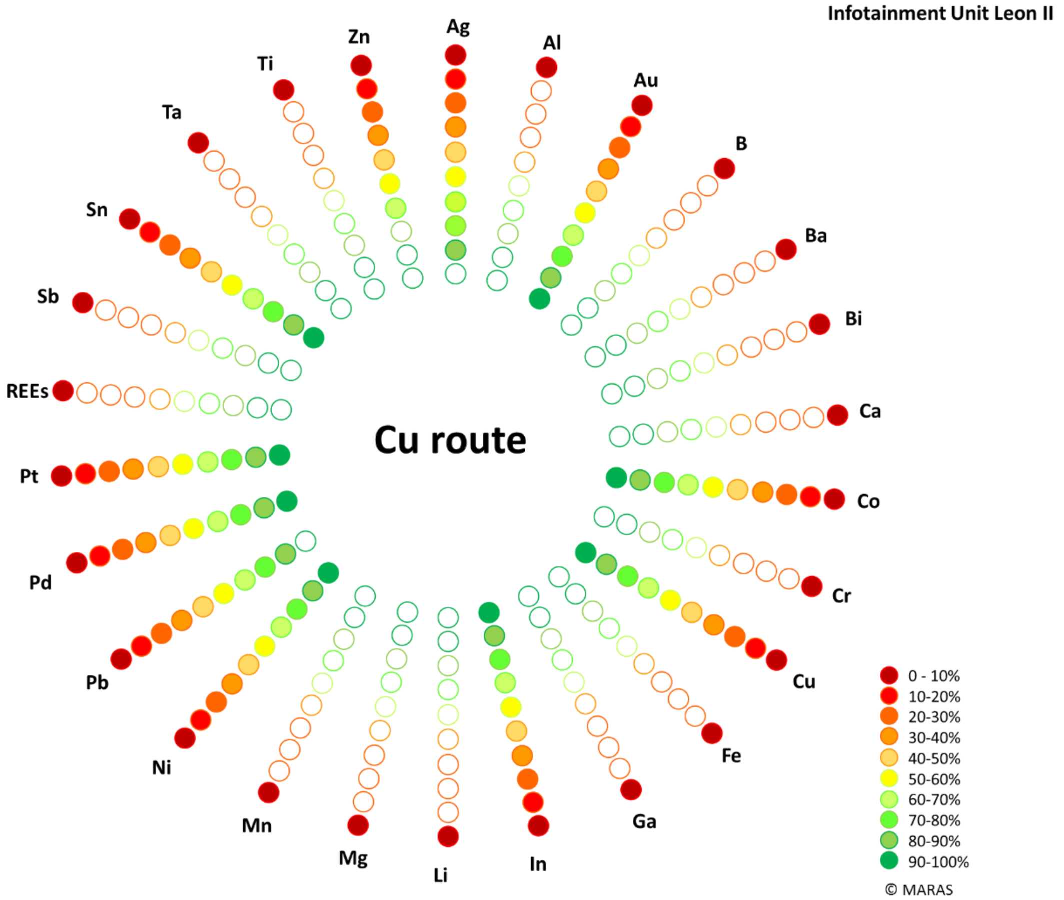
4.3.1.3 Individual material recycling rates

As clearly visible from Figure **13**, although the recycling rate is low due to the low level of Cu and related metals, resulting in a G class overall recycling rate (as explained above), only the Cu processing route for processing of the Infotainment unit Leon II produces high quality closed loop CE products (see level 1 in Figure **13**), without further sorting or upgrading required. Hence, it is only realistic for this route to present the individual material recycling rates. The Material Recycling Flower (Figure **14**) depicts the individual elemental recycling rates of a selection of materials / elements / compounds that are recycled into high quality products. Developed by Van Schaik and Reuter (Van Schaik and Reuter, 2016), this visualises the individual material recycling rates and illustrate the differences in recycling behaviour and performance of different elements / materials also relative to the total recycling rate. The Material Recycling Flowers allow for a transparent visualization of the individual materials/element recycling/recoveries and a comparison between the performance and differences between the various recycling routes and car parts, while considering the complete part at the same time. This makes obsolete any cherry picking outside the context of the complete composition of a part.

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 as presented in the Recycling Index. This is also the manner in which recycling is generally reflected. Therefore, the overall recycling rate is not sufficient to present the recycling results for a car part under consideration. Presenting individual material recycling rates, in particular of materials/elements, which are present in low percentages as is the case for most valuable and critical (CRM) materials requires the detail as presented by the Material Recycling Flower. Comparing individual material/elemental recycling rates is crucial when selecting the most optimal recycling option and will differ for the different car parts and is depending on the materials or elements defined as critical to recover.

In view of Circular Economy, quantification and, if possible, increase of recovery rates of individual materials, even when low in weight, is of high importance. The individual material recycling rates for the processing of the Infotainment Unit of the Leon II in the Cu processing route are presented for a selection of elements in Figure 14.

Figure 14 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product (in the other two routes, no closed loop high quality product is produced directly from the route)



4.3.1.4 Discussion of results of recycling processing of Infotainment unit from the Leon II

Cu processing route

It is crucial to understand, due the complex combination of functional materials in this car part, that significant losses during recycling are inevitable.

Figure 11 reveals that the Cu content is very low. Due to the low level of Cu and related metals present in the Infotainment unit of the Leon II (see green bullets in the copper segment in the Metal Wheel), only a small part of the car part can be recovered into valuable metals with a high quality to realise closed loop CE, such as Cu, Ag, Au, In, Sn, Pb, Pd, Pt, Ni, Co and Zn. The other metals present in the car part, which are not compatible with the Cu processing route, such as Al, Ba, Ca, Fe, Mg, Si (also present as Al_2O_3, BaO, CaO, FeO_x, SiO_2) are recovered in the slag, which is an open loop CE product. Off gas elements, such as Br, Cl, Cd, C, H, O, S, I, N will report to the flue dust and off gas, which is also an open loop CE (intermediate) product. In the copper segment of the Metal Wheel, the organics and plastics are used as energy carrier and reductant in the process. This is often the best economic and technological option, as these complex mixtures of organic materials cannot be recovered (or in other words unmixed) to the same quality (except for the physically present plastics, which could potentially be further disassembled if the construction of the car part allows for this).

However, due to the low copper grade in the car part, the copper routes require additional heat to heat slag for a specific operating point, i.e. these parts are processed on a backbone of copper metallurgy. Usually processing of these parts will be integrated and mixed with other copper and valuable materials and processed together to render processing economic as is the basis of the HSC Sim simulation.

Steel processing

The product of the steel processing route is a highly contaminated iron rich alloy, which carries many elements, some of which are harmful for steel metallurgy as these are deleterious to the standard steel alloy specifications. Due to the low nobility of the Fe, many elements will dissolve into the iron alloy (see also the Fe segment in the Metal Wheel). The iron alloy hence contains a wide range of metals, which are except for the alloying elements as required for steel processing (see the elements in Green bullets in the Metal Wheel) undesired or are even harmful to the alloy specifications. This includes next to Fe, other metals such as, Pb, Cr, Co, Au, Cu, Mn, Mo, Ni, Ag, V, Sn, Sb, As, Bi, Ga, In, Pd, Ru, Ta, Nb, W, Ge, Pt, C, Be, S, Zn. It must be noted, if iron is a collector of Au, Ag, Pt, Pd, Re, etc. there are process routes to oxidize/convert the Fe to slag, while concentrating these economically valuable elements for further hydrometallurgical processing. However, the car parts under consideration do not meet these requirements.

The alloy has also a significant C content (reaching cast iron), originating among others from the organics, which may to an extent dissolve into the alloy if it does not oxidize to CO_2 and CO. To render this alloy to a closed loop CE product, this alloy has to be diluted by pig iron or Direct Reduced Iron (DRI), but this may not achieve the tight specifications of steel alloys and carries with it the carbon footprint of the primary pig iron production. Therefore, this has a negative environmental consequence due to the addition of high amounts of primary sources, while nevertheless the many harmful elements will also then have a negative impact as mentioned due to steel alloy specifications. This alloy may also be used as reductant in non-ferrous metallurgy, however, better would be to send the car part directly to one of the other processing routes.

Design for Recycling or additional disassembly can change this situation, if this mitigates the deportation of the harmful elements into the EAF (Electric Arc Furnace).

The slag produced during the steel processing, will contain Al, Ba, Ca, Mg, Si (present as Al_2O_3, BaO, CaO, SiO_2, etc). Volatile elements will report to the flue dust. These fractions could be applied in open loop CE.

Due to the high level of other metals present together with the Fe, in this route a high input of both primary resources and energy is required. As the EAF is a smelter, using power for the electrodes, no energy recovery from the organics takes place in this route.

Energy route

In the energy recovery route, the car part is processed with the major purpose to recover the energy as contained in the organic compounds of the car part, which contributes for a relatively high percentage to its composition (see Figure 11).

). In this process, also a metal phase and calcine are produced. These are both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading, e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE. However, smelting this “junk” has an economic cost and is not desirable, also from an exergetic point of view.

Environmental indicators/assessment linked to recyclability analyses in recycling process simulation models (HSC Sim)

As environmental impact calculations are directly linked in HSC Sim, LCA indicators and assessment on the EoL can be calculated from this. Recent work has combined processing with LCA and exergy to quantify the quality loss of material through the circular economy (see Reuter et al., 2015). Although this is not part of this deliverable, Table 3 illustrates that environmental indicators (as well as exergy assessment - not shown here) could be included in the selection of the most suitable and optimal recycling processing route. These are Scope 1 and directly calculated by the simulator.

Table 3 A small selection of environmental (LCA) indicators which can be derived from the recycling process simulations models as HSC Sim is directly linked to environmental assessment- here shown only as a general example

Environmental indicators	Amount	Unit
Cu processing route		
Scope 1 GWP	0.43	kg CO2/kg Module
Scope 1 AP (SO_x + NO_x)	Low	kg SOx-eq/kg Module
Energy recovery route		
Scope 1 GWP	0.42	kg CO2/kg Module
Scope 1 AP (SO_x+NO_x)	Low	kg SOx-eq/kg Module

4.3.1.5 Conclusion

In spite of low recovery rate, the best option for processing the Infotainment Unit from the Leon II in its current composition, is processing via the Cu processing route, where high quality closed loop CE products can be realised.

Recommendation for additional disassembly would therefore be to separate the high Fe containing and high organics containing sub-parts from the Cu and related metals-based parts or components. In this manner, the concentration of valuable elements can be increased in the Cu based part, the presence of harmful elements in the Fe based parts can be mitigated and the metal content of the organic based fraction for energy recovery can be decreased. This would allow (if possible, from a design and disassembly point of view) to process these three different modules (Cu based, Fe based with low level of contamination metals and organics based) in the induvial most suitable processing route. In this way, both overall as well as individual material/element recycling rates can be increased and losses and required additional physical sorting and/or chemical upgrading (and related requirement of primary resources/energy) can be minimised or decreased. The creation of low valuable intermediate materials is therefore, to an extent, mitigated.

Design for Recycling (DfR) as part of Eco-design recommendations, could be derived from the recycling assessment. DfR should be focussed, when possible, from a functional point of view, on designing sub-parts/modules and harmonizing with the different sections in the Metal Wheel. However, functionality of the part may limit this/ Avoiding, where possible, the mixture of incompatible materials in sub-parts/components and/or could be derived by additional disassembly, if this is possible from a structural design point to view.

The individual recycling rates are quantitatively supporting and guiding which options in both additional disassembly and/or DfR will have the highest impact in improvement of recyclability. Also rarity based % as defined in WP3.1 could be used as a driver to select materials/elements and disassembly and DfR options.

