D2.2: Sustainability & Circularity Advisory methodology definition

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EXECUTIVE SUMMARY

The structure of the Deliverable was organised as follows. The introduction informs the reader about the activities of task T2.2 contained and addressed in this deliverable and the relationships with other project activities. Chapter §2 presents the study of the state of the art of strategies, methodologies, and tools to support End of Life (EoL) product decisions in the use cases of disassembly and recycling of electronic components, and to support Beginning of Life (BoL) decisions in the use cases of eco-design of electronic products. The SoA study found room for improvement for current EoL advisory strategies and highlighted the absence in the literature of an advisory methodology that integrates circularity and sustainability to support eco-design decisions. Chapter 3 presented the activity of the workshops divided into the use cases of disassembly, recycling and eco-design. This activity served to gather information on the decision-making processes currently in use at the pilots and to sketch future to-be processes that take into account the use of Key Enable Technologies (KETs) and possible advisory functions. In Chapter §3.1, the objectives of the workshops are presented, in Chapter §3.2, the workshop structure is presented, and in Chapter 3.3, the main workshops findings are presented, which were used as a starting point for the subsequent activities of proposing an advisory methodology in Chapter §4. The sustainability advisory framework is in fact presented in Chapter 4.1, where an interpretation of the decision-making processes of the three use cases is proposed and the decisions that can be supported by the advisory are highlighted. In this proposal, the use cases of disassembly and recycling have been treated together since a high interdependence between the two and a lower need for advisory was found. For the use case of eco-design, on the other hand, a greater need for advisory was found and two lines of decision-making were developed, one characterising re-design, and another characterising new design. In chapter §4.2, a proposal for integrating the advisory tool with the rest of the TREASURE platform is proposed and discussed, dashboard possibilities are presented in relation to the three modules of the platform, and different users for advisory in the role of decision makers are considered. Finally, chapter 4.3 dealt with providing a survey methodology to identify with the future users of the advisory tool the indicators to be selected. The survey was intended to provide an instrument ready to be used in subsequent tasks to select KPIs, indicators, and to investigate aggregation needs. The conclusions of the deliverable are available in Chapter 5. They summarise and interpret the findings of the state-of-the-art study, the results of the workshops and the results of the proposed advisory framework.

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1. Introduction

D2.2 "Sustainability & Circularity Advisory methodology definition" is meant to describe the activities carried out during the related task T2.2, presenting at the same time the obtained results. The methodology here described aims at providing support to decision makers involved in life cycle of the car electronic components so that their choices are made also considering the sustainability and the circularity perspective and not only the techno-economical one.

Referring to TREASURE project and its ambitions, the focus of the advisory is on the End-of-Life phases (EoL) of car electronic components, that is on the disassembly and recycling. Also, the Begining-of-Life phase (BoL) is considered since the components and car design could orient higher circularity performances and thus affecting the disassembly and the recycling phases. On the contrary, the Middle-of-Life phase has not a primary role in the project, so the decision taken concerning car use and maintenance, or the energy consumption of the electronic components are not taken into account by the advisory. In the literature, there are not many advisory frameworks oriented towards sustainability decision-making in the use cases of disassembly, recycling and eco-design. This deliverable intends to fill this gap by presenting a study on the state of the art, the interactions with pilots through dedicated workshops and, finally, by proposing a sustainable advisory framework elaborated according to the achieved findings and other project activities.

1.1. T2.2 activities covered in this deliverable and other associated project activities.

The contents of this deliverable reflect the activities of T2.2. T2.2 is meant to define the TREASURE advisory methodology framework and tools. Specifically, the use of interactive optimization, a multi-criteria decision-support method integrating assessment models in a decision framework, and its integration in the LCS&CA methodology has been evaluated. The final goal is to provide metrics allowing decision makers to justify their choices. In connection with T2.1, T2.2 is meant to regulate the contribution of stakeholder's consultation to the advisory methodology definition.

1.1.1. Relations with other activities within the work package

The development of T2.2 as well as the drafting of D2.2 was done considering the interactions with task T2.1, in particular for the choice of input and output indicators for the advisory. The use cases defined in T3.1 were used to set up workshops with the pilots. Recommendations on disassembly and recycling for traditional components developed in T3.2 T3.3, recommendations for eco-design from T3.2, and information on the architecture of TXT from T4.1 were also considered.

2. State-of-the-art on (AI-based) sustainability and circularity advisory

In accordance with the objective of T2.2 of TREASURE, which is to define an advisory methodology to be provided to the three project use cases, i.e., Disassembly, Recycling, and Eco-design, this Chapter reports a state-of-the-art analysis of existing methods and tools that can provide Life Cycle Sustainability & Circularity Advisory (LCS&CAd), and how AI is exploited to improve sustainability and circularity performance of processes by providing decision-making support.

The integration of strategies that can optimize product performance along each stage of the life cycle in terms of sustainability and circularity has become critical for companies/organizations. In particular, there are three main reasons for a company to undertake sustainable initiatives (Rousseaux, Gremy-Gros, et al., 2017). The first motivation is related to regulations. Companies' operations and results must be compliant with national and international standards and regulations. In this regard, there are numerous directives at the European level focused on waste management and product specifications suitable for the automotive context on which TREASURE project acts:

- Directive 2000/53/EC - the "ELV Directive" for recycling and recovery of End of Life Vehicles (European Union, 2000);
- Directive 2005/64/EC on the type-approval of motor-vehicles with regards to their reusability, recyclability and recover-ability (European Union, 2005);
- REACH Regulation for the safe use of chemical substance (European Union, 2006);
- Restriction of the Use of Certain Hazardous Substances Directive (2002 and revised 2012) regarding the ban of hazardous substances in electrical and electronic equipment (European Commission, 2012c);
- Directive 2002/96/EC Waste management of Electrical and Electronic Equipment (2002 and revised 2012) (European Commission, 2012a).

The second motivation to adopt sustainable and circular strategies is driven by competitiveness. In fact, the integration of sustainability aspects in product development can promote strategic positioning in the market leading to increased consumer demand and competitive advantage (Baumann, Boons, et al., 2002; Bey, Hauschild, et al., 2013).

The last aspect is related to moral responsibility. In fact, over time there is increasing pressure from institutions and stakeholders for companies to act more responsibly and sustainably by integrating these aspects into their products and production processes (Bey, Hauschild, et al., 2013; Brones, de Carvalho, et al., 2014).

To pursue the goals set by regulatory compliance, competitive advantage, and moral responsibility motivations, organizations need to be supported, receiving advice to implement best practices, meeting technical requirements, economic constraints, and sustainability awareness. Thus, advice provided by experts and appropriate tools is a key step in meeting the mentioned goals, particularly in terms of sustainability.

First, it is necessary to specify the meaning of advisory. The term "advisory" refers to something that provides information or a warning and/or has the ability to help make decisions on a topic. Generally, advisory is provided by either human experts or advisory systems, classifiable as a type of expert system, which are able to solve problems that are difficult to solve by human experts. The latter are built by electrifying knowledge from human experts and encoding it in a form that can be used by a computer in evaluating alternative solutions to problems within the domain of expertise. They do not make decisions but guide the decision maker through the decision-making process, leaving the human user with the final decision-making authority. The human decision maker works in conjunction with the advisory system to identify problems that need to be addressed and to iteratively evaluate possible solutions (Aronson & Turban, 2001; Forslund, 1995).

Over time, the need for and application of intelligent decision support, which can integrate Artificial Intelligence (AI), has grown more and more (Phillips-Wren & Jain, 2006).

But what is meant by AI? One of the earliest definitions of the term comes from John McCarthy who defined it in 1995 as, "The goal of AI is to develop machines that behave as though they were intelligent" (Ertel, Black, et al., 2017). Another definition, according to (Deng, 2018), AI is a branch of computer science and technology aimed at developing the theories, methods, algorithms, and applications for simulating and extending human intelligence. AI brings many benefits but, with reference to decision support, helps the decision-maker to select actions in real time, enable up-to-date information and provide dynamic response with intelligent agents, and manage uncertainty in decision problems (Phillips-Wren & Jain, 2006).

Having clarified the meaning of advisory and of AI, it is necessary to explore how advisory methodologies have been implemented, how AI can support the decision-making process, and which benefits both advisory and AI can bring. Specifically, referring to how the three use-cases involved in the TREASURE project can be supported to make the automotive value chain more circular and sustainable. In accordance with this goal, manufacturers can generally implement two strategies to improve the recovery of products at the end of life (Rose, 2001):

- Curative strategy, i.e., improving the recovery processes to be applied to end-of-life products;
- Preventive strategy, that is, improving, through better design, the recoverability (Recovery-conscious Design (RCD)) and sustainability of the product.

Existing advisory methodologies are extrapolated below to enable the implementation of curative strategy and preventive strategy-driven methodologies. Not all methodologies and tools exploit AI.

2.1. Curative strategy: methodologies and tools to support end-of-life advice

Sustainable development, with its aim of reducing impacts to ensure resources for future generations, has generated the development of numerous environmental policies and legislation focused on decreasing the environmental impact of products at all stages of the life cycle, thus, from raw material extraction to end-of-life (EOL) management.

Focusing on end-of-life, waste management has become a crucial issue, linked to the growth of the world's population and the steady increase in demand for products. In fact, consumers are disposing of products much faster due to consumerism and the increasing pace of technological evolution. For this reason, according to (Ellen MacArthur Foundation, 2019), it is necessary to implement more and more circular actions, focusing in particular on the principles of the circular economy. First, waste and pollution are designed out. Second, products and materials are kept in use. This includes favoring activities that increase product utilization, and reuse to preserve the embedded energy, labor, and materials.

What role can AI play to help the implementation of circular economy strategies in EoL stages?

It turns out that AI can enhance and enable circular economy innovation by optimizing circular infrastructure. To innovate processes and infrastructure for reuse and recycling, feedback loops need to be established at several stages of product life. Products and components at the end of their use should be recycled to recover their materials. By enhancing the procedures for sorting and disassembling items, remanufacturing components, and recycling materials, AI can assist in developing and strengthening the infrastructure needed to "close the loop" on products and materials. The fact that EoL streams, whatever their nature, are varied and heterogeneous in terms of materials, products, and by-products, makes it difficult to extract value from used material streams. Pure, homogenous flows of material and products are necessary for the efficient recovery of valuable materials. In general, the better material streams are pre-sorted and separated, the higher the recovery level, the more components can be identified for reuse and remanufacture, and the higher the quality of materials extracted during recycling (Ellen MacArthur Foundation, 2019). By using visual recognition algorithms to filter post-consumer mixed material streams, AI is already demonstrating how it can add value by creating circular material flows and enabling better product and material value. For instance, ZenRobotics[2] uses cameras and sensors, whose picture input enables AI to manage smart garbage sorting robots. When sorting a variety of material streams, from plastic packaging to construction trash, these robots can achieve an accuracy level of 98%.

Considering specifically the electronics sector, one of the fastest growing problems in the world is e-waste management, due to the volume and complexity of waste streams, which include all kinds of end-of-life Electrical and Electronic Equipment (EEE) (EU Waste Electrical Electronic Equipment (WEEE) (European Commission, 2003b) .

According to (United Nations Environment Programme (UNEP), 2019), the world produces as much as 50 million tons of electronic and electrical waste a year, and only 20% of this is formally recycled through channels that allow for recovery of valuable materials while avoiding damage to the environment or to human health. Most of the e-waste is discarded rather than recovered or recycled, which leads to the loss of embedded energy, resources and value, as well as severe negative environmental and social consequences. For example, primary and secondary exposure to toxic metals, such as lead, results mainly from open-air burning used to retrieve valuable components such as gold. Combustion from burning e-waste creates fine particulate matter, which is linked to pulmonary and cardiovascular disease.

With a focus on their recyclability, e-waste consists of many useful recyclable materials, such as Metallic Fractions (MFs) like aluminum, copper, lead, zinc and metal alloys, and Non-metallic Fractions (NMFs) such as plastics, the epoxy-based substrates for printed circuit boards (PCBs), that indeed contains metals as well, and glass. In addition, e-waste contains not only toxic and dangerous pollutants, but also precious metals such as gold, silver and platinum if handled properly (Cui & Forssberg, 2003), (Ongondo, Williams, et al., 2011). It is extremely important, net of the considerations made above, to carry out the disassembly of e-waste so that as many materials as possible can be recovered. Special focus is on the sorting process, where AI is playing a crucial role, as described in the following case studies from literature.

In the study by Gundupalli et al., a robotic manipulator is adopted for the automated classification of metallic fractions (MF) and non-metallic fractions (NMF) from e-waste, dividing them into general categories: metal, PCB, plastic and glass. This classification is performed with a support vector machine (SVM) using the extracted keypoint features from recyclable materials via thermal imaging camera operating in the long-wave infrared range (LWIR) (Gundupalli Paulraj, Hait, et al., 2016).In the study by (Gundupalli, Hait, et al., 2018), a robotic manipulator is adopted for the automated classification of metallic fractions (MF) and non-metallic fractions

[22] https://www.terex.com/zenrobotics

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(NMF) from e-waste, dividing them into general categories: metal, PCB, plastic and glass. This classification is performed with a support vector machine (SVM) using the extracted key point features from recyclable materials via thermal imaging camera operating in the long-wave infrared range (LWIR) (Gundupalli Paulraj, Hait, et al., 2016).
The system overall work with the proposed technology is reported as a detailed example. First, e-waste is collected through take-back systems by organizations, manufacturers, retailers, and recyclers designated for recycling purposes, and transported to local dismantling units. Once there, a trained operator dismantles the e-waste equipment of various sizes into MF and NMF and sends the dismantled e-waste fractions to material recovery facilities, where the system capable of classifying and sorting recyclable waste using thermography would be placed.
Detailing the process (Figure 1), the first step in the process is the introduction into the system of the e-waste fractions that have been previously dismantled (a). Then, they are introduced into a hot chamber (b) and transported by a conveyor belt to an adjacent inspection area (c). At this point, the thermal imaging camera (d), positioned in a downward-facing vertical configuration at an adjustable height from the conveyor belt, takes over, which scans each component. Finally, the robotic manipulator sorts the identified recyclables at the end of the conveyor belt (e) and places them in their respective containers (f).