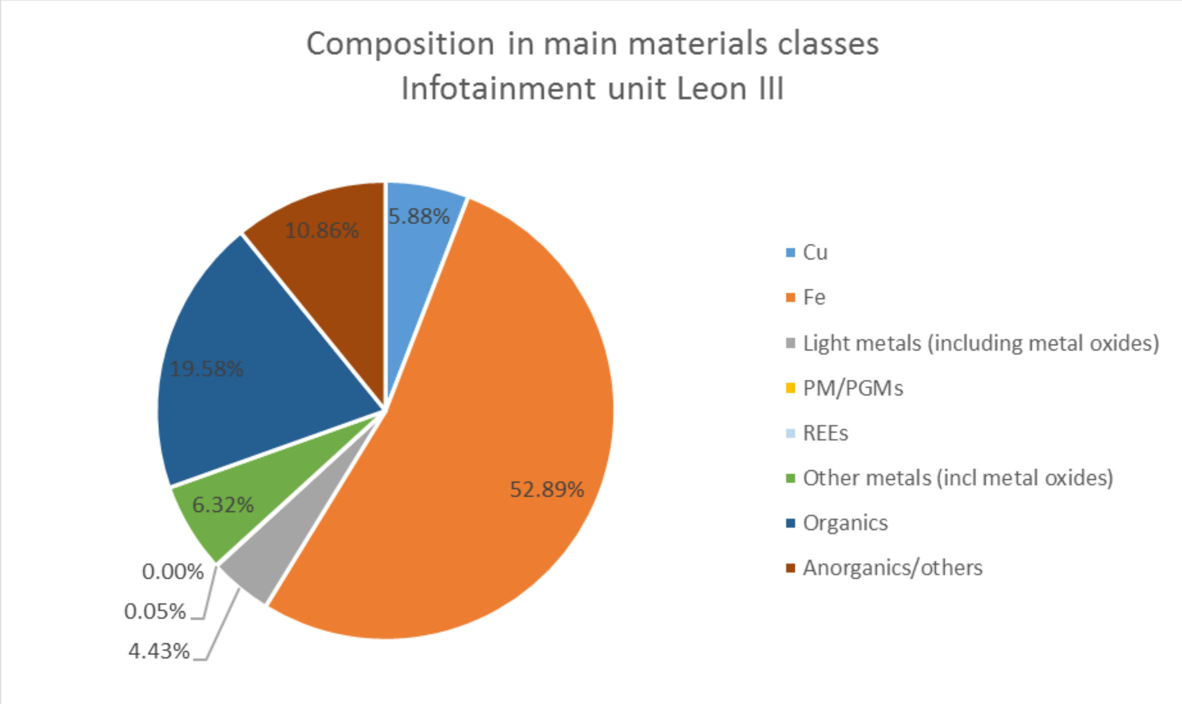
4.3.2 Results recycling assessment Infotainment unit Leon III

4.3.2.1 Composition of car part

Figure 15 shows the major composing materials/compounds of the Infotainment unit of the Leon III. Similar to the Infotainment of the Leon II is the low (mass) based content of Cu and related valuable (incl. part of the CRM) materials. The Fe content is very high (although lower than of the Leon II). Also, many other elements/materials/compounds are present. The percentage of organics is also relatively high (close to 20%). Due to the high Fe content (close to 53%), the presence of Cu (close to 6%) and associated metals as depicted in the Cu segment of the Metal Wheel and the relative high content of organic compounds (close to 20%), the following three possible processing routes for the recycling of the Infotainment unit have been assessed, similarly to the assessment of the Infotainment Unit of the Leon II:

- Cu processing route (see Figure 6)
- Steel processing (see Figure 8)
- Energy recovery (Figure 9)

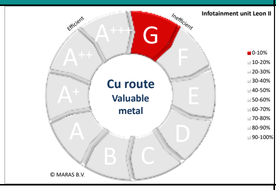
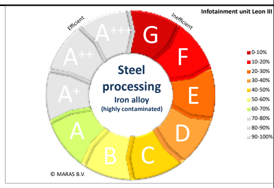
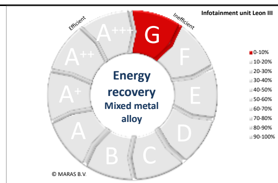
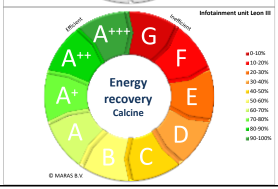
Figure 15 Major composing materials of Infotainment Unit of the Leon III (classified)

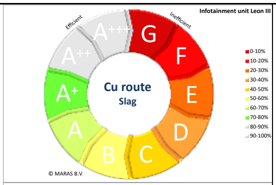
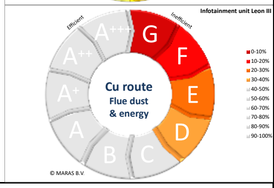
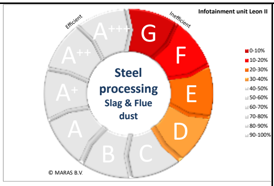


4.3.2.2 Overall/total recycling rates

The overall recycling rate for this car part for the three assessed routes is given in Figure **16** by the Recycling Index (RI).

Figure 16 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route, Steel processing and Energy recovery) – Infotainment unit Leon III

Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		No high quality CE products	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			 

3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.12 MWh/t feed	No energy recovery (energy input required in the process)	1.53 MWh/t feed

4.3.2.3 Individual material recycling rates

As clearly visible from Figure **16**, also for this car part, similar to the Infotainment of the Leon II, only the Cu processing route for processing of the Infotainment unit Leon III produces high quality closed loop CE products, without further sorting or upgrading required. Hence, also for this car part it is only realistic for this route to present the individual material recycling rates, similarly to the Infotainment Unit of the Leon II. The Material Recycling Flower (Figure 17) depicts the individual elemental recycling rates of a selection of materials / elements / compounds that are recycled into high quality products for the Infotainment Unit of the Leon III.

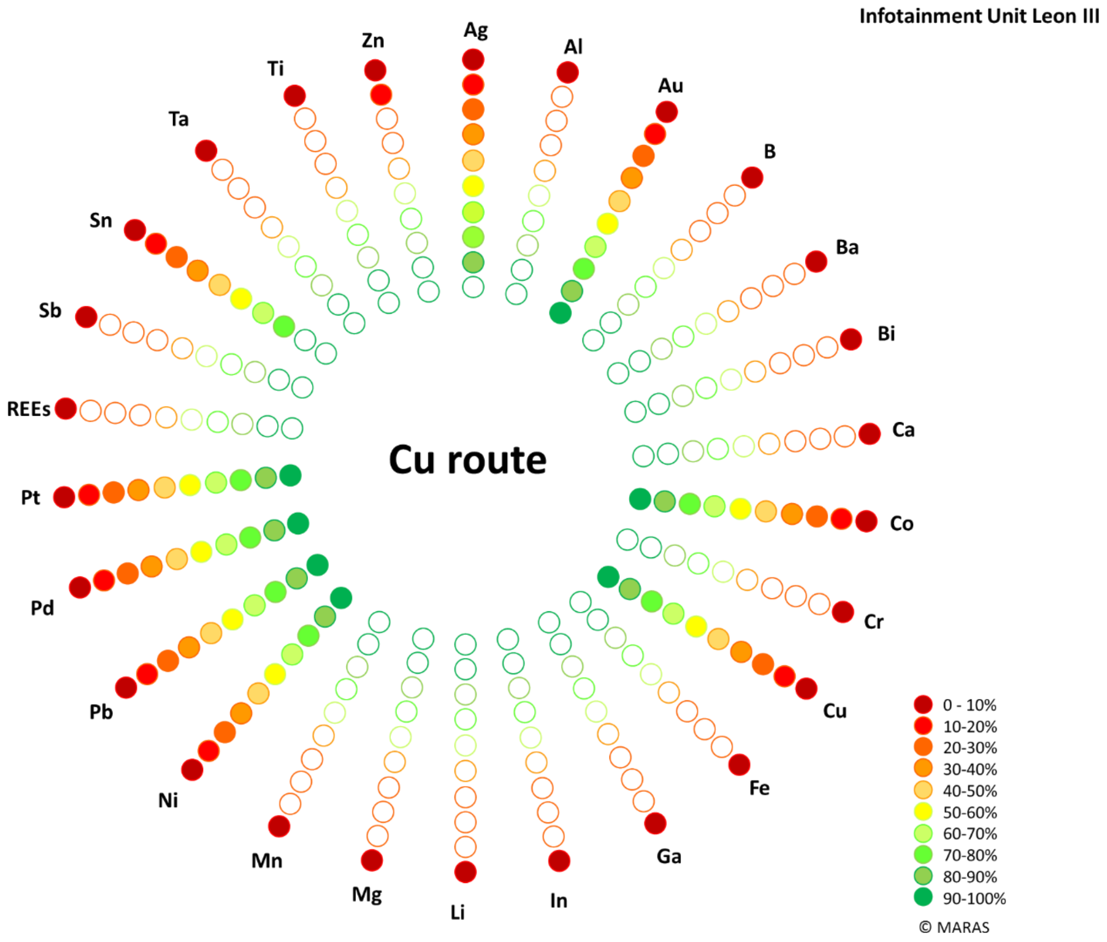
4.3.2.4 Discussion of results of recycling processing of Infotainment unit from the Leon III

The overall recycling results as presented in Figure 16 and individual material recycling rates as shows in Figure 17 show that the results of the recycling assessment of the Infotainment Unit of the Leon III are comparable to the results of the Leon III. Due to the (small) differences in composition, minor differences in the recyclability of both parts of the two car types can be observed. However, the discussion of the results of the Infotainment unit from the Leon II are equally valid for the Leon III. Therefore, these results are not repeated here, but please refer to section 4.3.1.4 for the discussion of the results.

4.3.2.5 Conclusion

As the results of the recycling assessment of the Infotainment unit of the Leon III are comparable to that of the Leon II and composition is comparable (in spite of small differences), the conclusions as defined for the Leon II are equally applicable for this car part type of the Leon III (see section 4.3.1.5).

Figure 17 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product from the Infotainment Unit of the Leon III (in the other two routes, no closed loop high quality product is produced directly from the route)



4.3.3 Results recycling assessment Combi-Instrument Leon II

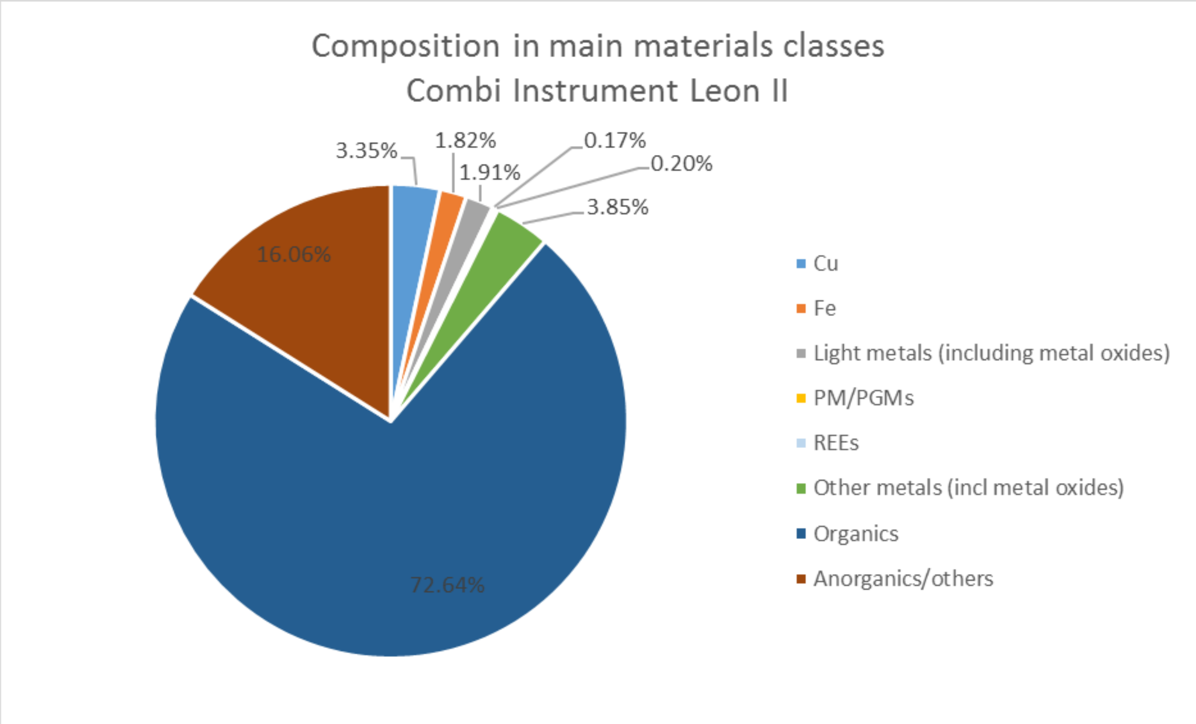
4.3.3.1 Composition of car part

Figure **18** shows the major composing materials/compounds of the Combi instrument of the Leon II. This part is characterised by a very low Cu and related valuable material (incl. part of the CRM) content (see metals in green dots in the Cu segment of the Metal Wheel). The Cu and related valuable metal concentration lies under 4%. The Fe content is very low (<2%) and differs significantly from the Infotainment unit parts. The percentage of organics is very high and composes almost 73% of the part. The high organics content a priori dictates that no high or even reasonable recycling rate can be achieved for this type of part! Only the recovery of the energy content of the organics lies within the options of recycling, if possible combined with the recovery of the Cu and Cu related metals.

Due to the very low Fe content, processing of this car part type in the Steel processing route is not feasible at all. In spite of the low presence of Cu and associated metals as depicted in the Cu segment of the Metal Wheel and the focus on recovery of the minor (incl. CRMs) from EoL vehicles, the recycling of the Combi instrument has been assessed for the Cu route, in which part of the high organics content can also be partially recovered. The very high content of organic compounds dictates that energy processing route should be included in the assessment. Hence the following two possible processing routes for the recycling of the Combi instrument have been assessed:

- Cu processing route (see Figure 6)
- Energy recovery (Figure 9)

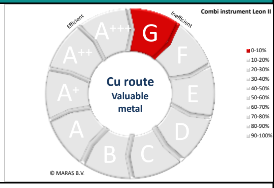
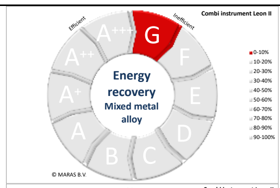
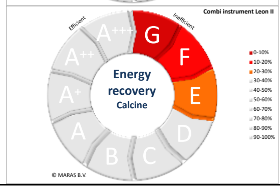
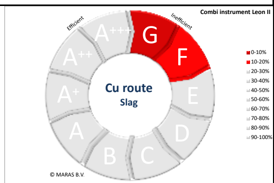
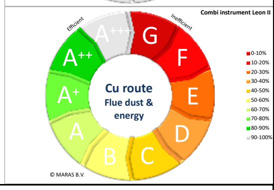
Figure 18 Major composing materials of the Combi Instrument of the Leon II (classified)



4.3.3.2 Overall/total recycling rates

The overall recycling rate for this car part for the two assessed routes is given in Figure 19 by the Recycling Index (RI).