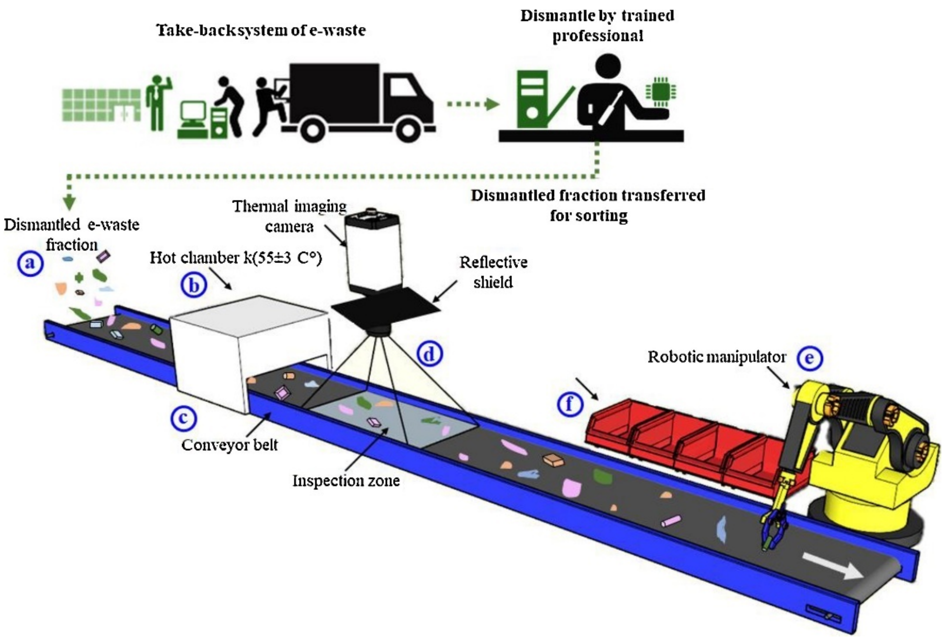

Figure 1: Functional principle of thermal imaging-based sorting technology.

Another similar example of application exploiting AI to process e-waste is presented by (Tehrani & Karbasi, 2017). The authors present a technique which combines hyperspectral imaging technology and a neural networks-based algorithm for identification and separation of different types of e-waste plastics (e-plastics).

Moreover, AI can be trained to help tune and optimize existing recycling equipment and infrastructure to handle specific types of material flows. E-waste comes in many sizes, shapes and conditions. These different features can require tailored settings and processes, requiring manual adjustment of recycling equipment and causing machine downtime. AI could handle some of this work in existing recycling, refurbishing and remanufacturing facilities by identifying the condition of end of use consumer electronics and automating adjustments to the settings of processing equipment. Refind Technologies[3] has developed several proof-of-concept systems which are capable of automatically identifying and sorting batteries or classifying and sorting mobile phones, with a view to implementing AI in the e-waste treatment process by bringing sustainability benefits to the actual process.

How is it possible to provide sustainability and circularity advisory in EoL stages?

The support of AI in processing e-waste can lead to sustainability benefits, that in case of Refind Technologies have been quantified by (Barletta, Johansson, et al., 2015). The case study of the "WEEE ID" (WEEE Identification) project funded by VINNOVA (Swedish Agency for Innovation Systems) is reported, which developed an intelligent, automated sorting equipment for used electronics' segregation and grading (Barletta, Johansson, et al., 2015). The sorting unit is designed to prevent operator exposure to hazardous materials during separation and, due to improved sorting efficiency and accuracy, allows for increased recovery rates in downstream processes. An automatic sorting device for e-waste turns the development into reality, through a small demonstrator called e-grader, whose CAD representation is shown in Figure 2.

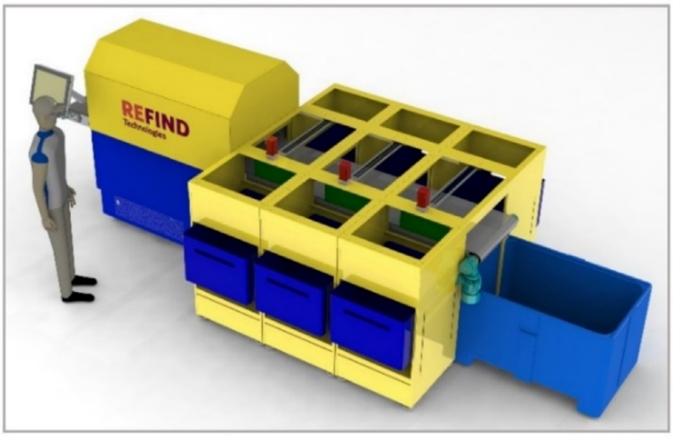

Figure 2: Automatic equipment for e-waste sorting and grading developed within the WEEE ID project

Using sensors and intelligent data processing, the demonstrator identifies in real time whether used electronics are suitable for reuse, refurbishment or recycling, and sorts them accordingly. One of the criteria for this feature is based on the knowledge that reusable spare parts are available from a specific model. The demonstrator is programmed to list the products in optimal fractions by making them instantly available for trading.

Given the technical advantages of the demonstrator, the case study reported by (Barletta, Larborn, et al., 2016) describes an assessment of the sustainability impacts, both environmental, economic and social, that the demonstrator can bring within an existing e-waste sorting facility, where the alternatives evaluated consist of i.) adoption of the smart sorting unit with a conveyor belt to support versus ii.) maintaining the status quo, therefore a plant with manual sorting, in a real use case.

The **economic benefit** brought by the device are determined through a static calculation sheets and Discrete Event Simulation (DES) of AnyLogic software.
The indicators used to assess impacts evaluate both economic and operational performances.

[3] https://echord.eu/essential_grid/refind-technologies/index.php.html

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In particular, the operational indicators are:

- Throughput (rate of items being processed)
- Lead time (from input storage to the end of the line)
- Utilization of the sorting unit.

While the economic indicators are:

- Income, the revenues generated by selling the recyclates, that is also related to the quality of the recyclates.
- Gross profit margin, which is the percentage of revenue remaining after the cost of goods sold:

$$Gross\ profit\ margin = \frac{Revenue - Cost\ of\ good\ sold}{Revenue}$$

- Return of investment (ROI), which measures the amount of return on an investment relative to the investment's cost:

$$ROI = \frac{Gain\ (or\ loss) from\ the\ investment}{Cost\ of\ the\ investment}$$

In conclusion, at the economic level, the smart e-grater solution has advantages in Throughput, but results in an increase in COGS, though it presents higher Gross profit and optimal ROI values.

The **environmental benefit** brought by the device are determined through a life cycle assessment (LCA) according to the (ISO, 2006), calculating the environmental impacts through OpenLCA software.
Two environmental impacts generated by e-grater users can be identified: the impact from the production of the sorting unit (including the sorting unit's bill of materials) and the impact from the use phase of the sorter within the facility. The first environmental impact mentioned has been calculated according to the impact assessment method of ReCiPe midpoint (Goedkoop, 2013) according to the hierarchist (H) perspective, but a comparison analysis on environmental impacts cannot be performed, as As-Is (manual) processing cannot be evaluated. The second environmental impact mentioned is less significant than the first because, even if the proposed technology results in increased environmental impacts and energy consumption in relation to the individual item, both the e-grader and the conveyor belt constituting the sorting facilities require low power compared to that required by the technical building services (TBS) of a facility, such as cooling and ventilation.

The **social benefit** brought by the device is assessed within the boundaries of the sorting system. To this end, a set of social indicators was used to assess the consequences of the introduction of the e-grader on workers within the analyzed plant (Taghavi, Barletta, et al., 2015).
As a result of data collection through literature reviews, in-company interviews, etc., it emerged how the use of the e-grader demonstrator brings social benefits in that it can support, for example, skills development. It is important to highlight that, in order to implement the technology in a socially sustainable manner, the following must be ensured:

- Education and training for employees
- Creating awareness in workers of the new responsibilities they will have.

To investigate further, a map was made, showing the influences that occur among all stakeholders after the introduction of the e-grader and throughout the life cycle in relation to the three sustainability assessments. It emerges that:

- Operations carried out by recyclers, if connected to informal e-waste treatment activities, cause huge damage to the communities of developing countries affected by illegal e-waste dumping. More accurate sorting and higher reuse initiatives can indirectly reduce the amount of e-waste otherwise intended for informal e-waste recycling;
- Policy makers can incentivize the adoption of the e-grader unit within sorting and recycling centres through several means, for instance monetary incentives (e.g., tax reductions).

The above-described use case serves as a showcase of how AI can drive circularity in the industrial processes as multiplier of resource recovery. However, the sustainability performance is evaluated only downstream the technical and the functional requirements: in the decision-making process, sustainability aspects are not treated at the same level of requirements for the definition of the sorting technology, and functional requirements are not modified according to sustainability considerations. Moreover, this use case is focusing only on one of the different step of the recycling process that has the objective to create fractions from which the materials can actually be recovered in final treatment processing.

A step forward to a global approach is the one developed by MARAS through recycling flowsheet simulation models as defined in 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 (Reuter, M.A., Schaik, A. van and Ballester, 2018; Schaik, A. van and Reuter, 2013, 2014; A. van Schaik, Reuter, et al., 2002). This approach allows analysing and processing the chemical composition of the components and subcomponents of products, to calculate recycling and recovery rates from product level till elementary level, optimizing recycling processing flowsheet architectures related to an improved disassembly strategy, to simulate and evaluate recycling routes based on metallurgical processes, links design to recycling through digitization, and develops physics-based recycling labels, shows results through a visualization tool called Recycling Index (M. A. Reuter & van Schaik, 2016). The recycling flowsheet processing simulation models cover the entire recycling flowsheet including disassembly, shredding, physical sorting and metallurgical and other final treatment processing. Recycling assessment (i.e., recycling rate calculations) and underlying calculations are performed by the application of rigorous and physics-based process simulation models. These include the complex interlinkages of functional materials in the car parts, E-waste or any other multi-material product under consideration, pinpointing that only this level of detail allows to predict recycling rates and improve system performance of the EoL recycling system related to design. It goes down to the level of including all chemical transformation processes in the reactors in the system model in versatile flowsheet simulation modules. In the recycling simulation models 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 approach quantifies each stream not only in kg/h units but also in MJ/h or kW, allowing not only recycling rate calculations, but at the same time environmental analysis including exergy assessment. 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.

The research is following a Product Centric approach towards recycling as defined by Reuter and Van Schaik (Reuter, M.A., Hudson, C., Van Schaik, A., Heiskanen, K., Meskers, C. and Hagelüken, 2013). This implies that the focus goes beyond only representing Critical Raw Materials (CRMs) or other selecting of materials, 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 and determine both recoveries, losses, emissions and recycling product qualities, which can be achieved in the Eol stage. This approach permits the rigorous evaluation of the recyclability of a product within the circular economy, including all compounds/materials/elements in a product.

(M. Reuter & Schaik, 2015) shows the link of both process simulations for plant design and recycling (as described above) with LCA in one tool. On the basis of different examples taken from industry (including WEEE recycling from LED lamps), the work demonstrates the combination of accurate process simulation using recycling process simulations in HSC Chemistry Sim (producing closed mass and energy balances as well as exergy flows) is linked to environmental impact software. This provides a very useful basis to evaluate complex material flows and metal production plants and systems, identify gaps in current LCA for recycling systems, develop innovative engineering and Design for Recycling including recycling rate and environmental (LCA and exergetic) optimisation.

AI or fuzzy based modelling for recycling assessment and Design for Recycling has been developed by Van Schaik and Reuter for automotive recycling. This has been, linked to LCA and LCC within the EU 6th framework project SuperLightCar (Krinke S, van Schaik A, Reuter MA, 2009). The figure below (Figure 3**Errore. L'origine riferimento non è stata trovata.**) (Bartie, Cobos-Becerra, et al., 2021) shows also the development of process simulations linked to AI., 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.

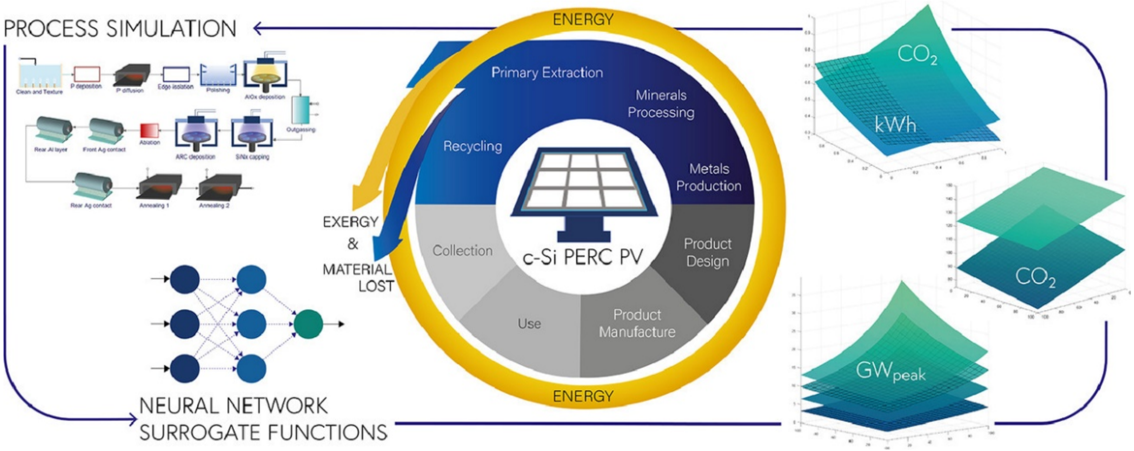

Figure 3: Process simulation and the link to neural network surrogate functions for use in AI for rapid calculations (Bartie, Cobos-Becerra, et al., 2021)

To conclude, e-waste should be a concept of the past in the circular economy of the future for electronics, thanks in part to the AI boosting. It is true that investments in infrastructure will be required for collection and sorting to enable reuse, remanufacturing, and recycling, given that, however, a new approach to design of products and materials is adopted. Such a design should enable devices that can be used and reused or disassembled in components that are easily replaced and easily stripped of its materials. Indeed, it emerges how intrinsically the EoL performances are linked to the BoL ones. Indeed, acting on the barriers to material recovery in the circular economy sense, namely keeping valuable material in the loop, means not only optimizing EoL from the process performance point of view, but also acting at the BoL to prevent the limitations to recovery correlated to the functional design stage.

2.2. Preventive strategy: methodologies and tools to support eco-design advice

Related to the motivations introduced in the previous chapter (§2.1) and the importance of implementing circular actions, it is necessary for manufacturers to also focus on the efficient integration of circular strategies at the product design stage. It is critical that designers are pushed to change the view of products, considering not only the costs associated with material selection and manufacturing activities, but also the entire product life cycle, including end-of-life (EoL) (Gehin, Zwolinski, et al., 2008). To this end, designers put in place arrangements such as changes to product characteristics, materials, or geometries from the outset so that they have products that can be configured to have closed-loop scenarios, allowing parts or materials to be reintroduced into the production chain (reuse of the entire product or some components, remanufacturing of components, or recycling of materials). One example is provided by TNO in WP5: a new design of an in-mold electronics part is provided that facilitates dismantling at end-of-life to ensure the possible recycling of metal, SMD components and plastics.

By optimizing products in the design phase from a CE perspective, it is crucial not to forget the aspect related to the impacts generated in the three areas of sustainability, environmental, economic and social. In fact, focusing on the environmental sphere, according to the European Commission (European Commission, n.d.), all products during their life cycle have an impact on the environment at all stages, from the use of raw materials and natural resources to production, packaging, transportation, disposal and recycling. More than 80 percent of that impact is determined at the design stage.

In order to make advisories that can enable the creation of circular products that are sustainable, the following is a collection of tools that can provide support. The tools are distinguished into: Sustainability-conscious Design methodologies and tools and Recovery-conscious Design methodologies and tools.

2.2.1. Sustainability-conscious design methodologies and tools

Following a literature search, a number of tools have emerged to support the eco-design stage, which can provide suggestions and advice to the designer in terms of sustainability. Depending on the objective of the tool they are classified into 3 different groups: analysis tool, useful in several phases of the product development or procurement processes, comparison tool, intended for later stages of the design process, when there are different product concepts to be compared and prescription tool, useful at the beginning of the in the design process.

Starting with analysis tools, all follow an approach that considers the product throughout the entire life cycle. The first analysis tool identified is "ABC-Analysis" developed by (U, E, et al., 2000), used to qualitatively assess the environmental impacts of a product. The tool can evaluate the product according to 11 different criteria and classify it as: problematic (action required), medium (to be observed and improved) and harmless (no action required). Another tool is the one developed by (Frankel, 1996), called "The Environmentally Responsible Product Assessment Matrix (ERPA)" where the matrix is used to estimate the potential for improving a product's environmental performance. Each phase of the life cycle (pre-production, product manufacturing, product delivery, product use, and reconditioning/recycling/disposal) is assessed against five criteria (material choice, energy consumption, solid residues, liquid residues, gaseous residues). The environmental impact for each of the life cycle stages is estimated by ranking each criterion from 0 (highest impact) to 4 (lowest impact). Thus, the tool is able to provide quantitative output data without requiring quantitative input data. The last analysis tool is the tool developed by (Brezet, 1997) called MET-Matrix. The purpose of the tool is to identify the most important environmental problems during the life cycle of a product, which can be used to define different improvement strategies. Environmental problems should be classified into the categories: Materials cycle (M), Energy use (E), Toxic emissions (T). The results and data can be both qualitative and quantitative.

Regarding comparison tools, five tools have been identified.
The first, developed by (H., 1997) called "Philips Fast Five Awareness", is used to judge and compare different product concepts towards a reference product. Five criteria are chosen: energy, recyclability, hazardous waste content, durability/reparability/preciousness, alternative ways to provide service. The tool performs a qualitative assessment throughout the product life cycle. Another is the one developed by (Schmidt-Bleek, 1999), called "Funktionkosten", which uses a quantitative approach to identify cost-effective product alternatives for development or can be used as an estimate of cost changes as a result of implementing an ecological design principle. General product functions are described, and the cost of each alternative solution is calculated for each function. Unlike the previous tool, it does not implement a life-cycle perspective.
As for the EcoDesign Checklist (U, E, et al., 2000), it allows for the identification of major environmental issues throughout a product's life cycle- The user has to evaluate whether the solutions in the checklist are good, indifferent, bad or irrelevant, so this is a qualitative approach. Another comparison tool is the Econcept Spiderweb (U, E, et al., 2000), which can be used for an estimation to decide between design alternatives. The user defines an appropriate set of criteria to be used for the estimation. For each solution a qualitative evaluation of the criteria is made and gives an environmental profile for each solution.
The last comparative tool is the tool called "LiDS-wheel" (Brezet, 1997), which allows to give an overview of environmental improvement potential to the designer, thus a qualitative output. Eight environmental improvement strategies are utilized in the tool: selection of low-impact materials, reduction of material usage, optimisation of production techniques, optimisation of distribution system, reduction of impact during use, optimisation of initial lifetime, optimisation of end-of-life system and new concept development. Data from a reference product are entered into the diagram and according to the eight strategies; improvement options for the product should be identified.

The last type of tool to support eco-design are prescribing tools.
The first one identified is the Strategy List (U, E, et al., 2000), which, through a qualitative approach, can be used to improve the environmental performance of a product concept or to compare different product concepts. The tool consists of a list of suggestions for each life cycle phase (product manufacture, product use, product recycling, product disposal, distribution) to improve the environmental performance. The suggestions are based on the criteria: optimize material input, optimize energy use, reduce amount of land use, increase service potential, reduce pollutants, reduce waste, reduce emissions, reduce health and environmental risks.
Another tool, also qualitative, are the Ten Golden Rules (Luttropp & Karlsson, 2001). The 10 Golden Rules is a summary of many guidelines that can be found in company guidelines and in handbooks of different origins. Before it can be used as a tool in a company, it should be transformed and customized to the particular company and its products. The tool can then be used to improve the environmental performance of a product concept or to compare different product concepts.

The last tool is the "Volvo's Black List, Volvo's Grey List, Volvo's White List" (T., 1998a, 1998b; T, 1998). The purpose is to list chemical substances which must not be used (black list), should be limited in use (grey list) in Volvo's production processes, or chemical substances which may be critical from a health and environmental point of view (white list). The white list also suggests alternatives which, according to experiences and assessments made at Volvo, are potentially less hazardous.

2.2.2. Recovery-conscious design methodologies and tools

By reviewing the literature, it was possible to find that there are numerous studies focused on optimizing EOL treatments of waste after consumption and not implemented early in the design phase. Nevertheless, after exploring existing developments in Recovery-conscious Design (RCD), i.e., design focused on maximizing and optimizing product recoverability, it was possible to identify several categories of methods focused on material recovery, differentiated according to the number and type of processes that are considered in the recovery system. Four groups emerge: Dismantling-conscious Design (DCD), Dismantling for Recovery-conscious Design (DRCD), Shredding-conscious Design (SCD) and Recovery System-conscious Design (RSCD).
Analysing the dismantling-focused methods, they aim to ensure the suitability of the product for manual disassembly so as to increase the recoverability of the product at the end of life. These differ from DRCD methods in that the latter optimize the dismantling operation, which is the first stage, so as to prepare the product for subsequent recovery pathways.
Another group are the SCD methods that implement the design of a product oriented in such a way that the parts and materials obtained after shredding the product are easily recoverable. The last category, namely RSCD methods, are the methods considered most comprehensive, as they acknowledge the recovery of a product as a combination of processes such as dismantling, shredding, sorting, and recycling (Furuhjelm, 2000).
Incorporating all the steps necessary to carry out recycling, RSCD methods are the ones that research has focused on, going on to identify what tools exist to support the designer so as to advise him or her in decision-making.
Unfortunately, there are not many developments of this topic due to the need to introduce numerous factors, both qualitative and quantitative, such as environmental impact, quality, legislative factors, and cost, in order to develop a decision model and select the best performing alternative (Ilgin & Gupta, 2010).

An interesting method is the one proposed by (Mathieux, Froelich, et al., 2008), called ReSICLED, Recovery Systems modelling and Indicator Calculation Leading to End-of-life-conscious Design, developed for electric and electronic equipment manufacturers and automotive manufacture. The tool allows the design team to quantitatively assess the recoverability of a product according to a number of different scenarios and different recoverability criteria. Relative to the scenarios, these are accomplished through a combination of elementary recovery processes. These recovery processes identified by the tool developers, specific to EEE recovery are shredding; sorting; recycling; incineration with energy recovery; selling recycled materials and recovered energy; burying in controlled landfill; and logistics.

Regarding the criteria for evaluating recoverability, they are:

- Weight criterion, to meet legislative requirements established by (European Commission, 2012a). This criterion is a quantitative evaluation of the recovery rate per weight that will be reached from recovery of a product at the end of its life;
- Economic criterion, to ensure cost control during the implementation of the WEEE Directive requirements. This criterion is a quantitative evaluation of the overall cost, or the economic benefit, of recovery of the product, as it is paid, or earned, by the last

owner of the product. This cost e or benefit e includes the cost of collecting and processing the product and the economic benefits obtained when selling recycled materials and recovered energy that are produced;

- Environmental criterion, to guarantee the corporate image of the company as well as to cope with new legislation (e.g., (European Commission, 2003a)). This criterion is a quantitative assessment of the overall environmental impact, or benefit, of recovery of the product at the end of its life. It includes the environmental impact of collecting and processing the product and the environmental benefits associated with the use of recycled materials and recovered energy in downstream life cycles.

Through this assessment, the team is able to identify and implement improvements in product design. Specifically, the tool allows for: minimizing the amount of waste disposed in landfills, establishing economically viable recovery systems, conserving resources, and reducing pollution.

Another approach for evaluating and managing the EoL of products at the design stage is developed by (Favi, Germani, et al., 2017). The goal of the design methodology is to improve product sustainability by increasing the percentage of components with a closed life cycle by encouraging reuse, remanufacturing and recycling scenarios through the evaluation of the most convenient EoL scenarios for product components, considering both environmental and economic aspects. It is based on indices, which are fundamental as they assess the feasibility of each EoL scenario considered (reuse, remanufacturing, recycling and incineration), that together with the analysis of preferable disassembly pathways, allow designers to control the sustainability of the product in terms of economic and environmental impact. environmental impact.

Analysing the methodology in detail consists of 3 phases, summarized in Figure 4. In the first phase, a disassemblability analysis is performed. Starting from the structure of the product (e.g., from a 3D CAD model), it is possible to analyse the disassemblability of the product by calculating the best disassembly sequence for a specific component or for the entire product and the relative disassembly time to minimize disassembly operations. In the second stage, EoL indices are calculated, based on data derived from the previous stage, retrieved automatically from the 3D CAD model (e.g., constituent materials and component weight) and/or the PLM system (e.g., component cost and material cost). The indices of interest result: Reuse index, Remanufacture index, Recycling index, and Incineration index.

The evaluation of EoL indices is useful to enable companies to determine whether a closed-loop scenario can be conveniently implemented for the product, component, or part under analysis. The third stage of the method is the redesign process. Having defined the EoL strategy, the company must define the target values to be achieved during the redesign, which must be defined according to the characteristics of the component under analysis (e.g., the value of materials) and to the business objectives (e.g., business models).