Figure 19 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route and Energy recovery) – Combi-Instrument Leon II

Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		Not feasible for this car part due to the low Fe content	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.			
4.Energy recovery from feed	0.58 MWh/t feed		3.53 MWh/t feed

4.3.3.3 Individual material recycling rates

Figure 19 clearly shows that once again only the Cu processing route produces high quality closed loop CE products, without further sorting or upgrading required. Hence only for this route the individual material recycling rates (for a selection of elements) are presented in The Material Recycling Flower of Figure 20.

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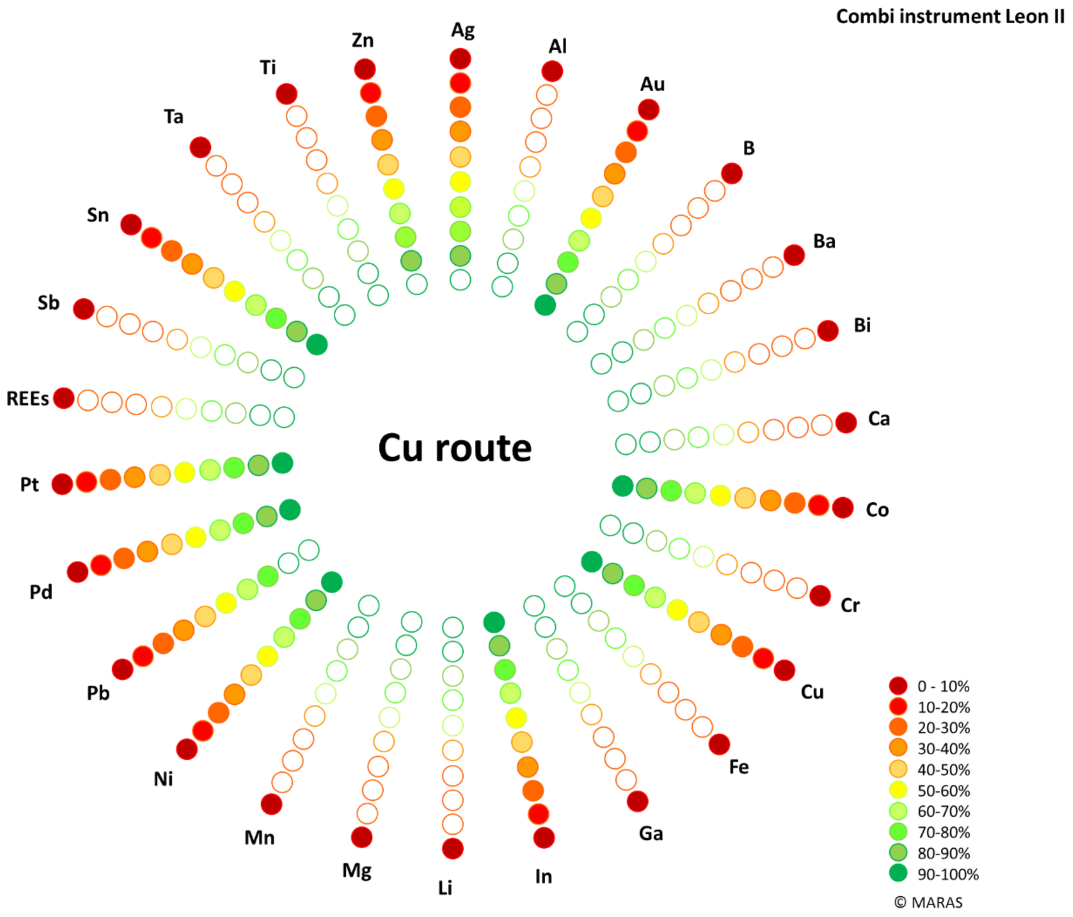
Figure 20 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product



4.3.3.4 Discussion of results of recycling processing of the Combi instrument from the Leon II

Cu processing route

The composition of the Combi-instrument of the Leon II, Leon III and the Ibiza is characterised by a low Cu content and an even lower Fe content (see Figure **18**, Figure 21 and Figure 24).

Due to the low level of Cu and related metals present in the Combi instrument (see green bullets in the copper segment in the Metal Wheel), only a small part of the car part can be recovered into valuable metals with a high quality to realise closed loop CE, such as Cu, Ag, Au, In, Sn, Pb, Pd, Pt, Ni, Co and Zn. The other metals present in the car part, which are not compatible with the Cu processing route, such as Al, Ba, Ca, Fe, Mg, Si (also present as Al_2O_3, BaO, CaO, FeO_x, SiO_2) are recovered in the slag, which is an open loop CE product. Off gas elements, such as Br, Cl, Cd, C, H, O, S, I, N will report to the flue dust and off gas, which is also an open loop CE (intermediate) product. The Combi instrument is a very high in organic content. In the copper segment of the Metal Wheel, i.e. the Cu processing route, the organics and plastics are used as energy carrier and reductant in the process. This is often the best economic and technological option, as these complex mixtures of organic materials cannot be recovered (or in other words unmixed) to the same quality (except for the physically present plastics, which could potentially be further disassembled if the construction of the car part allows for this).

As for the Infotainment unit, due to the low copper grade in the car part, the copper route requires additional heat to heat slag for a specific operating point. Usually processing of these parts will be integrated and mixed with other copper and valuable materials and processed together to render processing economic as is the basis of the HSC Sim simulation.

Steel processing route

Due to the very low Fe content, the steel processing route provides no feasible option to recycle the Combi instrument, when being processed in its total composition.

Energy route

In the energy recovery route, the car part is processed with the major purpose to recover the energy as contained in the organic compounds of the car part. Due to the very high presence of organics, this processing route can be considered as most suitable to process the Combi instrument, when no further disassembly would take place to concentrate the valuable metals separate from the organic parts. Although, in this process, also a metal phase and calcine are produced, these are both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE. The energy recovery per ton of input is considerable higher than the amount of energy recovered in the Cu route.

4.3.3.5 Conclusion

The selection of the best processing route for the Combi instrument of the Leon II depends on the objective of the recycling. There is no one best route.

When the focus is to recover as much (valuable and critical) metals from the car part, the most preferred route from a closed loop CE point of view, would be to process this part in the Cu route. In spite of low recovery rate, in the Cu processing route high quality closed loop CE products can be realised, while at the same time recovery of (part of the) energy contained in the organics fraction is realised. It has however to be considered, that due to the low Cu content, recycling of this car part requires a significant input of heat and primary resources to obtain the correct operation point. This can be considered as a negative point for this processing route. Although not part of this deliverable, exergetic analyses of the recycling process can reveal this balance very well. In practice, the car part would have to be processed together with other recyclates and input flows, with a much higher Cu and valuable metal content.

Due to the very high organics content, the energy processing route would be the best option to recover the energy as contained in these organics. In this process, also a metal phase and calcine are produced, however these are both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading, e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE.

Recommendation for additional disassembly would therefore be to separate the organics containing sub-parts from the Cu and related metals-based parts or components. In this manner, the concentration of valuable elements can be increased in the Cu based part, while the metal content of the organic based fraction for energy recovery can be decreased. In general, this implies that by physics-based disassembly recommendations the mixture of incompatible materials in sub-parts/components have to be separated as far as possible into different sub-parts, when this is possible from a structural design point to view. This would facilitate (if possible, from a design and disassembly point of view) to process the car sub-parts as derived from additional disassembly (Cu based and organics based) in the most suitable processing route. In this way, both overall as well as individual material/element recycling rates can be increased and losses and required additional physical sorting and/or chemical upgrading (and related requirement of primary resources/energy) can be minimised or decreased. The creation of low valuable intermediate materials is therefore, to an extent, mitigated. For the case of the Combi-instrument, it could also be considered if in the organic containing parts, also organics are present as well dismantlable plastics, for which physical recycling into a new high quality plastic product could be an option. Important to note, plastic recycling might be limited due to possible additives and fillers in the plastics, or a mix of plastic, for which quality demands for plastic processing could not be met.

This additional disassembly was already investigated in T3.2, and matches with the recommendations as given above based on the assessment of the level 1 disassembly of the Combi-instrument of the Leon II (and other models). The results of additional level 2 disassembly are assessed in this study and are discussed in section 4.4 below.

Design for Recycling (DfR) as part of Eco-design recommendations, can also be defined based on the performed recycling assessment. DfR should be focussed, when this is possible from a functional point of view, on designing sub-parts/modules in which their composition is harmonized with the compatibility of the metals in the different sections in the Metal Wheel. However, functionality of the part may limit this. The individual recycling rates as calculated in the recycling assessment quantitatively support and guide, which options in both additional disassembly and/or DfR will have the highest impact in improvement of recyclability. Also rarity based % as defined in WP3.1 could be used as a driver to select materials/elements and disassembly and DfR options.

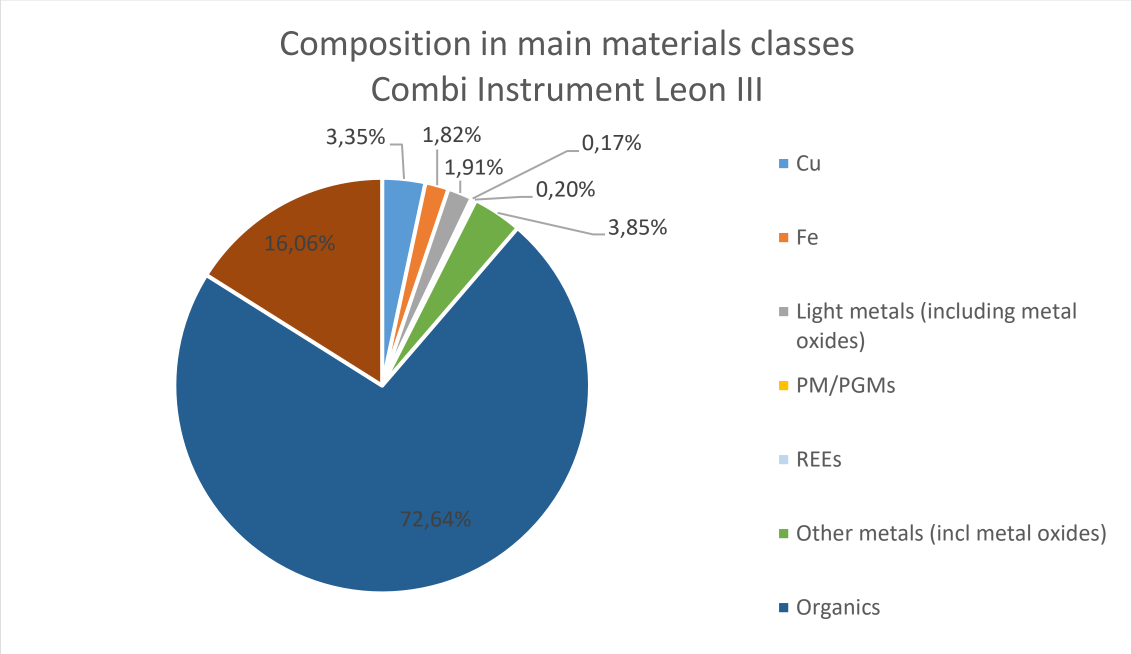
4.3.4 Results recycling assessment Combi-Instrument Leon III

4.3.4.1 Composition of car part

Figure 21 shows the major composing materials/compounds of the Combi instrument of the Leon III. As the content is comparable to that the of the Combi-instrument of the Leon III, the same recycling routes have been assessed to process this part. The organic content is even higher than for the Combi-instrument of the Leon II. Also, the Cu content is slightly higher, but still low in absolute terms.

- Cu processing route (see Figure 6)
- Energy recovery (see Figure 9)

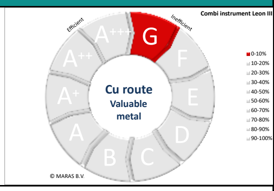
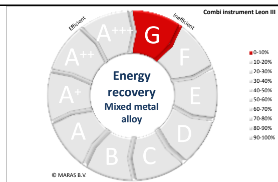
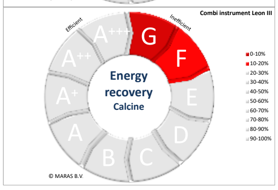
Figure 21 Major composing materials of the Combi Instrument of the Leon III (classified)

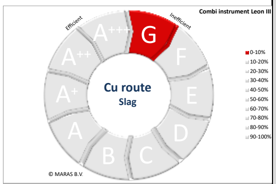
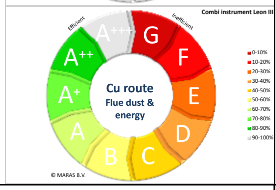


4.3.4.2 Overall/total recycling rates

The overall recycling rate for this car part for the assessed routes is given in Figure **22** by the Recycling Index (RI) as developed by Van Schaik and Reuter (Van Schaik and Reuter, 2016) to visualize the overall recycling rate of a product, part or module in a clear and easy to understand manner.