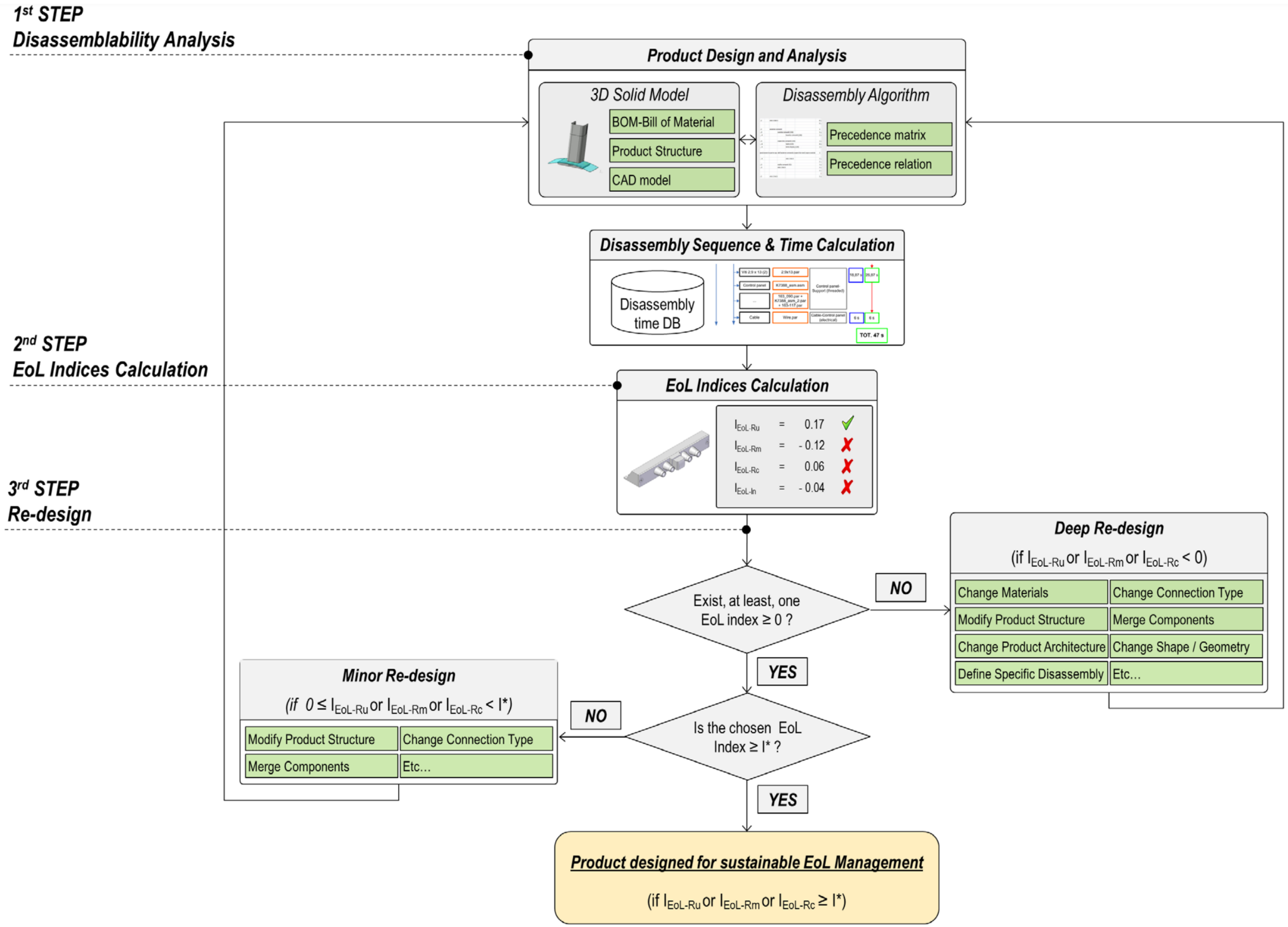

Figure 4: Framework of the eco-design methodology proposed by (Favi, Germani, et al., 2017)

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Instead, (Remery, Mascle, et al., 2012) developed a multicriteria decision-making approach, which provides a systematic evaluation of alternatives based on a set of criteria during the initial design phase of the product development process, called the EOL scenario evaluation method (ELSEM). The primary objective of the tool is to support the designer in identifying applicable EOL scenarios according to the company's business and environmental objectives and to determine the technical characteristics of the product suitable for the chosen scenario.
Analysing the application of the method, the first place the designer at the beginning of the design must estimate the main functional components, their relationships and their materials and weights (Brissaud & Zwolinski, 2004). Having determined the components, called "modules," the designer must evaluate the various scenarios by going to assess: the materials that form the product, their relative recovery rate and energy recovery rate, and also a set of 13 technical characteristics for each individual module. The EoL scenarios are Reuse (RU), Remanufacturing (RM), Recycling with disassembly (Rwd), Recycling without disassembly (Rwod), Incineration with energy recovery (IER) and Disposal (Disp).
Next, ELSEM is able to provide a ranking of each EOL scenario for each module, namely reuse, remanufacturing, recycling with disassembly (Rwd), recycling without disassembly (Rwod), incineration, and disposal. From this, the designer is able to determine which scenarios are most suitable based on the business strategy.
To provide the ranking of scenarios, ELSEM exploits a multi-criteria fuzzy decision-making method, called fuzzy TOPSIS, which is able to rank the decision problem in a hierarchy taking into account economic, regulatory and environmental aspects. So, it proves to be a valuable tool that guides and facilitates the choice of the most suitable scenarios.

Another interesting methodology turns out to be the one developed by (Dostatni, 2018) emerged, which in order to guide companies in implementing a new design or improving an existing one, developed a system based on decentralized artificial intelligence, or agent-based technology. The design of the system was preceded by research on the construction of an agent-based system ontology. A knowledge model was developed containing a set of definitions describing the state of the art of recycling-oriented eco-design.

To realize the tool, first, the design process and its steps were analyzed. Then, based on these analyses and regulatory requirements, the authors created a recycling-oriented eco-design procedure (Figure 5). The procedure was made to evaluate all aspects to assess recyclability, such as recyclability of materials, their compatibility and identification, materials incompatible for recycling, harmful and hazardous materials, availability of materials, types and variability of joints, time and cost of disassembly, as well as tools necessary for disassembly.

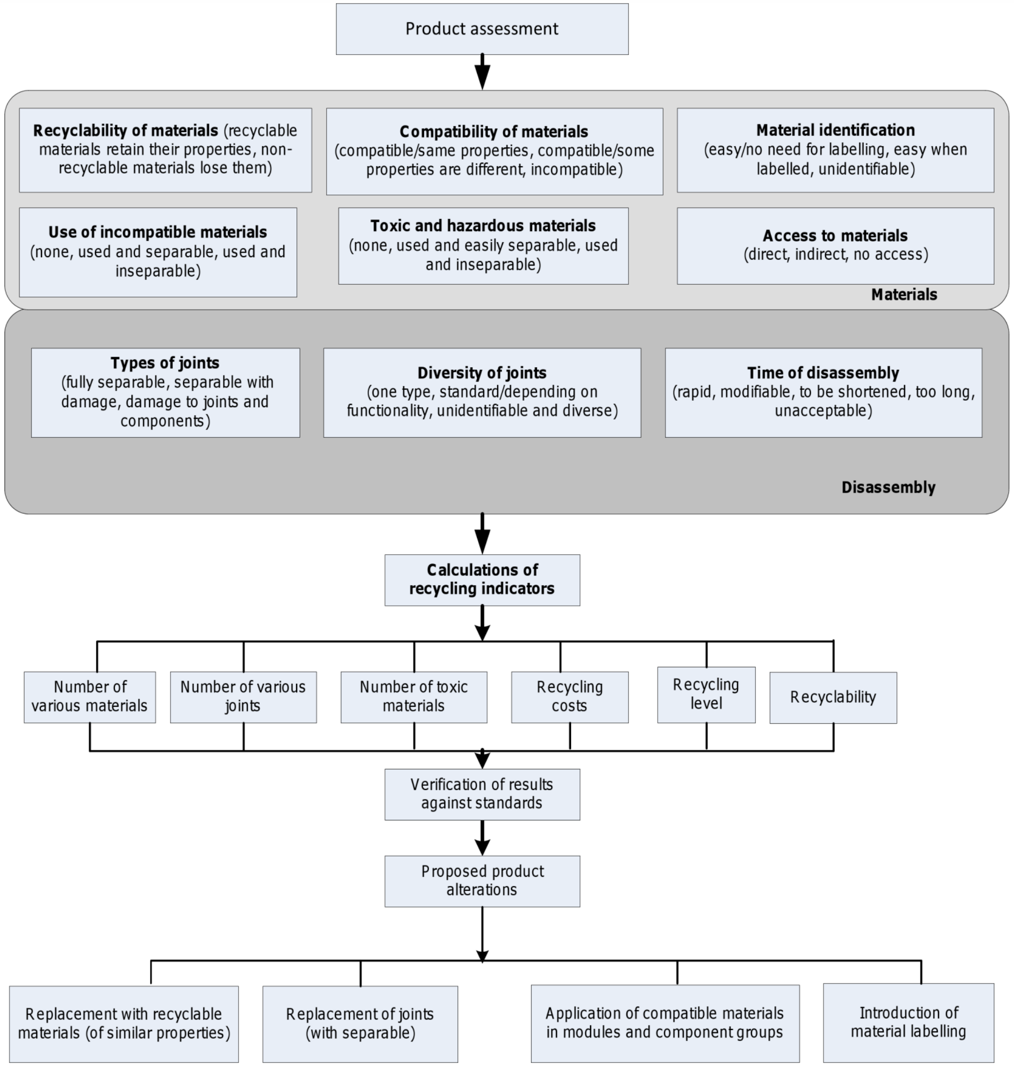

Figure 5: Recycling-oriented eco-design procedure

Once the the procedure was defined, it wasimplemented by the authors into the IT system supporting designers in recycling-oriented eco-design.
In conclusion, exploring the functionality, the system developed focuses on values derived from recycling and disassembly indicators, in accordance with DfD and DfR. The tool is able, by analyzing the product structure, to detect changes in lendable parameters, highlight those responsible for such changes and/or unacceptable values, suggest changes, and report the use of hazardous materials. All functions are performed based on data from any source or 3D CAD system.

Specific tool for eco-design EEE

Once the tools that can support recovery-focused design in line with the focus components of the TREASURE project, i.e., Electrical and Electronic Equipment (EEE), were analysed, research was conducted on existing methodology to support the design phase of EEE.

In a study developed by (Bovea, Pérez-Belis, et al., 2016), focused on the characterization of small waste electric and electronic equipment, from two different points of views: disassembly properties and material identification, one part of the analysis focused on the disassembling a sample of equipment with the aim of analyzing the properties of the disassembly process.
To do this, it was necessary to identify disassembly properties by performing a literature review of the main disassembly criteria considered during the Design for Disassembly/Recycling (DfD/DfR) stages. From this process, the following table (Table 1) is extrapolated containing the selected disassembly properties and the research studies that consider them.

Table 1: Disassembly properties and design recommendations from literature review (Bovea, Pérez-Belis, et al., 2016)

Disassembly property	Design recommendations from DfD/DfR
Easy to identify: measures the ease of identification of materials	- Mark materials according to ISO standards - Use moulded-in marks for material identification
Easy to access: measures the ease of access to separate unions in order to extract components	- Maximize the accessibility by positioning the components adequately - Avoid dismantling parts from opposite directions - Simplify the product structure - Make joints visible and accessible - Identify the disassembly points
Easy to separate: measures the ease of separation of the assembly components)	- Standardise/minimise the type/number of joints - Modular design - Active disassembly - Use joints easy to remove - Use of removable joints instead of permanent joints (adhesives)
Uniformity of tools: measures the uniformity in the tools used to disassemble the product)	- Minimise the number of required tools - Use of screws with the same screw head - Need of use of standard tools
Easy to reassembly: measures the possibility of reassembling the product after inspection)	- Easy to reassembly after disassembly

The disassembly properties result in ease of identification, ease of access, ease of separation, uniformity of tools, and ease of reassembly. Recommendations for DfD and DfR are given for each disassembly property.

Another analysis is that conducted by (Bovea & Pérez-Belis, 2018), who identified which design guidelines enable circular product design, improving it from the perspective of the circular economy. To do this, all design guidelines for circular product design were collected from literature. This process resulted in 46 guidelines shown in Table 2.

Table 2: Design guideline from literature review (Bovea & Pérez-Belis, 2018)

Design guideline	References
1. Create a modular design	(Dowie & Simon, 1994); (Graedel & Allenby, 1998); (Al-Okush, Caudill, et al., 1999); (Chen, 2001); (Hata, Kato, et al., 2001); (Active Disassembly Research, 2005); (Truttmann & Rechberger, 2006); (Bogue, 2007); (Mital, Desai, et al., 2009); (Ijomah & Chiodo, 2010); (Poppelaars, 2014); (Mulder, Basten, et al., 2014); (Go, Wahab, et al., 2015); (Reuter, M.A., Schaik, A. van and Ballester, 2018)
2. Locate unrecyclable parts in areas easy to remove	(Dowie & Simon, 1994); (Behrendt, Jasch, et al., 1997); (E. Sundin, 2004); (Ijomah & Chiodo, 2010); (Hultgren, 2012); (Peeters, Vanegas, et al., 2012); (Pérez-Belis, Bovea, et al., 2013); (Go, Wahab, et al., 2015)
3. Minimise the number of components	(Behrendt, Jasch, et al., 1997); (Al-Okush, Caudill, et al., 1999); (Chen, 2001); (Desai & Mital, 2003); (Erik Sundin & Bras, 2005); (Bogue, 2007); (Mital, Desai, et al., 2009); (Ijomah & Chiodo, 2010); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
4. Ensure resistance to dirt accumulation	(E. Sundin, 2004); (Poppelaars, 2014); (Mulder, Basten, et al., 2014)
5. Use standardized components	(Active Disassembly Research, 2005); (Bogue, 2007); (Pérez-Belis, Bovea, et al., 2013); (Poppelaars, 2014)
6. Minimise product variants	(Dowie & Simon, 1994); (Bogue, 2007); (Ijomah & Chiodo, 2010)
7. Improve the ratio between the labour required to retrieve a component and its value	(Ijomah & Chiodo, 2010); (Poppelaars, 2014)
8. Avoid moulding or fusing incompatible materials	(Dowie & Simon, 1994); (ECMA, 2010); (Ijomah & Chiodo, 2010); (Hultgren, 2012); (Pérez-Belis, Bovea, et al., 2013); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
9. Consider the use of an active disassembly	(Bogue, 2007); (Ijomah & Chiodo, 2010); (Peeters, Vanegas, et al., 2012); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
10. Use standardized joints	(Erik Sundin & Bras, 2005); (Active Disassembly Research, 2005); (Ijomah & Chiodo, 2010); (Poppelaars, 2014); (Mulder, Basten, et al., 2014)
11. Prioritise latching to screws and bolts	(UNE 150062, 2000b)
12. Unify screw heads	(UNE 150062, 2000b)
13. Minimise types of connectors	(Dowie & Simon, 1994); (UNE 150062, 2000b); (Chen, 2001); (E. Sundin, 2004); (Active Disassembly Research, 2005); (Ijomah & Chiodo, 2010); (Huang, Liang, et al., 2012); (Peeters, Vanegas, et al., 2012); (Watelet, 2013); (Pérez-Belis, Bovea, et al., 2013); (Poppelaars, 2014); (Sawanishi, Torihara, et al., 2015); (Go, Wahab, et al., 2015)
14. Use fasteners rather than adhesives	(Dowie & Simon, 1994); (E. Sundin, 2004); (Truttmann & Rechberger, 2006); (Bogue, 2007); (Mital, Desai, et al., 2009); (ECMA, 2010); (Ijomah & Chiodo, 2010); (Hultgren, 2012); (Huang, Liang, et al., 2012); (Peeters, Vanegas, et al., 2012); (Watelet, 2013); (Poppelaars, 2014); (Mulder, Basten, et al., 2014); (Go, Wahab, et al., 2015)

15. Make joints visible and accessible	(Dowie & Simon, 1994); (Behrendt, Jasch, et al., 1997); (E. Sundin, 2004); (Erik Sundin & Bras, 2005); (Bogue, 2007); (Mital, Desai, et al., 2009); (ECMA, 2010); (Ijomah & Chiodo, 2010); (Peeters, Vanegas, et al., 2012); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
16. Use fasteners that are easy to remove	(Dowie & Simon, 1994); (Boothroyd, Dewhurst, et al., 1990); (Behrendt, Jasch, et al., 1997); (Truttmann & Rechberger, 2006); (Mital, Desai, et al., 2009); (Ijomah & Chiodo, 2010); (Go, Wahab, et al., 2015)
17. Minimise the number of joints and connections	(Dowie & Simon, 1994); (Behrendt, Jasch, et al., 1997); (Chen, 2001); (Bogue, 2007); (Mital, Desai, et al., 2009); (Ijomah & Chiodo, 2010); (Peeters, Vanegas, et al., 2012); (Sihvonen & Ritola, 2015); (Go, Wahab, et al., 2015)
18. Minimise the number of tools and use push/pull processes	(Watelet, 2013); (Sawanishi, Torihara, et al., 2015)
19. Use unseparable joints for components made of the same or a compatible material	(Dowie & Simon, 1994); (Boothroyd, Dewhurst, et al., 1990); (Chen, 2001); (Hata, Kato, et al., 2001); (Mital, Desai, et al., 2009); (Ijomah & Chiodo, 2010); (Watelet, 2013); (Pérez-Belis, Bovea, et al., 2013); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
20. Use materials with low environmental impact	(E. Sundin, 2004); (ECMA, 2010); (Arnette, Brewer, et al., 2014); (Go, Wahab, et al., 2015)
21. Use thin walls with nerves (plastics)	(UNE 150062, 2000a)
22. Use components made of pure materials	(Graedel & Allenby, 1998); (Desai & Mital, 2003); (Active Disassembly Research, 2005); (Lee, Lu, et al., 2014); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
23. Minimise the number of different materials	(Dowie & Simon, 1994); (Graedel & Allenby, 1998); (UNE 150062, 2000a); (Chen, 2001); (Hata, Kato, et al., 2001); (Desai & Mital, 2003); (Active Disassembly Research, 2005); (Bogue, 2007); (ECMA, 2010); (Ijomah & Chiodo, 2010); (Huang, Liang, et al., 2012); (Hultgren, 2012); (Watelet, 2013); (Lee, Lu, et al., 2014); (Wang, 2014); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
24. Avoid secondary finishes and coatings	(UNE 150062, 2000a); (Active Disassembly Research, 2005); (Bogue, 2007); (Mital, Desai, et al., 2009); (Hultgren, 2012); (Watelet, 2013); (Lee, Lu, et al., 2014); (Poppelaars, 2014); (Mulder, Basten, et al., 2014); (Go, Wahab, et al., 2015)
25. Use recycled and recyclable materials	(Dowie & Simon, 1994); (Boothroyd & Dewhurst, 1986); (Graedel & Allenby, 1998); (Al-Okush, Caudill, et al., 1999); (UNE 150062, 2000a); (Chen, 2001); (E. Sundin, 2004); (Bogue, 2007); (ECMA, 2010); (Hultgren, 2012); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
26. Use materials resistant to cleaning processes for components to be reused	(Ijomah & Chiodo, 2010); (Lee, Lu, et al., 2014); (Poppelaars, 2014)
27. Reduce the material content and energy required in the manufacturing process	(Al-Okush, Caudill, et al., 1999); (UNE 150062, 2000a); (Chen, 2001); (E. Sundin, 2004); (Bogue, 2007); (Poppelaars, 2014); (Mulder, Basten, et al., 2014)
28. Ensure the identification of materials using material code marks	(Dowie & Simon, 1994); (UNE 150062, 2000a); (Chen, 2001); (E. Sundin, 2004); (Mital, Desai, et al., 2009); (ECMA, 2010); (Pérez-Belis, Bovea, et al., 2013); (Wang, 2014); (Poppelaars, 2014); (Sihvonen & Ritola, 2015)
29. Minimise the use of toxic or hazardous materials	(Dowie & Simon, 1994); (Boothroyd & Dewhurst, 1986); (Graedel & Allenby, 1998); (Behrendt, Jasch, et al., 1997); (UNE 150062, 2000a); (Chen, 2001); (Bogue, 2007); (ECMA, 2010); (Watelet,

	2013); (Poppelaars, 2014); (Arnette, Brewer, et al., 2014); (Mulder, Basten, et al., 2014); (Go, Wahab, et al., 2015)
30. Use unplated materials for recycling purposes	(Active Disassembly Research, 2005); (Go, Wahab, et al., 2015)
31. Use low alloy materials for recycling purposes	(Active Disassembly Research, 2005); (Pérez-Belis, Bovea, et al., 2013); (Go, Wahab, et al., 2015)
32. Use cast irons for recycling purposes	(Active Disassembly Research, 2005); (Pérez-Belis, Bovea, et al., 2013)
33. Use components and materials with verified reliability	(Mulder, Basten, et al., 2014)
34. Do not combine components that have different life spans	(Hata, Kato, et al., 2001); (Sihvonen & Ritola, 2015)
35. Avoid using parts that require frequent replacement/repair	(Dowie & Simon, 1994); (Graedel & Allenby, 1998); (Al-Okush, Caudill, et al., 1999); (UNE 150062, 2000a); (Chen, 2001); (E. Sundin, 2004); (Active Disassembly Research, 2005); (Truttmann & Rechberger, 2006); (Bogue, 2007); (Ijomah & Chiodo, 2010); (Watelet, 2013); (Poppelaars, 2014); (Sihvonen & Ritola, 2015); (Go, Wahab, et al., 2015)
36. Minimise length of wires and cables	(Chen, 2001)
37. Minimise weight of components	(Dowie & Simon, 1994); (Chen, 2001); (Bogue, 2007); (ECMA, 2010); (Watelet, 2013); (Go, Wahab, et al., 2015)
38. Use components sized for easy handling	(Chen, 2001); (Erik Sundin & Bras, 2005); (Peeters, Vanegas, et al., 2012); (Watelet, 2013); (Poppelaars, 2014)
39. Maximise the accessibility of components	(Dowie & Simon, 1994); (Desai & Mital, 2003); (E. Sundin, 2004); (Bogue, 2007); (Ijomah & Chiodo, 2010); (Hatcher, Ijomah, et al., 2011); (Erik Sundin, Elo, et al., 2012); (Peeters, Vanegas, et al., 2012); (Watelet, 2013); (Pérez-Belis, Bovea, et al., 2013); (Poppelaars, 2014); (Go, Wahab, et al., 2015)
40. Avoid dismantling parts from opposite directions	(Erik Sundin, Elo, et al., 2012);
41. Simplify the product structure	(Dowie & Simon, 1994); (Behrendt, Jasch, et al., 1997); (Behrendt, Jasch, et al., 1997); (Desai & Mital, 2003); (Truttmann & Rechberger, 2006); (Bogue, 2007); (Ijomah & Chiodo, 2010); (Erik Sundin, Elo, et al., 2012); (Watelet, 2013); (Pérez-Belis, Bovea, et al., 2013)
42. Build monitoring equipment into the system	(Mulder, Basten, et al., 2014)
43. Ensure that the fewest possible technicians are required to perform a maintenance task	(Mulder, Basten, et al., 2014)
44. Position components that often need to be maintained closely and in an easily accessible place	(Mulder, Basten, et al., 2014)
45. Eliminate the need for special disassembly procedures	(Behrendt, Jasch, et al., 1997); (E. Sundin, 2004); (Truttmann & Rechberger, 2006); (Bogue, 2007); (Mital, Desai, et al., 2009); (ECMA, 2010); (Ijomah & Chiodo, 2010); (Go, Wahab, et al., 2015)
46. Use simple and standardised tools	(Dowie & Simon, 1994); (Behrendt, Jasch, et al., 1997); (Bogue, 2007); (ECMA, 2010); (Poppelaars, 2014); (Go, Wahab, et al., 2015)

An additional study is the one developed by (Berwald, Dimitrova, et al., 2021) who sets out a comprehensive set of design guidelines for circularity, established in a multi-stakeholder collaboration with industry leaders from the entire WEEE value chain.
The guidelines on WEEE are different guidelines depending on the stage of eco design development. The first group of guidelines refer to the stages from the beginning of the design to the validation of the concept (from start to concept), the second group related to the actual production of the product, thus development of functions, design and engineering of specific parts of the product, and implementation of a new structure (from concept to production).
Below are two tables, the first for the guidelines used in the from start to concept phase (Table 3), the second in the from concept to production phase (Table 4), containing the rationale for each WEEE guideline.

Table 3: WEEE design guideline – (from start to concept) with rationale

WEEE design guideline – (from start to concept)	
Use of material combinations and connections that allow easy liberation	
Avoid molding different material types together by multiple-K processes (different plastic materials injected into the same mold, over-molding, or in-mold decoration).	It is very challenging to separate different materials that have been joined by multiple-K processes. They will usually end up as residue or (depending on the density) pollute other plastic streams. If the material types are the same and only differ in color and additives (e.g., molding red PP containing antioxidants on black PP containing talc) multiple-K processes are not an issue. An in-mold assembly by multiple-K processes that does not result in a chemical bonding of the materials is acceptable since the materials will be separated during shredding.
Avoid connections that enclose a material permanently. Avoid methods such as molding-in inserts into plastics, rivets, staples, press-fits, bolts, bolt and nuts, brazing, welding, and clinching.	The mentioned processes are typical for tightly enclosing materials and should be avoided, if possible. Enclosing a material permanently makes separation more challenging and can pollute the recyclers' waste stream
Enabling easy access and removal of hazardous or polluting parts	
Use click/snap solutions to fix batteries in a product. Avoid permanent fixing such as glued, welded, and enclosed solutions.	Annex VII of the WEEE Directive requires selective treatment for several materials and components, such as batteries, which should be removed from any separately collected WEEE stream (European Commission, 2012b). If not detected and removed properly, batteries pollute the material streams and can explode during the recycling process. When using Li-ion batteries, hard cells should be preferred. Soft Li-ion batteries can be more easily damaged, which constitutes a safety and fire risk.
Fix valuable parts (e.g., printed circuit boards (PCBs), cables, wires, and motors) in a product with metal screws, click fingers, press-fit, shrink foil, self-screwed/tapering, or connectors. Avoid permanent fixings such as pressure sensitive adhesive (PSA) tapes, glue, and welded solutions.	Recycling is mainly driven by economic considerations. Facilitating the separation of valuable parts will lead to a higher yield and less loss in other material streams. Furthermore, Annex VII of the WEEE Directive requires selective treatment of PCBs with a surface greater than 10 square centimeters (European Commission, 2012b).
Use detachment possibilities for hazardous and polluting parts/materials (e.g., dust bags, lamps, cord sets, cord winders, paper, cardboard, textiles, wood, foams, glass, and ceramics).	It is important to provide detachment possibilities for hazardous and polluting parts since they could otherwise pollute the material streams. Annex VII of the WEEE Directive requires selective treatment of hazardous components such as polychlorinated biphenyls containing capacitors, electrolyte capacitors containing substances of concern, mercury containing components or components containing refractory ceramic fibers (European Commission, 2012b). Providing detachment possibilities will facilitate compliance and can reduce recyclers' operating costs. In the case that this is not possible (e.g., for functional reasons), markings can help at the first stage of the dismantling/recycling process where the product breaks open.

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Use one module for hazardous parts in the product structure to enable taking out one non-recyclable module instead of searching for several different hazardous part.	Concentrating hazardous parts on one or very few modules facilitate the recycling process since it is easier for the recycler to detect them during the manual dismantling step instead of searching for multiple parts. This feature saves time and effort in the process, which can help reduce operating costs.
Use of recyclable materials that will be recycled by WEEE recyclers	
Avoid thermosets and composites.	Thermosets and composites cannot currently be recycled with existing technologies. When they are necessary (e.g., for functional reasons), materials outside the density range of commonly recycled plastics (0.85–1.25 g/cm3) should be preferred.
Do not use plating, galvanizing, and vacuum-metallization as a coating on plastics.	The mentioned techniques connect plastics with metals, a combination that cannot be separated in the recycling process.
Avoid the use of coatings on plastics.	All forms of coatings pollute the material stream or make the recycling process more challenging. Coatings change the density of the plastic, which can cause the plastic to end up in the wrong material stream. Printing numbers or lines for level-indication are not considered problematic and are usually better than using a sticker for the same purpose. Other options are screen-printing, in mold texturing or laser engraving. When a coating is still needed, a density difference.
Minimize the use of thermoplastic elastomers	Thermoplastic elastomers are currently not recycled and have to be separated. Particles that are not separated pollute the waste stream.
Avoid the use of foam.	Foam can lead to issues during the recycling process. When foam is necessary (e.g., for functionality), thermoplastic foam should be preferred to foam from elastomers or thermosets.
Minimize the use of magnets.	
Use of recycled materials	
Consider more textured surfaces for injection molding plastic parts. Avoid uniform high-gloss surfaces.	Traces of elastomers and glass reduce the quality of large high-gloss surfaces.