Figure 22 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route and Energy recovery) – Combi-Instrument Leon III

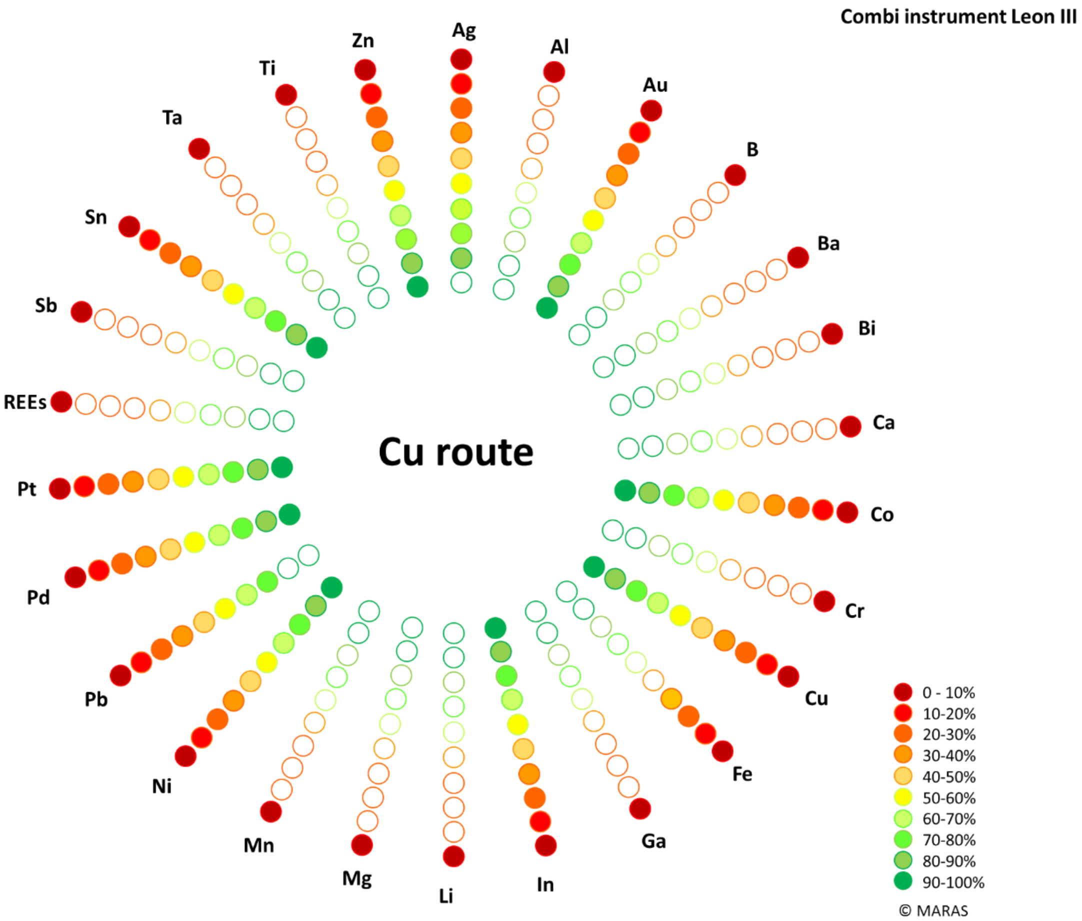
Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		Not feasible for this car part due to the low Fe content	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			 

3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.51 MWh/t feed		3.81 MWh/t feed

4.3.4.3 Individual material recycling rates

Figure **23** presents the individual material recycling rates for the Combi-instrument of the Leon III in the Cu route, as only in this route, valuable metals are recovered with a high quality allowing for closed loop CE, without further processing required.

Figure 23 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product



4.3.4.4 Discussion of results of recycling processing of the Combi instrument from the Leon III

The overall recycling results as well as individual material recycling rates of the Combi-instrument of the Leon III show that the results of the recycling assessment of the Combi-instrument of the Leon III are comparable to the results of the Leon II. Due to the (small) differences in composition, minor differences in the recyclability of both parts of the two car types can be observed. However, the discussion of the results of the Combi-instrument from the Leon II are equally valid for the Leon III. Therefore, these results are not repeated here, but please refer to section 4.3.3.4 for the discussion of the results.

4.3.4.5 Conclusion

As the results of the recycling assessment of the Combi-instrument of the Leon III are comparable to that of the Leon II and composition is similar (in spite of small differences), the conclusions as defined for the Leon II are equally applicable for this car part type of the Leon III (see section 4.3.3.5).

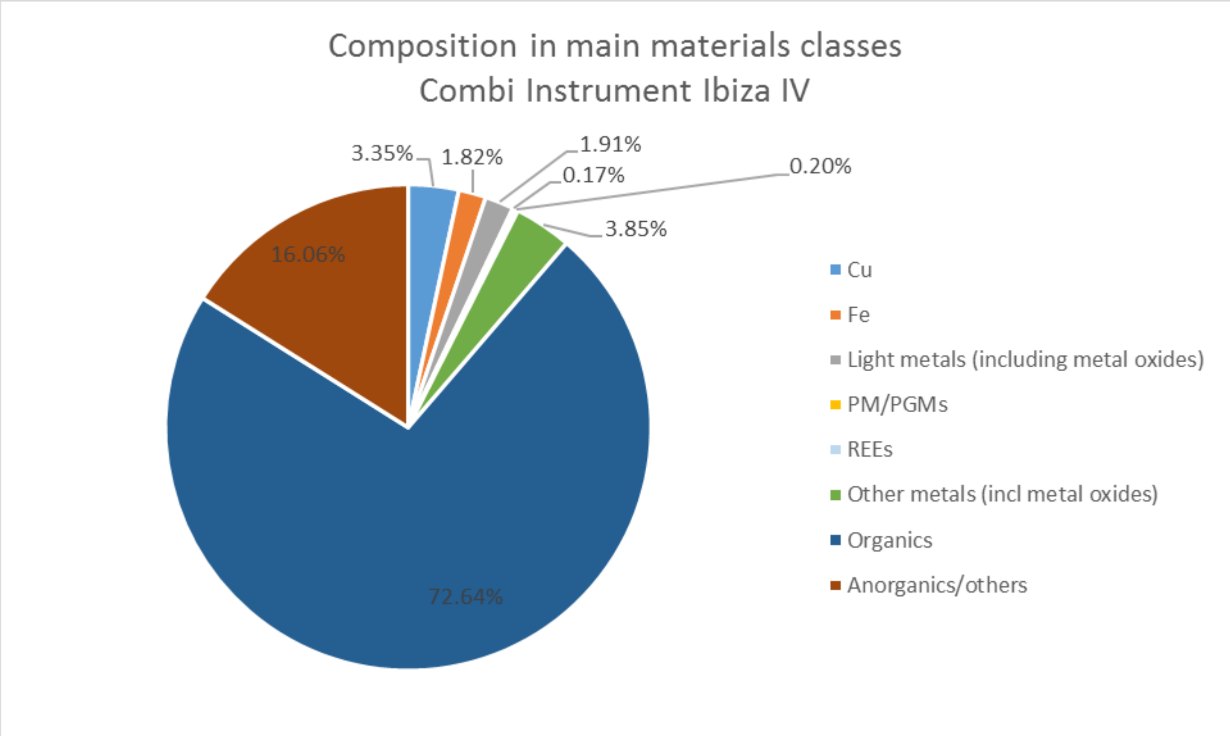
4.3.5 Results recycling assessment Combi-Instrument Ibiza IV

4.3.5.1 Composition of car part

Figure 24 shows the major composing materials/compounds of the Combi instrument of the Ibiza IV. As the content is comparable to that the of the Combi-instrument of the Leon II and III, the same recycling routes have been assessed to process this part. The organic content is the highest compared to that of the Combi-instrument of the Leon II and III (almost 80%). The Cu content is comparable to that to the Leon III higher (a bit lower than 6%), and still very low in absolute terms. The same applies to the Fe content (<2%).

- Cu processing route (see Figure 6)
- Energy recovery (see Figure 9)

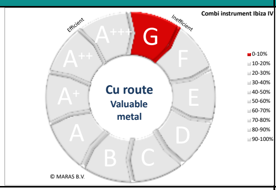
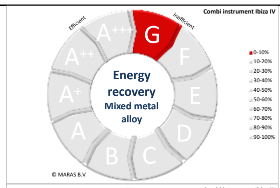
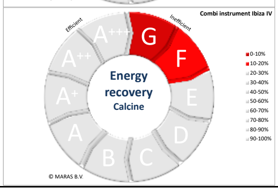
Figure 24 Major composing materials of the Combi Instrument of the Ibiza IV (classified)

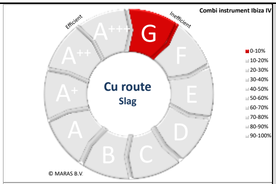
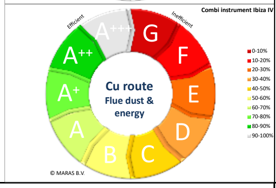


4.3.5.2 Overall/total recycling rates

The overall recycling rate for this car part for the assessed routes is given in Figure **25** by the Recycling Index (RI).

Figure 25 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route and Energy recovery) – Combi instrument Ibiza IV

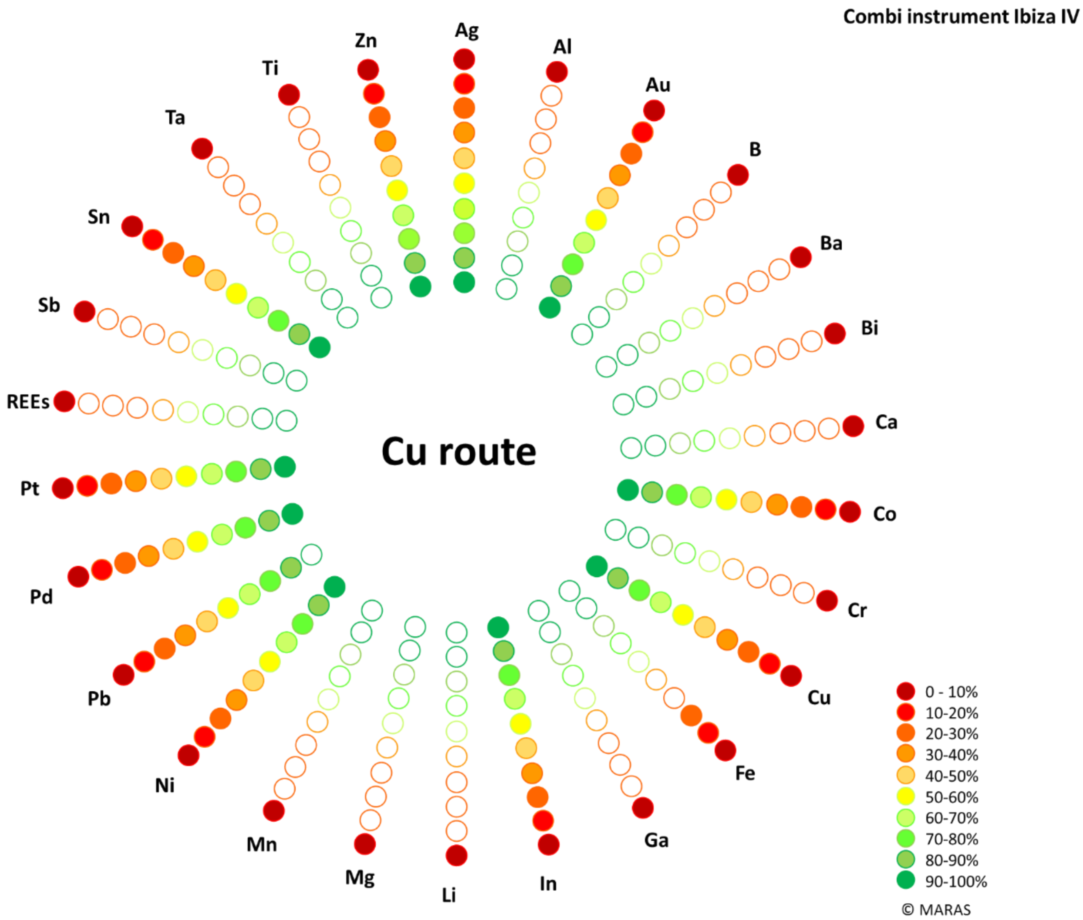
Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		Not feasible for this car part due to the low Fe content	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			

3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.64 MWh/t feed		4.30 MWh/t feed

4.3.5.3 Individual material recycling rates

As clearly visible from **Figure 25**, in spite of the low recycling rate, only the Cu processing route for processing of the Combi instrument of the Ibiza IV produces high quality closed loop CE products, without further sorting or upgrading required. Hence, it is only realistic for this route to present the individual material recycling rates, similarly to this part of the Leon II and III. The Material Recycling Flower (Figure 26) depicts the individual elemental recycling rates of a selection of materials / elements / compounds that are recycled into high quality products for the Combi-instrument of the Ibiza IV.

Figure 26 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product



4.3.5.4 Discussion of results of recycling processing of the Combi instrument from the Ibiza IV

The overall recycling results as well as individual material recycling rates of the Combi-instrument of the Ibiza IV show that the results of the recycling assessment of the Combi-instrument of the Ibiza IV are comparable to the results of the Leon II as well as the Leon III. Due to the (small) differences in composition, minor differences in the recyclability of both parts of the three car types can be observed. However, the discussion of the results of the Combi-instrument from the Leon II (and Leon III) are equally valid for the Ibiza IV. Therefore, these results are not repeated here, but please refer to section 4.3.3.4 for the discussion of the results.

4.3.5.5 Conclusion

As the results of the recycling assessment of the Combi-instrument of the Ibiza IV are comparable to that of the Leon II and III and composition is similar (in spite of small differences), the conclusions as defined for the Leon II and III are equally applicable for this car part type of the Leon III (see section 4.3.3.5).