Table 4: WEEE design guideline – (from concept to production) with rationale

WEEE design guideline – (from concept to production)	
Use material combinations and connections that allow easy liberation	
Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners. For example, do not use a screw (ferrous metal) to attach a part to aluminum (non-ferrous).	If a product that contains joined ferrous and non-ferrous materials goes into shredding, it is very likely that either the ferrous or the non-ferrous stream will be polluted. The materials are

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	shredded into small pieces and either the screw will go with the host part to the non-ferrous stream, or the non-ferrous part will follow the screw into the ferrous stream
Do not permanently fix aluminum (Al), copper (including brass), stainless steel, or steel together in the following combinations: - If the main material in a part is Al (cast), do not attach a part of stainless steel, or steel on it. • If the main material in a part is Al (wrought), do not attach a part of Al (cast), copper, stainless steel, or steel on it. • If the main material in a part is stainless steel, do not attach a part of copper on it. • If the main material in a part is steel, do not attach a part of copper or stainless steel on it. • If the main material is copper, do not permanently fix a part of iron, lead, antimony, or bismuth to it	The listed combinations are based on the thermodynamic properties of the materials, indicating which materials can be combined and which ones cannot. Depending on the main material in a part, smaller amounts of other materials will end up polluting the stream. Some materials are easy to separate, while others are rather problematic. A good and easily separable material combination will lead to less polluted material streams. Since polluted streams often end up as a waste fraction, this rule can also lead to waste prevention.
Enabling easy access and removal of hazardous or polluting parts	
Avoid magnetic parts on printed circuit boards (PCBs).	PCBs contain many valuable non-ferrous metals. If magnets are placed on the PCB, the entire board might end up in the ferrous stream. In this case, the valuable non-ferrous metals are lost and pollute the ferrous stream.
Use of recyclable materials that will be recycled by WEEE recyclers	
Use common plastics in the product such as ABS, PP, PA, PC, PC/ABS, HIPS, PE (polyethylene), where possible).	Common plastics can be easily recycled with existing technologies and processes and should be considered as a first choice. If other materials are required, the reasons should be motivated and supported. Other plastics currently occur in too small volumes for economically viable recycling [43]. If other than the common plastics are used, alternatives outside the density range of 0.85–1.25 g/cm3 should be considered to facilitate separation
Avoid polymer blends.	Mono-material streams should be favored. Blends like • POM/ABS (polyoxymethylene/acrylonitrile butadiene styrene) • PA/ABS (polyamide/acrylonitrile butadiene styrene) • PC/PBT (polycarbonate/polybutylene terephthalate) • PPE/PS (polyphenol ether/polystyrene) • PET/PBT (polyethylene terephthalate/polybutylene terephthalate) pollute material streams (except for PC/ABS, since it can be properly recycled with existing technologies).

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Avoid glass fibre-filled plastics.	Glass fibers pollute material streams, reduce mechanical properties (e.g., impact strength), and cause wear. For a high modulus, mineral filled plastics such as PP-talc should be considered, since they can be recycled. Carbon fibers are also considered a better alternative
Minimize the use of thermoplastic elastomers.	Most of the elastomers can be filtered out during the separation steps. Those elastomers that are not filtered out are likely to end up in the PS stream. When elastomers are necessary (e.g., for functionality), minimize their use and choose, if possible, Styrol-Ethylen-Butylen-Styrol (SEBS) based thermoplastic elastomers (TPE). If a SEBS-based TPE ends up in the PS stream, it may act as an impact modifier, causing the least harm.
Avoid the use of thermoset rubbers.	Thermoset rubbers cannot be recycled and should be reduced, if possible.
Minimize additives in plastic materials.	Additives reduce the purity of the plastic streams. For this reason, the real necessity for additives should be evaluated cautiously
Use of recycled materials	
Choose geometries for injection-molded parts that allow easy flow paths. Avoid tight and narrow geometries.	High shear rates caused by narrow geometries can stress and degrade polymers.
For injection mold plastic parts, do not use long injection paths.	Recycled polymers are more sensitive to shear and temperature. A possible solution could be the use of multiple injection points. Consider increasing the wall thickness.
For injection mold plastic parts, consider more or wider venting ports.	Recycled polymers can have higher emissions during production due to pollutants or degrading polymers.
Use virgin plastics for very demanding parts (e.g., transparent light guides).	Recycled plastics are different from virgin plastics and cannot as yet meet every demanding requirement.
Avoidance of hazardous substances	
Avoid the use of brominated flame retardants (BFRs) such as polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), polybrominated biphenyls (PBBs), Hexabromocyclododecane (HBCD), etc., in the product.	According to Annex VII of the WEEE Directive, plastics containing BFRs have to be removed from any separately collected WEEE (European Commission, 2012b). Usually, they can be separated by recyclers and end up in incineration. Several BFRs are already restricted, and it is possible that more will be banned in the future. If these substances are used in materials today, it is likely that they will not meet the requirements to be recycled and reused in new products in the future (legacy substances).
Avoid the use of substances of very high concern (SVHC) according to the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) Regulation (European Union, 2006) and substances classified as carcinogenic (Carc. 1A or 1B), mutagenic (Muta 1A or 1), or reprotoxic	If a substance is identified as a SVHC, it is included in the REACH Candidate List. The European Chemicals Agency (ECHA) regularly assesses the substances on the Candidate List to determine if they should be moved to the Authorization List (Annex XIV). Once a substance is on an Authorization List, it can only be used or produced with a specific authorization and

(Repr. 1A or 1B) by the Classification, Labelling and Packaging (CLP) Regulation in housing/housing parts (European Commission, 2008).	under specified circumstances for defined applications. If these substances can be avoided at the design stage today, they will not cause problems in future recyclates.
Avoid the use of substances that are listed on the 'SIN list' (Chemsec, 2021).	These substances are mainly used in plastics as surfactants, solvents, stabilizers, plasticizers, anti-corrosions, pigments, and coatings. They should not be used in concentrations above 1000 ppm, (0.1% per article) per substance. Background: The 'SIN' (substitute it now) list is a list of substances that are not yet restricted but are candidates for the SVHC list in the future (see above). SIN list substances represent an indication of substances to be restricted/banned in the future. If these substances are used in materials today, future waste stream might not meet the requirements to be recycled and reused in new products.
Do not use halogenated polymers (e.g., Polyvinyl chloride (PVC), Polytetrafluoroethylene (PTFE)).	PVC degrades at the typical processing temperatures of other polymers such as ABS, PC, PC/ABS, PP, PA (polyamide), and HIPS. The generated hydrochloride acid corrodes normal extruders and molds.

The guidelines presented so far indeed still consider trivial Design for Recycling rules with no technological physics-based backbone, which can quantitatively pinpoint where problems occur in recycling and take metallurgical processing (the closer of the material cycle) into account. Only when a rigorous quantitative basis, in which the effect of multi-material complexity and material connections (mineralogy) is considered related to the true (industrial) performance of the recycling processes within the recycling flowsheet applied to recycle the product or part under consideration, some of the suggested steps make sense. For instance, when an indication similar to "Use recycled and recyclable materials" is provided, this indeed does not tell how to do this, how to quantify recycling, what the use is of recycled content if this cannot be recycled. Many of these rules have been derived for simplistic products, but do not understand nor capture the issues to be dealt with when dealing with complex multi-material product, for which functionality has high demands on build-up, design and composition.

In order to solve these aspects and avoid recommendations that are lacking any backbone to quantify or verify this in terms of true recycling, Van Schaik and Reuter (Schaik, A. van and Reuter, 2013) have defined a physics and recycling industry-based approach to Design for Recycling for WEEE, based on rigorous process physics and thermodynamics of industrial recycling processes over the entire EoL system (disassembly, shredding/liberation, sorting and (metallurgical) processing), taking into account particulate quality, physical and chemical composition and (in)compatibility as well as industry feedback on problems in recycling. 10 Design Rules and simulation derived guidelines have been defined. The proposed methodology shows how simulation models are applied to truly evaluate and improve Design for Recycling, considering product functional requirements and including full metallurgical knowledge to avoid trivial and non-valid rules. These rules balance the optimization of resource efficiency through product design for recycling and system design for optimized resource efficiency.

10 Design Rules and Simulation Derived Guidelines (Schaik, A. van and Reuter, 2013)
These rules were grouped into five fundamental design rules and five derived guidelines and constitute the basis of the greenprinting of recycling.

Fundamental DfR rules
1. DfR rules are product and recycling system specific; oversimplification of recycling by defining general DfR rules will not produce the intended goal of resource efficiency
2. DfR needs model and simulation based quantification
3. Design data should be accessible/available in a format which is compatible with the detail required to quantify and optimise recycling performance of products for all metals, materials and compounds present
4. Economically viable infrastructure and rigorous tools must be in existence for realizing industrial DfR rules and methodologies
5. CAD/Design tools must be linked to recycling system process simulation tools to realise technology based, realistic and economically viable DfR

Possible DfR guidelines – Derived from Fundamental DfR Rules Iteratively checked by simulation and validity
Various DfR guidelines can be derived by applying the above-listed fundamental DfR rules and principles which should be iteratively checked by simulation and for validity, while being subject to a mindful consideration of product/component functionality. Recycling process simulation tools are used to define, validate and quantify the set of guidelines per product (of which the

list below shows some possible guidelines). This physics-based approach can also set priorities between the different guidelines and quantify the necessity and potential result of DfR. Through the implementation of the fundamental rules and simulation as a basis to derive and refine these, unique sets of guidelines are derived per product as a function of material mix and (BAT) recycling systems, including a mindful consideration of product functional demands (whereas a fixed set of all possible guidelines will leave no room for the designer to design/construct a product). The Possible DfR guidelines are listed hereinafter:

6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting
7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials
8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e. Metal Wheel)
9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility for easy identification (and removal) from recyclates and waste streams
10. Be mindful of liberation of materials in design (Design for Liberation)

The Metal Wheel as developed by Reuter and Van Schaik is applied as a qualitative Design for Recycling tool, however also guiding the selection of most suitable recycling processes in view of modular recycling of product (see Errore. L'origine riferimento non è stata trovata.). Recycling assessment and Design for Recycling for the Fairphone 2 has been dealt with by Van Schaik and Reuter (Reuter, M.A., Schaik, A. van and Ballester, 2018). Recycling simulation models have been applied to assess product recyclability and definition of most optimal EoL processing routes. Modular recycling through a combination of modular (reparability driven) design and modular disassembly driven recycling is demonstrated to be the most favourable approach to optimise recycling and recovery of both base and minor elements/metals from complex WEEE products.

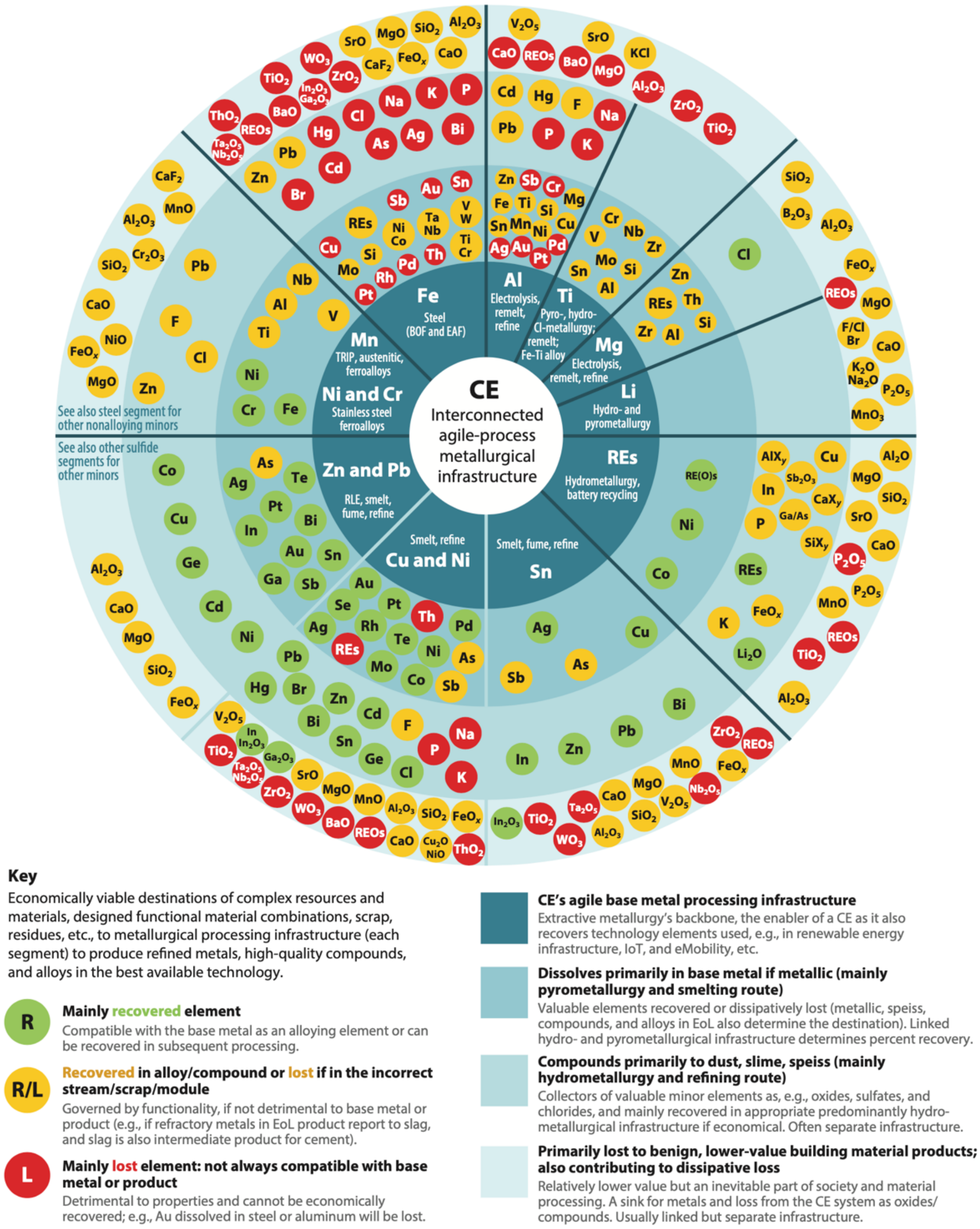

Figure 6: The Metal Wheel, based on primary metallurgy but equally valid for metals recycling reflects the destination and hence recoverability or losses of different elements in a product/component for different interlinked metallurgical processes

In conclusion, the analysis of methodologies and tools to assist decision-making during the realisation of eco-design revealed numerous supporting tools. Specifically, they are differentiated into methods focusing on sustainability and methods focusing on circularity.

The need arises for an integration of the two aspects, i.e., tools that consider the implementation of circular designs that at the same time reduce sustainability impacts. The development of the TREASURE Advisory tool to support eco-design will be based on this need.

Another relevant aspect is the low uptake of AI, which is used by a small number of tools and methodologies. Greater integration of AI represents a possible field of action.

3. Support from use-cases through workshop sessions

This chapter is meant to describe the workshop carry out with the project partners involved with pilots in order to infer and depict the decision-making process and identify when and how the sustainability advisory can provide support to perform design, disassembly so that a higher level of economic, environmental, social and circularity performances is guaranteed. After the description of the workshops objectives and structure, the detailed activities carried out with the partners are presented, while the results derived from the discussion are reported in §4 where the Sustainability Advisory is described.

3.1. Objectives of the workshops

The AI based advisory tool will be created within the TREASURE project and is based on the indicators identified in T2.1 and the interactions with the project use cases, disassembly, recycling, and eco-design. To meet this second aspect, workshops with the use cases have been organised. The objectives of these workshops included:

- the mapping of the AS IS decision making process, in order to understand which decision-makers are currently involved, which kind of decisions are taken and the possible gaps to be solved in terms of support needs. The advisory tool in fact is meant to support the current decision process, without necessarily disrupt it.
- the mapping of the TO BE process of the various use cases, where the advisory will be exploited in the future. This analysis is meant to facilitate the identification of critical issues, processes, and decisions to be supported.
- extract the sector decision rules used, to align the advisory tool with the decision drivers of the industry that are already in place.
- determine the information flows to and from the advisory tool;
- present conceptual advisory ideas and discuss and collect feedback from stakeholders;
- define the links between the various use cases by highlighting which choices, if made in one use case, influence the outcome of the other use cases.

3.2. Structure of the workshops

The organisation of the workshops required as a first step the identification of the categories of workshop participants: Advisory users, Tech providers, Advisory developer, Contributors and other partners interested in participating. This preliminary categorization allows to better structure the workshops organization and management since it helped to identify the partner needed and their roles, depicting also the contributions to be expected from each partner.

The most important category is the Advisory users, since this is the category that needs to be supported by the advisory: Pollini (disassembly); Ilssa (recycling); and Walter Pack, EuroLCDs (ecodesign). The Tech providers category is the one that provides the key enable technologies and is needed to map the TO BE processes: Polimi and UNIZAR (disassembly), Univaq (recycling), and TNO (ecodesign). The Advisory developer category indeed included only TXT, in the role of supervisor of the aspects relevant to the integration of advisory with the rest of the platform. The Contributors category included partners associated with that specific use case but not directly involved with the use of the advisory tool: SEAT (disassembly); SEAT, TNO, MARAS (recycling), and SEAT (ecodesign). During some Consortium meetings preceding the workshops, the various project partners were asked who else was interested in participating and the category "other partners interested in participating" was identified: MARAS, TNO, Edge, Ilssa (disassembly); Unizar, Edge, Walter Pack (recycling); and Univaq, Maras, Unizar, Edge (ecodesign). Table 5 summarises which participants in which category took part in the workshops.

Table 5: Role of workshop participants.

Which workshop / Participant's category	Car electronics disassembly process	Car electronics recycling process	In-mold/structural electronic prototyping process
Advisory users	Pollini	Ilssa	Walter Pack, EuroLCDs
Tech providers	Polimi, Unizar	Univaq	TNO
Advisory developer	TXT	TXT	TXT
Contributors	SEAT	SEAT, TNO, MARAS	SEAT
Other partners interested in participating	MARAS, TNO, Edge, Ilssa	Unizar, Edge, Walter Pack	Univaq, MARAS, Unizar, Edge

The activities took place on the Miro platform and were recorded. The link to the Miro board is given below:

https://miro.com/app/board/uXjVONUDRTI=/

3.2.1. Advisory Workshop "Car electronics disassembly process"

Before the organisation of this workshop, Pollini has been consulted to understand and describe the As Is disassembly process. An explanation of how daily disassembly activities are conducted without the help of key enable technologies has been provided identifying who are the actors involved in the decisions, what are the material outputs and inputs of each phase, and what are the informative outputs and inputs. From this first interaction it was possible to derive and map, through a flow chart, the current decision-making process for the disassembly use case. Additionally, it was possible to identify initial critical points related to this use case. The AS IS process of the disassembly use case can be summarised as follows: 1) The vehicle arrives at Pollini. 2) The operator removes hazardous materials and recyclable components with the help of management software. 3) The hazardous materials are sent to the specialised disposal process while the recyclable components are sent to the specialised recycling plant. 4) The management software generates the list of components to be disassembled in accordance with market requirements. 5) If there are components to be disassembled immediately then they are disassembled and stored, if there are components to be disassembled in the future the operator puts the vehicle into the depot, if there are not any components to be disassembled at the moment or in the future the operator sends the vehicle to the next recycling process. 6) The system keeps track of components that have not been disassembled and are left in the vehicle in the depot. 7) When a customer searches for a specific component the system checks availability and if the component is in stock it is sold, if the component is in a vehicle in depot, then it is disassembled and sold. The diagram in Figure 7 summarises what has just been explained and a version with a better resolution is available at the following Miro link: https://miro.com/app/board/uXjVONUDRTI=/

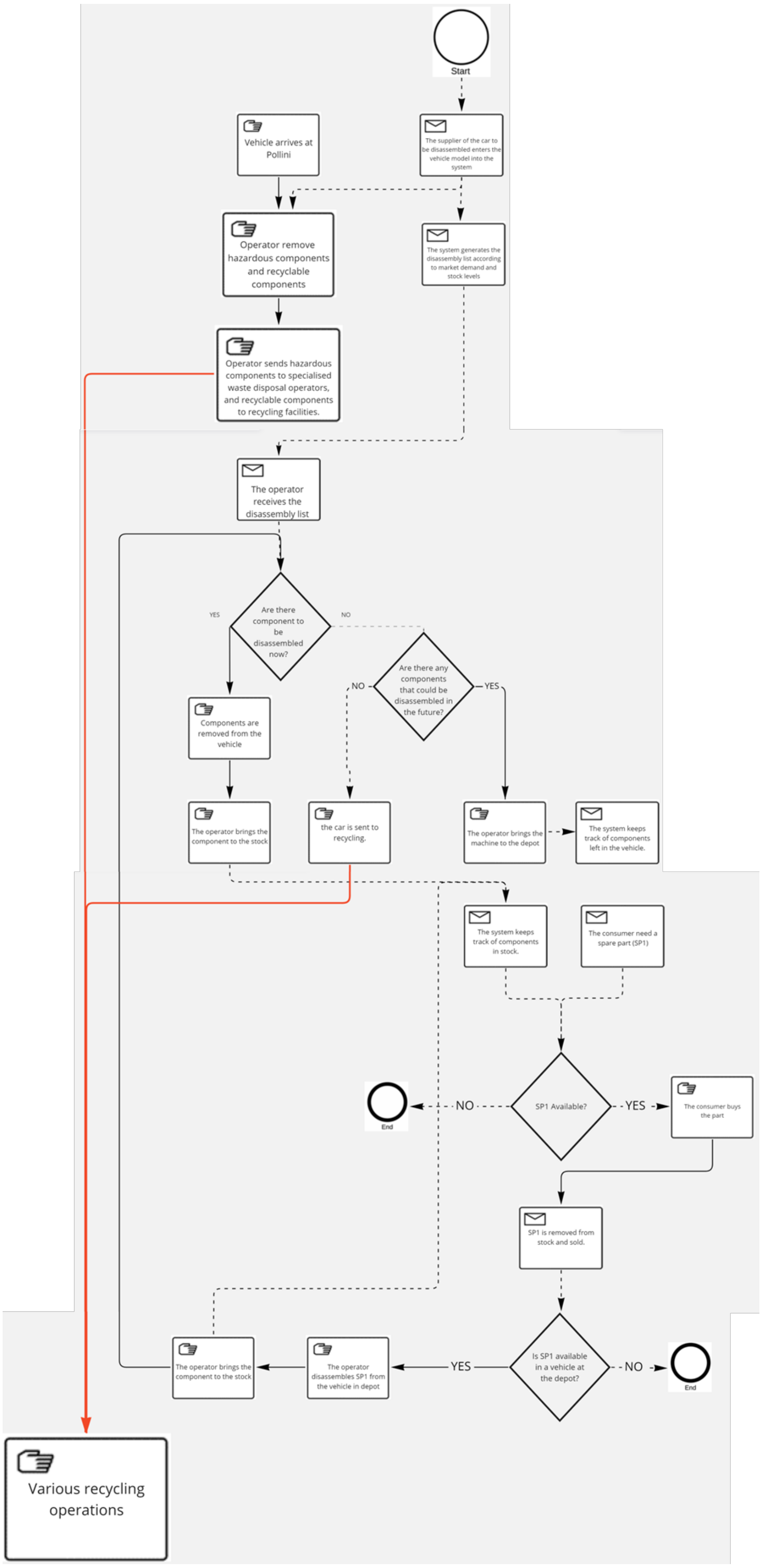

Figure 7: AS IS disassembly process currently adopted by POLLINI.

The As Is process has been used as a starting point to develop a proposal for a To Be process that has been prepared before the workshop. Specifically, KETs (AI based Advisory tools and cobots) have been added or in some case replace the current process. The resulting To Be process proposal, together with the identified critical points, were the first objects of discussion in the workshop. The reference TO BE scheme was set as follows: 1) The electronic component manufacturer provides material information and disassembly guidelines to the platform. 2) The car manufacturer provides information to the platform about the vehicle and the electronic components in it, such as positioning, vehicle CAD, and disassembly guidelines. 3) When the vehicle enters the disassembly facility, the operator performs the same hazardous material removal and treatment procedures as in the AS IS process. 4) The management system generates the disassembly order as in the AS IS process but components with PCBs are added to the list. 5) The operator consults the disassembly order, CAD, and disassembly guidelines. 6) The advisory supports the facility manager by providing information on the value of the contained materials, recycling routes to be followed, and costs. 6) The operator disassembles the components, removes the PCBs, and takes them to storage. 7) For each new process performed, the operator provides feedback to the platform. 8) When the stock PCBs reach the threshold value suggested by the advisory, they are picked up and taken to the cobot station. 9) The cobot disassembles the SMDs from the PCBs and the platform records feedback from the operations. 10) The SMDs follow the recycling route suggested by the platform. Figure 8Figure 8**Errore. L'origine riferimento non è stata trovata.** presents the scheme just described, which was then used as a discussion topic with the workshop participants.

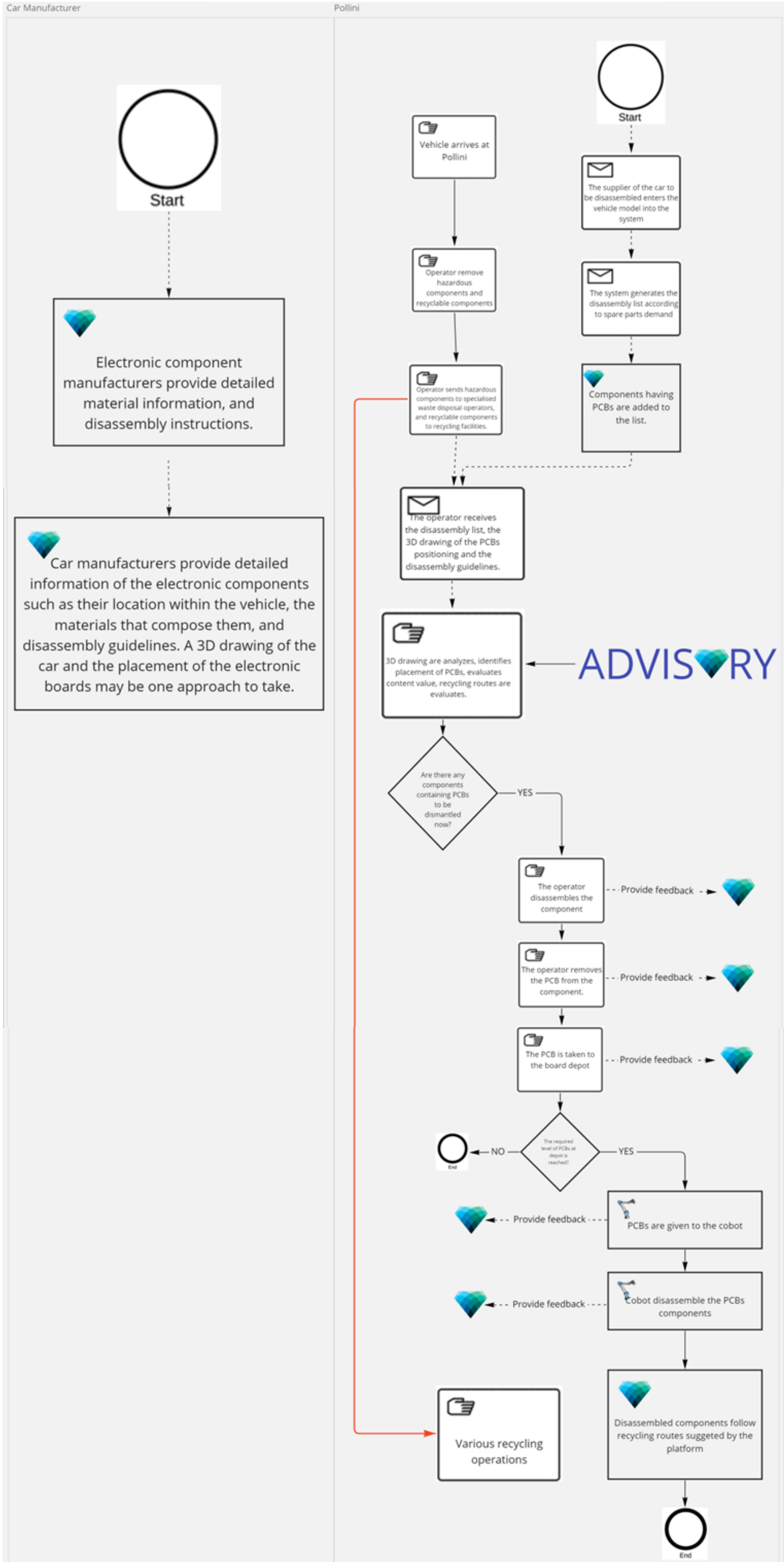

Figure 8: TO BE diagram of the disassembly use case proposed during the workshop as a discussion instrument.