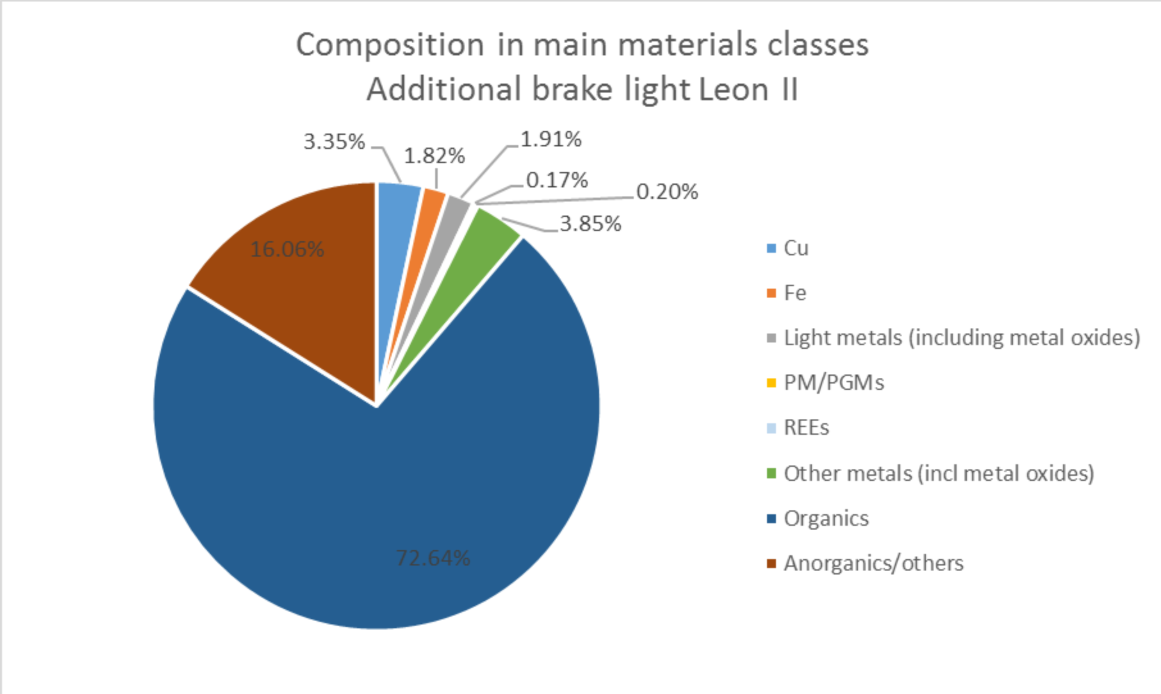
4.3.6 Results recycling assessment Additional brake light Leon II (Mirror / lighting)

4.3.6.1 Composition of car part

Figure **27** shows the major composing materials/compounds of the Additional Brake Light of the Leon II. This graph clearly shows that this part is mainly composed out of organics (almost 95%). The concentration of Cu and related metals is very low (close to 1%). The Fe content lies around 0.04%. The composition determines that in fact only energy recovery would be a feasible option for processing of this part in its current composition (without further separation of the plastics from the part). In order to also include the option of recovery the small percentage of Cu and related metals from the part, the Cu route has in spite of the very low Cu content, been included in the assessment. The following routes has been assessed to determine the recyclability of this part.

- Cu processing route (see Figure 6)
- Energy recovery (Figure 9)

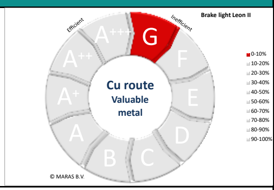
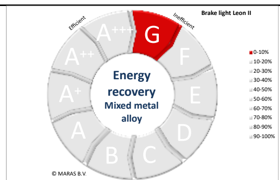
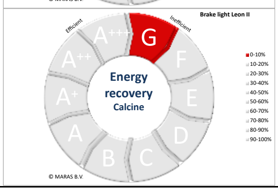
Figure 27 Major composing materials of the Additional Brake light of the Leon II(classified)

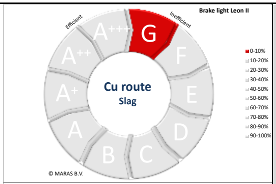
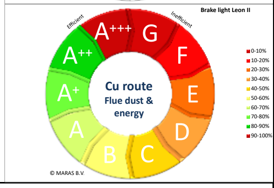


4.3.6.2 Overall/total recycling rates

The overall recycling rate for this car part for the assessed routes is given in Figure 28 by the Recycling Index (RI).

Figure 28 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route and Energy recovery) – Additional brake light Leon II

Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		Not feasible for this car part due to the very low Fe content (0.04%)	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			

3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.			
4.Energy recovery from feed	0.69 MWh/t feed		5.24 MWh/t feed

4.3.6.3 Individual material recycling rates

In spite of the low recovery rates, the Cu route is the only route in which high quality close loop CE products are obtained. Hence, only for this route the individual recycling rates are presented by the Material Recycling Flower in Figure 29.

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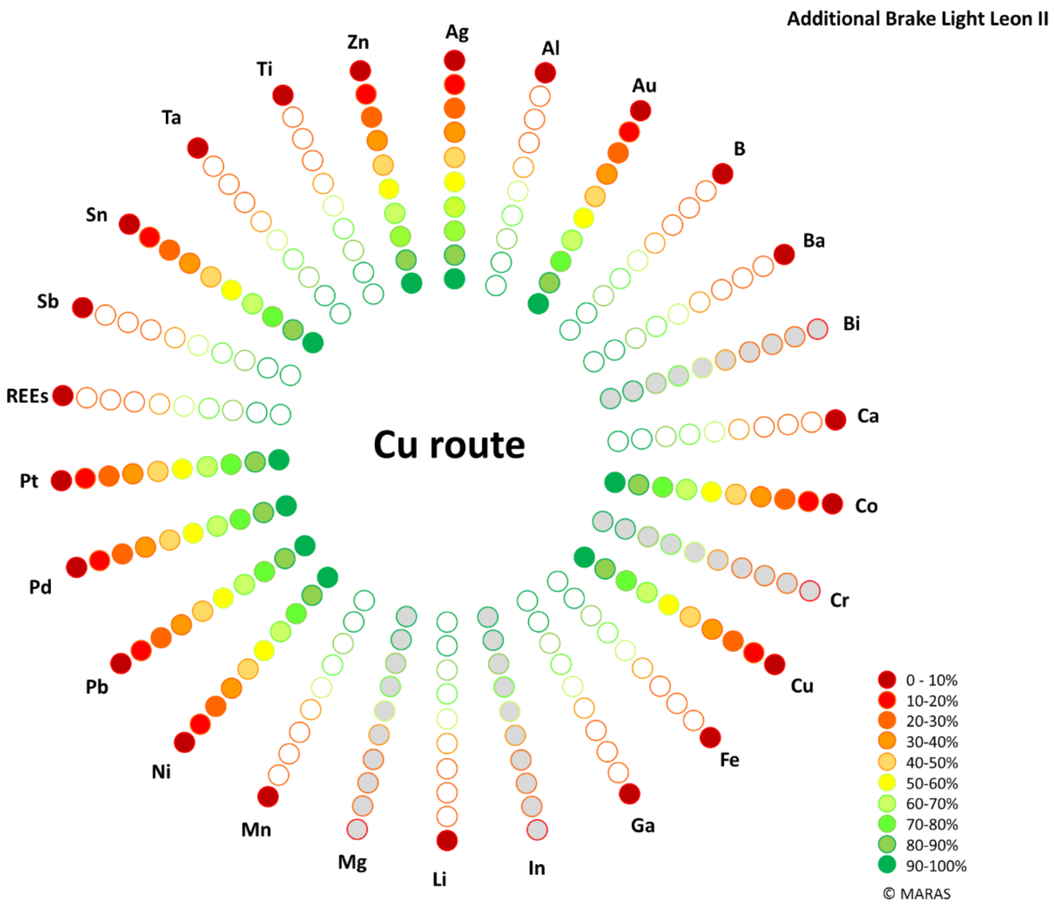
Figure 29 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product (note that the elements presented with grey bullets are not present in the car part)



4.3.7.4 Discussion of results of recycling processing of the Additional brake light Leon II

Cu processing route

The composition of the Additional Brake Light is, like for the Combi-instruments, characterised a low Cu content and very low Fe content. Comparable to the processing of the Combi-Instrument - from the Additional Brake Light, only a small part of the car part can be recovered into valuable metals with a high quality to realise closed loop CE (such as Cu, Ag, Au, In, Sn, Pb, Pd, Pt, Ni, Co and Zn). The other metals present in the car part, which are not compatible with the Cu processing route, such as Al, Ba, Ca, Fe, Mg, Si (also present as Al_2O_3, BaO, CaO, FeO_x, SiO_2) are recovered in the slag, which is an open loop CE product. Off gas elements, such as Br, Cl, Cd, C, H, O, S, I, N will report to the flue dust and off gas, which is also a open loop CE (intermediate) product. The Additional Brake Light is a very high in organic content, even higher than the Combi-instrument. Also, for this part, in the Cu processing route, the organics and plastics are used as energy carrier and reductant in the process.

As for the Combi-instrument and the Infotainment unit the low copper grade in the car part bears the consequence that the copper route requires additional heat to heat slag for a specific operating point. Usually processing of also this type of part will be integrated and mixed with other copper and valuable materials and processed together to render processing economic as is the basis of the HSC Sim simulation.

Steel processing route

Due to the very low Fe content, the steel processing route provides no feasible option to recycle the Additional Brake Light, when being processed in its total composition.

Energy route

Due to the very high presence of organics, the energy processing route can be considered as most suitable to process the Additional Brake Light, in case no further disassembly would take place to concentrate the valuable metal containing parts and separate them from the organic based parts. Similar to the processing of the other cars parts, in this process, also a metal phase and calcine are produced. These are however both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading, e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE. The energy recovery per ton of input is considerable higher than the amount of energy recovered in the Cu route and the highest for all assessed car parts.

4.3.3.5 Conclusion

The selection of the best processing route for the Combi instrument of the Leon II depends on the objective of the recycling. There is no one best route.

When the focus is to recover as much (valuable and critical) metals from the car part, the most preferred route from a closed loop CE point of view, would be to process this part in the Cu route. In spite of low recovery rate, in the Cu processing route high quality closed loop CE products can be realised, while at the same time recovery of (part of the) energy contained in the organics fraction is realised. As discussed for the processing of the Combi-instrument, it has to be considered, that due to the low Cu content, recycling of this car part requires a significant input of heat and primary resources to obtain the correct operation point. This can be considered as a negative point for this processing route.

Due to the very high organics content, the energy processing route would be the best option to recover the energy as contained in these organics. In this process, also a metal phase and calcine are produced, however these are both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading, e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE.

Recommendation for additional disassembly and Design for Recycling are the similar to the recommendations and motivation thereof as discussed for the other parts in the previous sections.

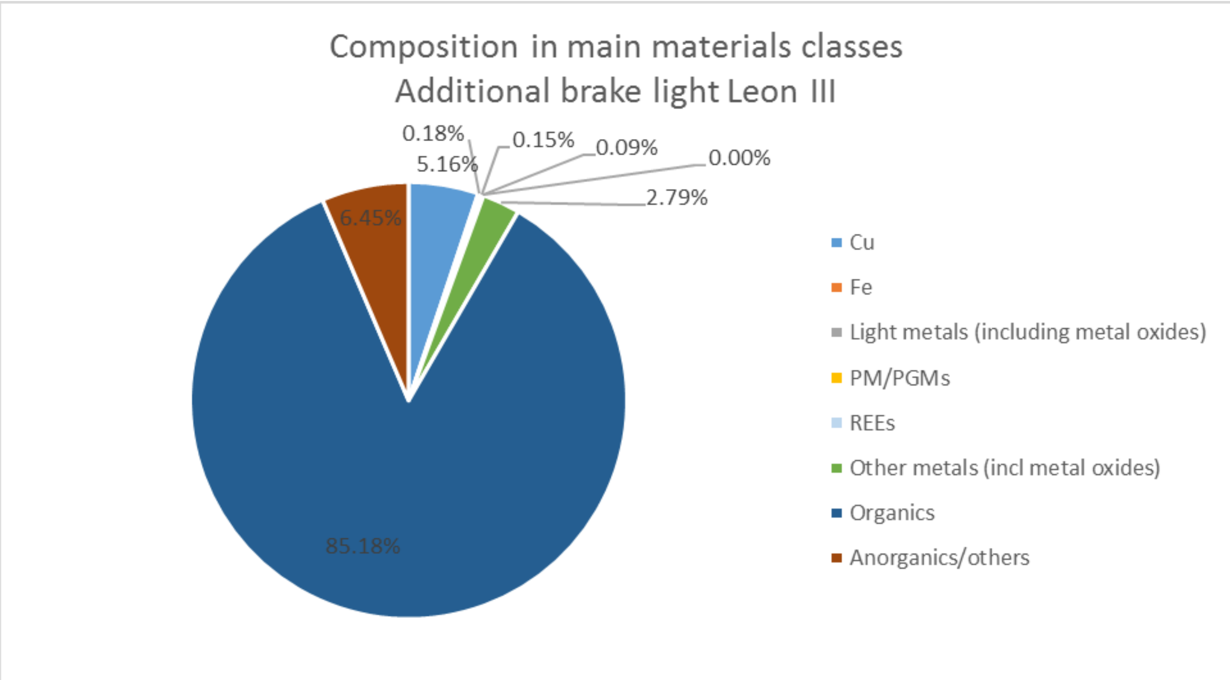
4.3.7 Results recycling assessment Additional brake light Leon III (Mirror / lighting)

4.3.7.1 Composition of car part

Figure **30** gives the composition of the Additional Brake light of the Leon III. This figure reveals that the composition is comparable to that of this part in the Leon III and is characterised by a very high organics content (>85%) and very low metal content. The Cu content and related metal content is however a bit higher than that of the Leon III (<6%). Therefore, the following recycling routes have been assessed to process this part (similar to the Leon II):

- Cu processing route (see Figure 6)
- Energy recovery (Figure 9)

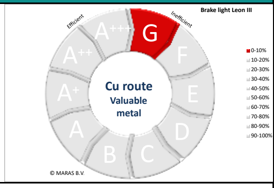
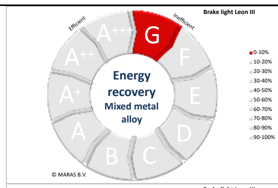
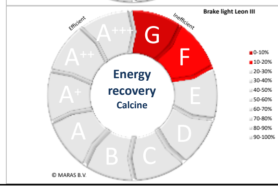
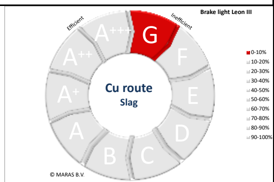
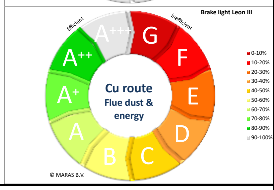
Figure 30 Major composing materials of the additional brake light of the Leon III (classified)



4.3.7.2 Overall/total recycling rates

The overall recycling rate for this car part for the assessed routes is given in Figure **31** by the Recycling Index (RI).

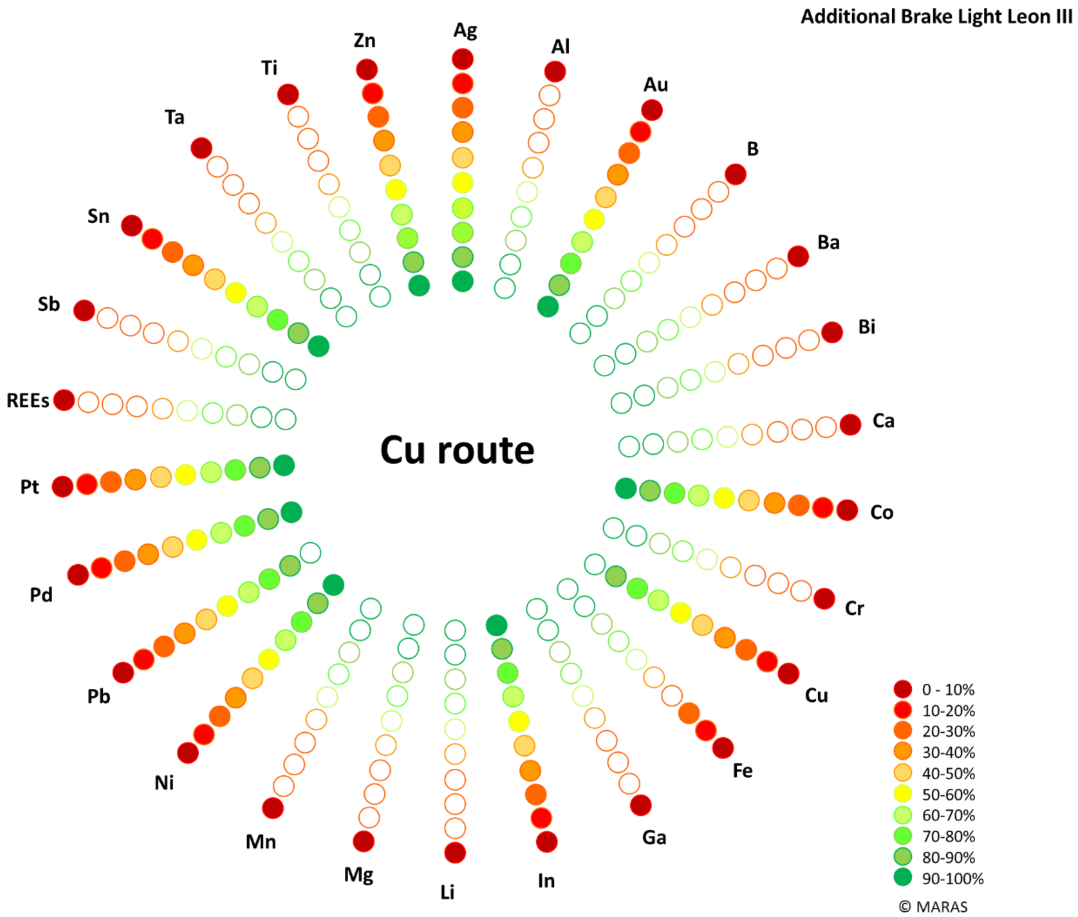
Figure 31 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car part in different recycling routes (Cu processing route and Energy recovery) – Additional brake light Leon III

Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		Not feasible for this car part due to the very low Fe content (0.18%)	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			 
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.65 MWh/t feed		5.70 MWh/t feed

4.3.7.3 Individual material recycling rates

In spite of the low recovery rates, the Cu route is the only route in which high quality close loop CE products are obtained. Hence, only for this route the individual recycling rates are presented by the Material Recycling Flower Figure **32**.

Figure 32 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the car part in the Cu processing route for the valuable metal product



4.3.7.4 Discussion of results of recycling processing of the Additional Brake Light of the Leon III

The overall recycling results as well as individual material recycling rates of the Additional Brake Light show that the results of the recycling assessment of this part of the Leon III are comparable to the results of the Leon II. Due to the (small) differences in composition, minor differences in the recyclability of both parts of these car types can be observed for this car part. In particular the Cu content of the Additional Brake Light of the Leon III is slightly higher, therefore resulting in a slightly higher recycling rate of Cu and related valuable metals in the Cu route. The discussion of the results of the Brake Light of the Leon II are equally valid for Leon II. Please refer to section 4.3.6.4 for the discussion of the results.

4.3.7.5 Conclusion

As the results of the recycling assessment of the Brake Light of the Leon III are comparable to that of the Leon II and composition is quite similar (in spite of small differences), the conclusions as defined for the Leon II and III are equally applicable for this car part type of the Leon III (see section 4.3.6.5).

4.4 Results recycling assessment of car sub-parts after additional disassembly (level 2) of the Combi-instrument of the Leon II

In T3.2 the disassemblability of car parts has been investigated. In order to determine the effect of more in depth disassembly of the car parts into different sub-parts, which should have a more homogeneous composition due to further disassembly (e.g. disassembly into PCB containing parts, plastic parts and Fe based parts), the recycling of the level 2 disassembly for the case of the Combi-instrument of the Leon II has been assessed. The results are discussed in this section and compared to that of the recyclability of the Combi-instrument without further disassembly as discussed in section 4.3.3. More recycling assessment of level 2 and 3 disassembly cases will be included in the next steps of the recycling assessment in this project (e.g. use-cases, etc.).

4.4.1 Composition of the sub-parts of the Combi-instrument of the Leon II

The Combi-instrument of the Leon II has been further disassembled into three main fractions/modules (see D3.2), which for some parts consist out of different sub-modules/parts (but are considered here as one part, however this could be further separated if needed from a recycling point of view):

- Plastic/organic parts (4 different parts dismantled) - 74.3 mass % of the Combi-instrument
- PCB containing parts (3 different parts dismantled) - 25.5 mass% of the Combi-instrument
- Ferrous based parts (1 part dismantled) - 0.2 mass% of the Combi-instrument

These 3 fractions build-up the entire Combi-instrument, no remaining parts are left after disassembly. The mass distribution over the 3 different fractions/modules reveals that the ferrous part only covers a very small fraction of the total Combi-instrument.

Figure 33 shows the composition of the different sub-parts of the Combi-instrument of the Leon II after disassembly. When comparing these graphs to that of the composition of the Combi-instrument, it becomes immediately clear that the additional disassembly of the Combi-instrument into plastic, PCB and ferrous based sub-parts has created sub-parts/modules, with a much more segregated composition, matching better with the different sections of the Metal Wheel, i.e. the compatibility of materials within the different metallurgical (and plastic/organics) processing routes.

Figure 33a reveals that the composition of the plastic parts is characterised by a high percentage of plastics/organics, which is higher than 85% on average. When looking at the four different plastic parts, it becomes apparent that three out of four parts consists (almost) 100% of plastics/organics and the one other part contains a percentage of anorganics and other metals, which effects the average composition of these plastics parts.

Figure 33 b show that the PCB parts are significantly higher in Cu and valuable metal content compared to the Combi-instrument without disassembly. Figure 33b reveals at the same time that the PCB parts still have an average Fe content of more than 6% and a light metals content of more than 7%. Both Fe and light metals are not recovered as metals, but will report to the slag. Also the anorganics fraction is very high in these parts (>65%), which will also report to the slag. Comparing the composition of the two individual PCB parts reveals a large spread in e.g. Cu content (38% versus 7%), Fe content (34% versus 2%), SiO_2 content (10% versus 72%) and light metal content (0% versus over 8%).

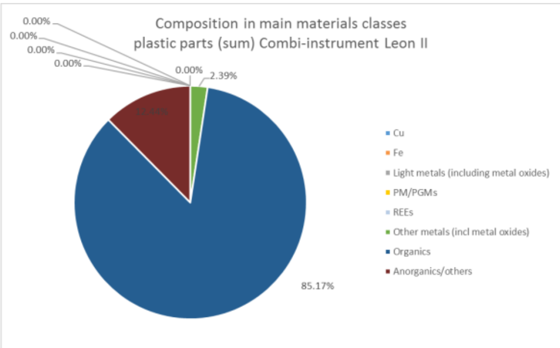
Figure 33c reveals that the ferrous based part is characterised by a very high Fe content (>90%), which is a significant difference with the Combi-instrument without further disassembly (see Figure 18).

Based on their content and their average composition, the following recycling routes have been assessed for the processing of the different sub-parts, which are in this case processed as the sum of the different sub-parts. The difference in composition between the sub-parts of the same category can however lead to a difference in recycling performance if processed/assessed as separate parts. This is not considered here, but can be included in a later stage to support disassembly decisions and Design for Recycling in more detail.

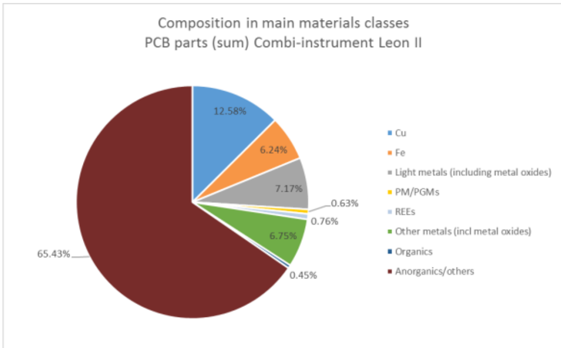
- Cu processing route for the processing of the PCB based parts
- Steel processing route for the processing of the ferrous based part
- Energy recovery for the processing of the plastics/organics based parts

Figure 33 Major composing materials of the sub-parts of the Combi-instrument of the Leon II with composition in main material classes of (a) the plastic parts (summed), (b) the PCB parts (summed) and (c) ferrous based part

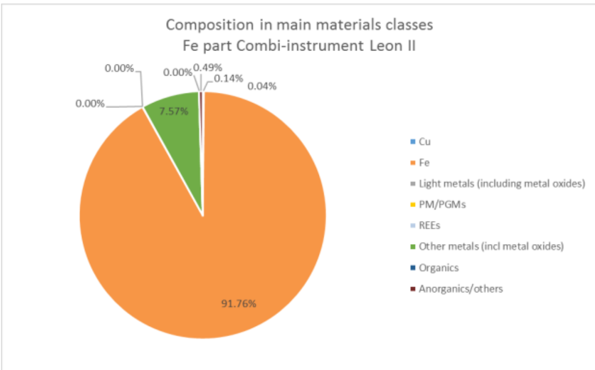
(a)



(b)



(c)



4.4.2 Overall/total recycling rates

The overall recycling rate for this car part for the assessed routes is given in Figure 34 by the Recycling Index (RI). The crucial difference with the results of the recycling of the entire car part without further disassembly, is that in this case, all results are achieved and not one of the routes, as all parts are processed in the most suitable recycling route, implying that all routes are applied at the same time, for each of the different parts. This reveals the true benefit and positive effect of additional disassembly on recycling performance. The recycling rates for the total car part (Combi-instrument) based on the processing of the sub-parts in the most suitable processing routes as discussed, is given in Figure 35.

Figure 34 Recycling Index for closed and open loop CE products and energy recovery as a result of the processing of the car sub-part in the most suitable recycling routes (Cu processing route for recovery of the PCB parts, Steel processing for the recovery of the ferrous part and Energy recovery for the processing of the plastics/organics parts from the Combi-Instrument of the Leon II (all results are achieved at the same time, this is different from Figure 19)

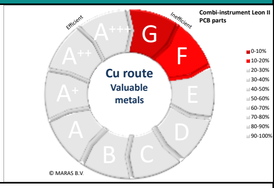
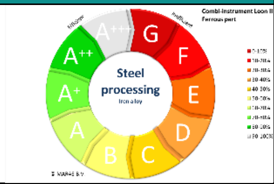
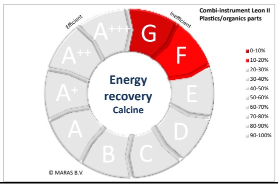
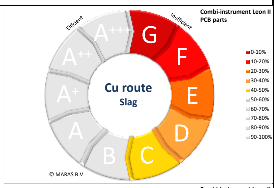
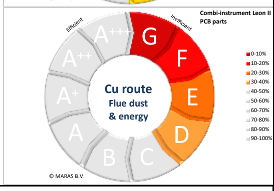
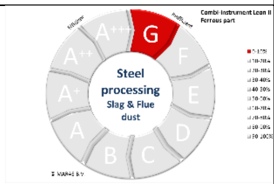
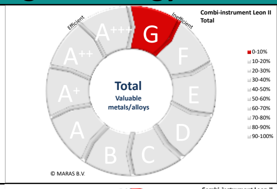
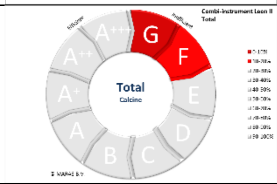
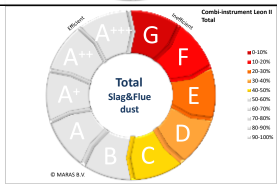
Recycling in terms of CE recycling products	**Recycling of PCB parts in Cu processing route 25.5% of total**	**Recycling of ferrous part in Steel processing 0.2% of total**	**Recycling of plastics/organics part in Energy recovery 74.3% of total**
1. Closed loop CE – high quality products which can go straight back into part or product			No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.001 MWh/t feed		4.69 MWh/t feed

Figure 35 Recycling Index for closed and open loop CE products and energy recovery of the **total** Combi-instrument as a result of the processing of the car sub-part in the most suitable recycling routes (Cu processing route for recovery of the PCB parts, Steel processing for the recovery of the ferrous part and Energy recovery for the processing of the plastics/organics parts

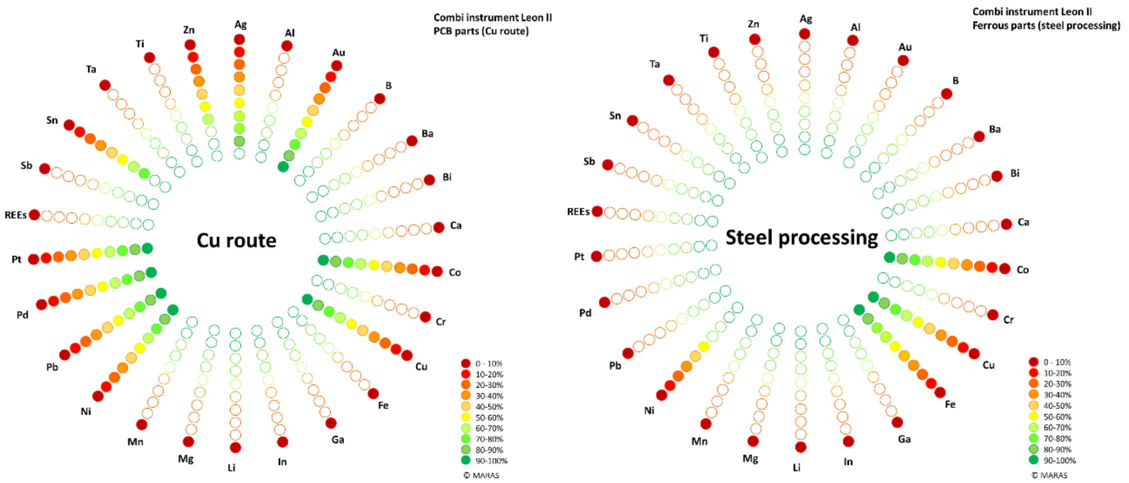
Recycling in terms of CE recycling products	Recycling rates of the Combi-instrument based on the separate processing of the level 2 disassembled parts in the combination of Cu route, steel processing and energy recovery (weighted average)
1. Closed loop CE – high quality products which can go straight back into part or product	
2. Open loop CE to be processed into closed loop CE – intermediate products	
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	
4.Energy recovery from feed	4.69 MWh/t feed

4.4.3 Individual material recycling rates

Figure 35 shows that both in the Cu route as well as in the Steel processing route high quality close loop CE products are obtained. Therefore, for both part types, the individual material recycling rates can be presented. Figure 36 makes clear that also e.g. Fe can now be recovered to high rates. The high recovery of Cu in the steel processing route, is unwanted, as this is a harmful element in steel processing and results in a decrease of the iron alloy quality.

Figure 36 Material Recycling Flower showing recycling rates for a range of selected elements for the recycling of the (a) PCB parts of the Combi-instrument of the Leon II in the Cu processing route for the valuable metal product and (b) ferrous part of the Combi-instrument in the Steel processing route

(a) (b)



4.4.4 Discussion of results of recycling processing of the car sub-parts after additional disassembly (level 2) of the Combi-instrument of the Leon II

Figure 34 shows that both Cu and related valuable metals, as well as the ferrous in the ferrous part can be recovered at the same time. Also the high recovery of energy from the plastic/organics parts in the energy route can be achieved simultaneously. As each module is directed to the most appropriate recycling route, no choice have to be made here. This is different from the results for the non-disassembled parts. Figure 34 also makes clear, that the creation of lower quality, open loop products such as slags and flue dust is much lower than when the Combi-instrument is processed in its totality. This is thanks to the fact that the streams are better matching the processing capabilities of the applied processing routes and the presence of slag forming or volatile components (ending in the flue dust) is much lower. Also the creation of a metal mix during energy recovery is avoided, as no (or a very low amount of) metals are present in these parts.

The effect of the disassembly (level 2) might not become directly apparent when looking at the total recycling results for the Combi-instrument as given in Figure 35 (based on the summation of the three applied processing routes, one for each particular fraction/module). This figure does not show a significant increase in total recycling rate compared to the processing of the Combi-instrument without dismantling. However, the additional disassembly has clear effects on the recycling efficiency:

- Both Cu and valuable metals (mainly contained in the PCB parts) as well as energy from the plastics/organic compounds can be recovered at the same time, without having to make a choice between the one or other processing option.
- The ferrous material can be recovered to a relatively high purity alloy.
- The individual material recycling rates (e.g. for Cu and Fe) are higher
- The creation of open loop CE products (slag and flue dust) is (to an extent) mitigated due to the much more segregated composition of the different parts. Losses and required

additional physical sorting and/or chemical upgrading (and related requirement of primary resources/energy) is therefore minimised or decreased.

This assessment could be extended by assessment of the possibility of physical recycling of (some of) the plastic parts to produce them into a new high quality plastic products. This would also require detailed information on the type of plastics applied, the quality requirements of the manufacturer for adopting high quality recycled plastics and information on e.g. quality degradation during recycling and/or use.

Due to the fact, that the Fe content in the Combi-instrument is very low (see Figure 18), it is evident that the disassembly and separate processing of this ferrous part is not contributing much to the increase of recycling rate in total in this case. This will however be different for parts with a high Fe content, such as the Infotainment unit, which is characterised by a very high Fe content (which can, according to the recycling assessment, only be recovered into a very impure alloy which needs a high input of primary to dilute). For the Infotainment Unit, it can already be predicted, based on the results of the level 2 disassembly on recycling, that for this part, the increase in recyclability will be much more evident. It should however be taken care of, that by additional disassembly of the Fe fractions of e.g. the Infotainment unit, the presence of harmful elements for iron/steel production (such as Cu, Sn, Sb, etc) can be separated from the Fe part(s) to ensure a high enough quality of the produced iron alloy.

4.4.5 Conclusions on the effect of additional disassembly on recycling performance

The recycling assessment on the level 2 disassembly for the Combi-instrument from the Leon II reveals that separating sub-parts, with a more comparable composition, matching with the different segments in the Metal Wheel allows for a better recyclability of the car part. This can be observed from:

- Increase in total recovery (although this depends very much on the mass contribution in the total part of each the separated leading materials (e.g. Fe content, Cu content, etc.) of product into closed loop CE high quality products
- Increase in the recovery of the individual elements/materials
- Mitigation of creation of open loop CE products (such as slags/flue dust)
- Recovery of (in)compatible materials is possible in different processing routes
- Ability of recovering both (valuable) metals and energy content without losses of valuable metals e.g. to open loop CE products (to be processed into closed loop CE) such as mix metal alloys and/or calcine

As the level 2 disassembly has change the composition of the different car (sub) parts, the the model based approached allows for optimization of the system architecture of the physical and metallurgical recycling processes linked to this improved disassembly strategy. Each sub-part or component can be directed into the most optimal recycling route through which both both metal and energy recovery are optimised and the creation of losses and dissipation of energy and exergy can be minimised. Recommendation to guide disassembly for both level 2 and 3 is to pay special attention to minimise the presence/mix of incompatible materials, in order to reduce the presence of elements which could be harmful to steel processing. In this way, dilution by primary materials to obtain the required alloy quality, and related environmental impact thereof, can be minimised or avoided.

5. Conclusions and recommendations

5.1 Recycling system modelling/physics-based approach to recycling

Recycling assessment of complex products requires the application of rigorous and physics-based process simulation models, which include the complex interlinkages of functional materials in the modules as well as all chemical transformation processes in the reactors in the system model in versatile flowsheet simulation modules. This approach permits the rigorous evaluation of the recyclability of a product within the circular economy, in which all materials/elements/compounds are included in full compositional detail and their behaviour in recycling processing. This is different from a simple cherry picking of elements, in which other materials and material interactions in recycling are disregarded hence leading to unreliable and erroneous results. On this rigorous basis, disassembly of selected car parts as defined in T3.2 have been tested from an EoL perspective incorporating the rigour of the process model.

Through an evolution of development of simulation models by MARAS (see references in this report and discussed background), MARAS further evolved a recycling system model to be applied within the TREASURE project. This model has been applied in T3.3 to assess the reuse/recycling/recovery of the car parts selected for disassembly in T3.2 in order to determine the recyclability of these parts, assess the effect of disassembling these parts on recycling behaviour, including the effect of additional disassembly, as well as define further recommendations for more in depth disassembly when required. Also, Eco-design recommendations are made based on the finding of the recycling simulations and derived insights into recoveries and losses of materials/elements/compounds of these car parts. In the model, all mass flows (kg or tonnes), recoveries and losses for metals/materials and elements/compounds (%) are calculated resulting in energy (kW), exergy (kW), and mass flows (tph).

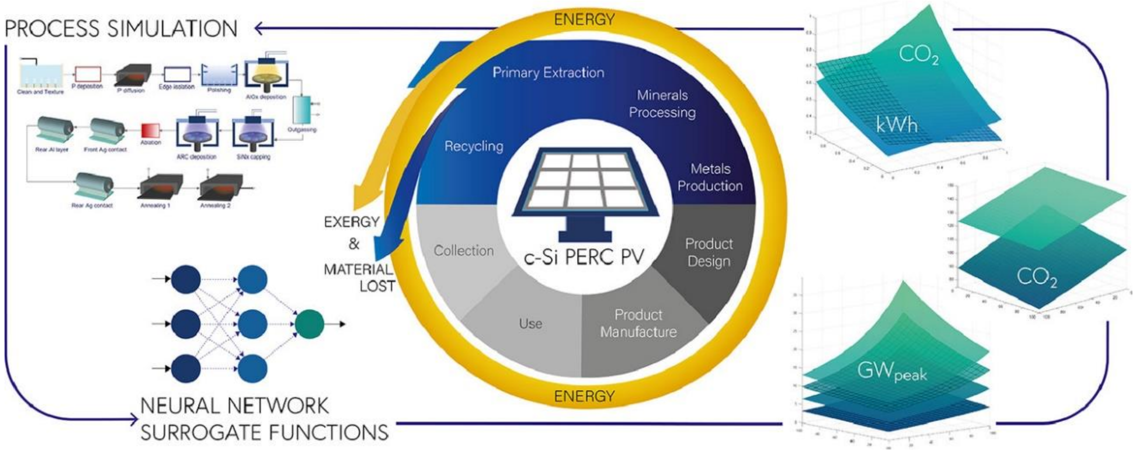
5.2 Data processing and automation

Successful accomplishment of recycling, environmental and exergetic assessment demands that the full 'mineralogy', i.e. the full chemical composition of all metals, materials, compounds (implying metals, metal oxides, organics, inorganics, etc) is available and applied for the recycling analyses. The MISS files as provided by SEAT on the composition of the car parts, require – in spite of their structure and build-up which has been designed to comply with ELV directive - a very extensive data analyses, processing, structuring and completion to prepare and structure the data into a consistent and detailed format, from which the input to the recycling simulation models can be defined. Data gaps have been filled, data description of organics have been added in terms of composition, the compounds are defined in terms of chemical/stoichiometric formulas rather than in a descriptive or CAS number format. This provides composition of the product/part and sub-parts, thus all compounds, functional materials, alloys, plastics etc. and their spatial position on the modules. The masses for all materials and compounds related to their distribution in the part are calculated. Hence the data processing as performed by MARAS allows that the data is available in a form that a thermochemically based simulator can recognise to provide the relevant thermochemical information, which is identical in structure for all car parts, i.e. a digital data twin of the car composition for recycling.

The data processing reveals that the car parts as included in the recycling assessment contain more than 320 different compounds (metals, alloys, oxides/sulphides, inorganics and organics), of which around 220 compounds are organics. We have classified the organics into different categories where possible, to reduce the number of different organic compounds to be included into the model and platform and make data transfer more efficient. It is crucial to be aware that the process of data classification can only be performed, the moment the full compositional detail of all organic compounds is known from the extensive data analyses and processing as has been performed on the MISS data files. This classification is also performed in view of the future step of including and transferring the recycling simulation platform into the Recycling Module of the TREASURE platform.

The processing, completion and structurisation of the data is extremely time consuming, as for this moment, this can only be done manually. In view of the development of the TREASURE platform and the integration of the Recycling Module into this, automation of the data processing needs to be part of this process. Automation/digitalisation of input data is essential so that it can link the product design easily to a digital twin of a metallurgical and energy recovery processing infrastructure. Classification of input composition is part of this process in view of preparation of data sets from the detailed simulation model to create surrogate functions that twin the simulation model. These neural net – AI (Artificial Intelligence) based tools can then be trained and easily integrated into design tools and the TREASURE platform. This has been done in the past by within the EU 6th framework project SuperLightCar (Krinke et al, 2009). The figure below (Figure **37**) (Bartie et al., 2021) shows this also clearly, i.e. a simulation model calculates all flows, can estimate exergy dissipation but also environmental footprint information. All these data can be integrated into surrogate functions for use in for example design tools for rapid calculations.

Figure 37 Process simulation and the link to neural network surrogate functions for use in AI for rapid calculations (Bartie et al. 2021)



5.3 KPIs

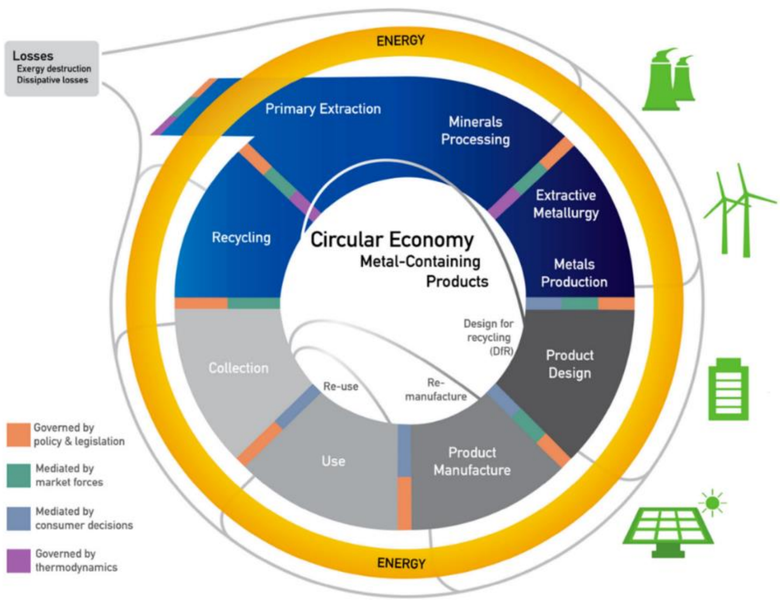
The development and application of Product Centric recycling process simulation tools generates the digital twins of the EoL circular economy. This permits the rigorous calculation of Recycling Indices for the entire part, as well as calculation of the individual recycling rates of all materials in a product, car part, sub-part or component as presented in the Material Recycling Flowers, hence providing physics based KPIs for CE and Eco-design. Whereas the overall recycling rates provide information on the recyclability of the entire part or product, the individual recycling rates/KPIs are the basis for true 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, the Material Flowers as developed by MARAS serve very well as a tool in this discussion and help to make the choice for a certain recycling route, not only driven by weight based considerations, but addressing the recycling of materials and elements, which are of interest to recycle or defined as critical and therefore require focus in selecting the most optimal recycling options.

A clear distinction has been made in the Circularity Level of the Recycling KPI. This has been classified into three categories depending on the true circularity level, i.e. 1. **Closed loop CE** (recycling into high quality products with material properties equal to original product/material); 2. **Open loop CE to be processed into closed loop CE** (intermediate products, such as low grade alloys, calcine, etc which require further physical sorting and/or chemical upgrading to achieve the required high quality material properties/alloy quality to render closed loop CE) and; 3. **Open loop CE** ((intermediate) products such as slag and flue dust for repurposing e.g. as building/construction material etc. - requires significant energy and thus exergy dissipation and thence costs to convert to level 1 closed loop CE materials)

In addition to the Recycling Indices which are expressed in kg, tonnes/hour or %, physics-based recycling standards based on exergy and energy can be derived from the simulation models in addition to the mass flows. The driving unit for exergetic and energy assessment is kW (this is not part of D3.3).

Figure **38** shows that energy and exergy are all flows in kW that represent the thermodynamic state of the system. Material flows are also energy flows, but degrade in quality expressed as exergy dissipation, which are the true losses of the system. The simulation model in this report can calculate the losses shown in the figure. Exergy and enthalpy are excellent to fundamentally explain the barriers shown in the figure below (Bartie et al. 2019)

Figure 38 Exergy and energy flows representing the thermodynamic state of the Circular Economy system and its true Circularity (including materials/mass flows expressed in terms of energy/exergy)



5.4 Recyclability results and most suitable recycling routes for processing of car parts

This report shows the various industrially available flowsheets that produce high quality materials that can return back for use into the same product. These flowsheets are integrated into the recycling simulation models. For each car part, depending on its composition (high organics/low metal) the two or three most suitable recycling routes have been assessed to determine recyclability. This selection is made from the range of industrially available recycling routes, which are selected based on the expert knowledge within MARAS. The following three route (or two out of three) have been included in the assessment:

- Cu processing route
- Steel processing route
- Energy processing

Based on the outcomes of the recycling assessment and the calculated recycling KPIs, the most suitable recycling route can be defined. Comparing individual material recycling rates is crucial in this discussion.

As the car parts are characterised by a complex mixture of materials/elements/compounds, which are connected and combined within one car part, there is no one best option to process these different parts, as each of the processing options, will lead to recovery of certain elements, and losses of other, as depicted qualitatively by the Metal Wheel. The selection of the best recycling route depends on the focus of the recycling optimisation. Exergetic analyses (although not part of this deliverable) could support the assessment of the most optimal (exergetic) recycling route.

The general conclusion on recyclability of these parts, when the focus is to recover the maximum of valuable metals (Cu and related) is to process them in the Cu processing route, where the valuable metals can be recovered in a high quality closed loop CE application, the slag and flue dust can be applied as lower quality open loop CE application and part of the energy as present in the organics is recovered. Due to the low presence of metals, the recycling rate for the parts remains is consequently very low. it has to be considered, that due to their low Cu content, recycling of the different car parts requires a significant input of heat and primary resources to obtain the correct operation point. This can be considered as a negative point for this processing route.

Considering the high content of organics for all parts and in particular for the Combi-instrument and Additional Brake light, energy recovery processing could also be considered as a possible option to process these parts, in order to maximise the recovery of the contained energy. Although in this process, also a metal phase and calcine are produced, these are both open loop CE fractions, which require further physical sorting into different metal fractions (the metal phase) and chemical upgrading, e.g. by being processed in the Cu processing route (sorted metals and calcine) to achieve the required high quality material properties/alloy quality to render closed loop CE. However, smelting this “junk” has an economic cost and is not desirable, also from an exergetic point of view.

The steel processing route is not a feasible option for the processing of the entire car parts (without further (level 2/3) disassembly). This also applies to the car parts with a higher Fe content (the Infotainment unit), due to the very contaminated, low quality, iron alloy which is created, as a result of the presence of many other metals in the car parts, which will dissolve in the alloy. To render this alloy to a closed loop CE product, this alloy has to be diluted by pig iron or Direct Reduced Iron (DRI), but this may not achieve the tight specifications of steel alloys and carries with it the carbon footprint of the primary pig iron production. Therefore, this has a negative environmental consequence due to the addition of high amounts of primary sources, while nevertheless the many harmful elements will also then have a negative impact as mentioned due to steel alloy specifications.

For the processing of the sub-parts created through additional disassembly (level 2), a combination of the different recycling routes (Cu route, steel processing and energy recovery) can be applied, resulting in a more optimised recycling of the part under consideration. As the composition of the parts, created through additional disassembly, is much better harmonised with the compatibility of the metals/materials as can be processed in the different recycling routes (as shown by the Metal Wheel), in addition to the Cu and energy recovery route, also the steel processing route is feasible. These routes can be applied together to process the different sub-parts in order to achieve most optimal recycling performance, instead of having to select one recycling route for the processing of the total part, which inevitably leads to losses.

5.5 Recommendations on additional dismantling and DfR/Eco design

5.5.1 Recommendations on additional disassembly

The recycling assessment, incorporating the full compositional detail of the car parts, recovered through metallurgical processing and energy recovery flowsheets and derived KPIs provide the physics-based quantification to optimise Design for Recycling and make decisions and recommendations for more in depth disassembly.

Additional dismantling is recommended to optimise the recyclability of the car parts and to ensure plastics and organics are recovered in their original quality. The positive effect on recyclability is illustrated by the assessment of the level 2 disassembly, which shows an increase in material recycling rates, improved energy recovery as well as minimisation of losses and or creation of lower quality open loop products from recycling. Therefore, recommendation for additional disassembly would be to separate the organics containing sub-parts from the Cu and related metals-based parts or components to increase the concentration of valuable elements in the Cu based part, while the metal content of the organic based fraction for energy recovery can be decreased. Also harmonising the composition of the created sub-parts with the compatibility of the metals in the different sections in the Metal Wheel is recommended, in order to avoid losses and presence of harmful elements for the production of high quality closed loop CE products.

In general, this implies that by physics-based disassembly recommendations the mixture of incompatible materials in sub-parts/components has to be separated as far as possible into different sub-parts, when this is possible from a structural design point to view. Based on the processed MISS data, specific recommendations can be made for each part under consideration.

This facilitates (if possible, from a design and disassembly point of view) to process the car sub-parts as derived from additional disassembly (Cu based and organics based) in the most suitable processing route as is illustrated by the assessment of the level 2 disassembly on the Combi-instrument. In this way, both overall as well as individual material/element recycling rates can be increased and losses and required additional physical sorting and/or chemical upgrading (and related requirement of primary resources/energy) can be minimised or decreased. The creation of low valuable intermediate materials is therefore, to an extent, mitigated as is illustrated for the case on the level 2 disassembly. It could also be considered to separate organic containing parts, in which organics are present as well dismantlable plastics, for which physical recycling into a new high quality plastic product could be an option.

As additional disassembly can change the composition of the different car (sub) parts, the model based approached as discussed here, allows optimization of the system architecture of the physical and metallurgical recycling processes linked to improved disassembly strategy. Each sub-part or component can be directed into the most optimal recycling route to optimise both metal and energy recovery and minimise the creation of losses and dissipation of energy and exergy. This is also clearly revealed in the results and discussion of the level 2 disassembly.

The further assessment of level 2 and level 3 disassembly and possible other disassembly activities based on feedback from the Recycling assessment, will be elaborated on and specified within the different use cases in the TREASURE project.

5.5.2 Eco-Design and Design for Recycling

Design for Recycling (DfR) as part of Eco-design recommendations, can also be defined based on the performed recycling assessment. DfR should be focussed, within the limits of product functionality, on designing sub-parts/modules in which their composition is harmonized with the compatibility of the metals in the different sections in the Metal Wheel. The individual recycling rates as calculated in the recycling assessment quantitatively support and guide, which options in both additional disassembly and/or DfR will have the highest impact in improvement of recyclability. Also rarity based % as defined in WP3.1 could be used as a driver to select materials/elements and disassembly and DfR options. Physics-based DfR as part of Eco-design will be further expanded and detailed in Task 3.4.

6. Abbreviations

CE	Circular Economy
EoL	End-of-Life
ELV	End-of-Life Vehicle
MISS	Material Information Systems
LCA	Life Cycle Assessment
EAF	Electric Arc Furnace
DRI	Direct Reduced Iron
RI	Recycling Index
MFA	Material Flow Analysis
TSL	Top Submerged Lance
TBRC	Top Blown Rotary Convertor
AI	Artificial Intelligence
CRMs	Critical Raw Material(s)
DfR	Design for Recycling

7. Definitions

Recycling for Circular Economy: Recycling of a product within the circular economy implies creating the same material quality after recycling so that it can be applied in the same product.

Compound: Material defined in its stoichiometric chemical composition, i.e. aluminium as Al, Al_2O_3, etc.

Design for Recycling: Designing a product or part with the objective to optimise its recyclability into high quality recycling products

Disassembly: Includes dismantling and implies taking selected car parts from the entire EoL car as well as understanding if the disassembled car parts can be further selectively disassembled into smaller parts that can be channelled into the correct processing for optimal recycling.

Energy recovery: Plastic compounds are used as an energy source as well as for feedstock recycling e.g. using C and H as reductants.

Feed composition: The simulation model requires a full description of the compounds as input to the model, which must add up to 100% in weight.

Flowsheet: A logical sequence of reactors that convert the input into among others high quality materials, compounds, alloys, metals, building materials, energy as well as residues and intermediates that can be ponded or used in further processes. These flowsheets are industrially realistic and economically viable for different processing routes.

Flows: All the flows of materials, solution, mixture, phases, gases, dust (among others) are quantified in terms of enthalpy and entropy (kWh/h) values in addition to the mass flows (both total mass flows and mass flows per compound) in kg/h or tonnes/h.

Car part: The selected cars part for disassembly from the EoL car.

Sub-parts: Specific parts on the car part that can possibly be removed and sent to more dedicated processing.

Plastic compounds: Full composition of all organic molecules of C, H, O, N, Br, Cl, metals atoms etc. in addition to fillers within the plastic. These are complex functional materials that are difficult to recycle to produce the same quality as for the original plastic compound.

Product data: This is the complete composition of the product, thus all compounds, functional materials, alloys, plastics etc. and their spatial position on the modules. This means aluminium in Al, an alloy of aluminium, Al_2O_3 as an oxidized/anodized layer on the aluminium, or a filler etc.

Reactor: A unit in which the input of material is converted to a product, energy, off gas, solution or similar.

Recycling rate: Within the circular economy paradigm this means producing the same quality material, alloy, metal, or compound that can be used within the different car parts. The recycling rate of each element thus implies the recycling into high quality products that can go back into the same part or product.

Simulation: Predicting the flows of all compounds and phases throughout the complete flowsheet on a thermochemical basis including the detail of the different reactor types in the system.

Metal Wheel: Depicting the paths of recycling of materials into different processing infrastructures.

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