Participants were shown the flowchart representing the As Is process and the subsequent proposal of the To Be process. A moment of discussion followed in which everyone was able to express his or her opinion, criticism, and feedback on the proposed model, either through direct intervention or through post-it notes with proposed changes in the points concerned. Then, model in hand, participants were asked to answer the following guiding questions: The main critical issues and elements of the discussion have been reported in the findings section (Chapter §3.3.)

3.2.2. Advisory Workshop "Car electronics recycling process"

The first part of this workshop investigated if the As Is process considered for Pollini and in general the critical points emerged from the "car electronics disassembly process" workshop were also valid for ILSSA. The discussion then shifted to the recycling process and its criticalities in an open discussion with the various partners. The current disposal process of automotive electronics waste was discussed, a process that does not include detailed and specific recycling, as electronic components in Pollini are shredded together with the rest of the vehicle and the subsequent sorting process is not able to select the PCBs fragments. Finally, the fragments end up in foundries which are able to recover only copper, steel, and aluminium. The discussion then shifted to the recycling process considered in TREASURE, which, thanks to the KET 'bio-hydrometallurgical material recovery process' and thanks to direct intervention in the disassembly process, makes it possible to optimise the recycling of WEEE vehicles and thus increasing the recovery of the metals contained in them. However, depending on the purity and metallurgical process to which these fragments are subjected, it is also possible to recover other metals, such as: Au, Ag, Pt, Pd, etc. But this does not happen in Pollini's current processes. In this debate, the recycling process of the KET 'In-Mold Structural Electronics (IMSE)' was also discussed. The conversation then moved on to the role of MARAS in this use case, to understand the division and interaction of activities between the advisory tool and the MARAS recyclability simulator. The workshop continued by presenting a conceptual representation of the role of advisory based on what had been elaborated so far. Since the three use cases showed to be interconnected, at least for the advisory role, these relationships were integrated into the proposed conceptual model. The workshop concluded with a further open discussion on the presented model, gathering feedback, criticism, and ideas on the role of the advisory from all partners presents. Figure 9 shows the concept of the advisory at the time of the workshops. The model is still available at the following link for those who wish to view it in an improved resolution: https://miro.com/app/board/uXjVONUDRTI=/. The main critical issues and elements of the discussion have been reported in the findings section (Chapter §3.3.)

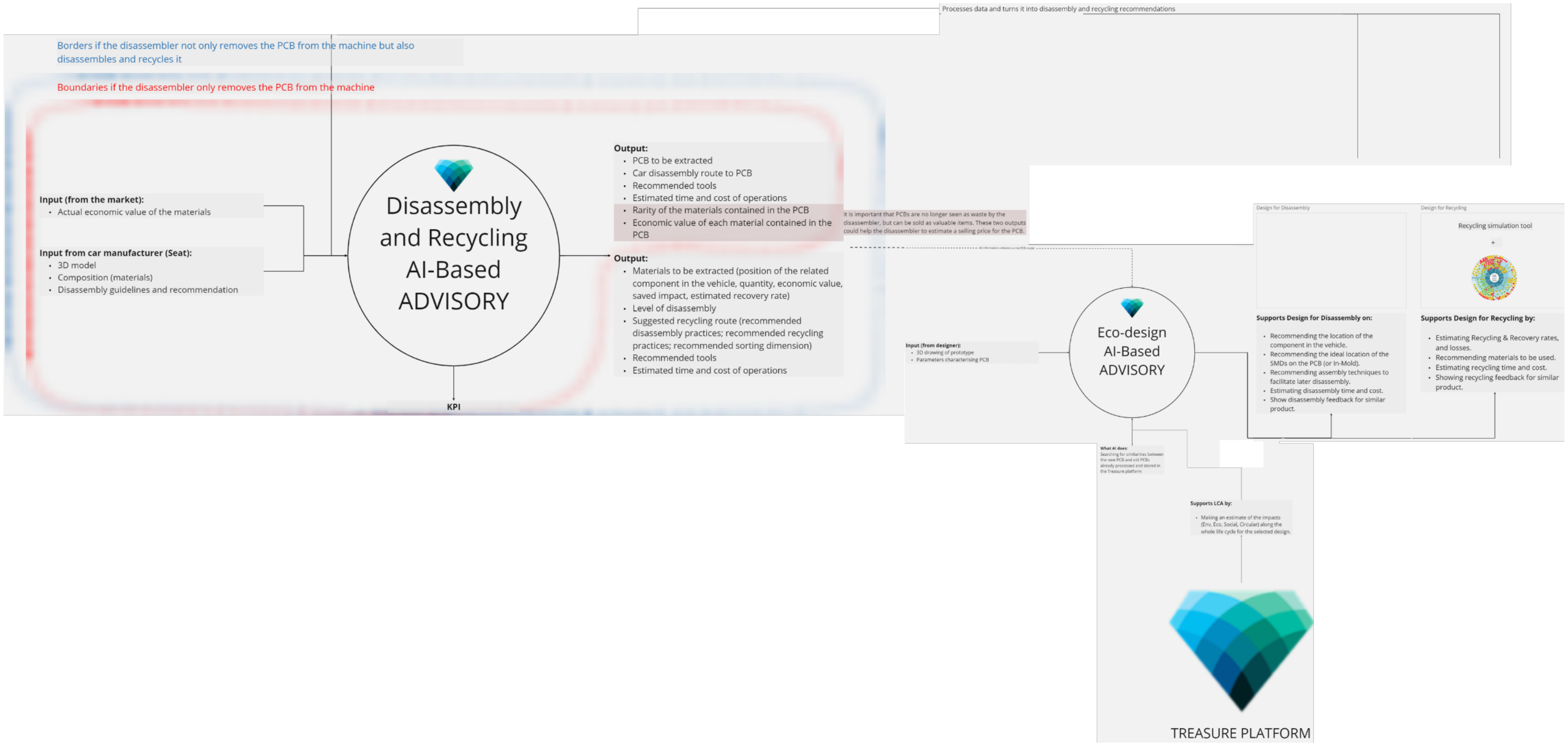

Figure 9: First conceptual advisory model as a result of the workshops.

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3.2.3. Advisory Workshop "In-mold/structural electronic prototyping"

Before the organisation of this workshop, the TNO partner was consulted to learn about the characteristics and differences in production, use and end-of-life between a traditional component and an IMSE component. The first activity of the workshop was to complete the information obtained from TNO by involving the industrial partners (WalterPack for the mass production of IMSE devices, SEAT for traditional components and EuroLCD for the life cycle phases involving LCDs). Using guiding questions, Walter Pack and EuroLCD were asked about the development of the industrial process. The aim of this discussion was to identify which processes were carried out in-house, which were outsourced, what were the criteria for choosing suppliers, if they use environmental and social criteria in the design process and if so, where did they come from (internal policies or industry regulations and standards). The information obtained allowed us to describe the processes and identify the decision-making moments that characterise the design use case. The workshop activities then focused on identifying the type of support that advisory can give to eco-design, considering the two macro areas of design for disassembly and design for recycling.

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3.3. Main findings from workshop sessions

Here are the main findings of the workshops, including the critical issues of AS IS status in the various use cases and initial considerations on the role and possible uses of sustainability advisory.

3.3.1. Disassembly use-case

The disassembly workshop defined the current As Is process of this use case and was an opportunity to address several topics, including the reuse of electronic components as spare parts. The discussion determined that this practice is intrinsically linked to the way in which these components are designed and critical issues that emerged include clean-up of previous use data, verification of correct functioning, quality, safety, and compliance with privacy and warranty standards. The other critical points that emerged in this workshop were listed below and used as input in subsequent workshops:

- The dismantler has no information about position of components in the car, value embedded in the components.
- Disassembly driver is merely economic, no environmental issue is taken into consideration.
- No regulation boosting WEEE recycling (now).
- No market demand for PCBs components, thus they are left within the scrap vehicle and shredded with it.
- All around Europe the faced situation is similar: there is no regulation boosting WEEE and no market demand for PCB's electronic components.

3.3.2. Recycling use-case

The current recycling process in Europe involves the shredding of the vehicle with PCBs and other WEEE inside. It consists of the following steps: shredding, sorting by magnetic, density and in some cases colour separation, and finally the sorted material is sent to foundries which complete the process by recovering metals such as steel, aluminium, and copper. With the current process, according to the disassembly workshop results, metals such as tin and precious metal such gold, silver, and palladium are lost. This statement would seem not to be entirely true, as MARAS reports that there is also an industrial reality where these metals and other materials are recovered. Even considering this situation, recovery should still be improved, as some PCB fragments do not end up in the correct recycling stream. To recover these metals, it is possible to act downstream, thus optimising the sorting process; or it is possible to act upstream, thus optimising the disassembly process. In both cases, design and recovery processes are also involved.
The downstream approach is to optimise the design process to increase the chances of finding quality shredded fractions of PCBs after shredding (e.g., only epoxy and SMD). By doing so, it might be that thanks to colour sorting it is possible to recover them, but the possibility is still low now. Now much of the PCB is lost as it is attached to steel.
With the upstream process, the one considered in TREASURE, PCBs and WEEE are disassembled from the vehicle before the shredding process so that they can be send immediately to the next disassembly process or to the right recycling process. Again, design plays a key role in facilitating disassembly and so recovery. The biohydrometallurgical process is a KET that will be tested in TREASURE. The bio-hydrometallurgical plant developed and tested in TREASURE will be evaluated as an alternative or another option to the existing metallurgical processes and technologies adopted by industry for the recovery of metals such as tin and copper and precious metals such as gold, silver, and palladium. Here the main critical points came up from the recycling process:

- Separation not oriented to the recovery of critical metals, but it is oriented to recover main metals (steel, ferrous and non-ferrous metal).
- PCBs shredded with all the vehicle, particles of PCBs act as impurities in the recovery of metals.
- PCBs not separated from the car cannot be recovered if they are not directed to the correct recycled fraction, as it is difficult to sort them.

To actually recover a PCB, it is essential:

- to act on the design to avoid embedding PCB fully into plastic (as traditional electronic does, while on the contrary in in-mould electronic the plastic is like a case, not fully embedding the PCB);
- to act on the easiness of disassembly, identifying where the PCBs are, and which are the most interesting to be recovered from the rarity/environmental/economic point of view before they arrive to shredding and not leaving them in the car to be shredded.

One of the main conclusions reached after the workshops on disassembly and recycling was that these two use cases are intrinsically linked. This also seems to be reflected in the design of the advisory. It was therefore concluded that the advisory should support these two use cases together. The sustainability advisory could be a list of information and evaluation put together to understand if a sort of convenience from and environmental, economic, and social point of view. The Advisory can give a rank of the most cost-effective PCBs to pull out; and give a sort of trade-off (from a circular point of view is convenient to recover everything, from an economic point of view it is consider the quantity of precious metals that can really be recover, from a sustainable point of view we have to consider the impact of the subsequent recycling process to extract that metal, and so on). It's impossible to remove all the electronic from the vehicle, first you remove the ones where the embedded value or the quantity of material is the most. It's necessary to do a selection of the PCB that should be remove first. A nice-to-have in the advisory is the full overview of the vehicle, that can come also come from the vehicle producer, that shows if PCBs are contained in the car, where are they located, what do they contain. Other information could be: How large they are. The recycling process in the project should consider what to take first and not to try to cover everything.

3.3.3. Eco-design use-case

The use case of eco-design seems to be the most suitable one for sustainability advisory support. The workshop on eco-design made it possible to outline the macro-stages that normally compose the design process of a component, and which are outlined here. Component manufacturers receive the 3D design, function and product requirements from the OEM, i.e. their customers. The component supplier is then responsible for developing the production process and proposing changes to the design once the first design has been compared with production requirements. The product design therefore undergoes changes during this process. Another point that emerged during the workshop was that the responsibility for sustainability requirements is expected to be the responsibility of the OEM, this is because product requirements are provided by the customer (i.e. the OEM), to the component manufacturer. One point that emerged is the involvement of raw material suppliers from the very beginning of the process, as some requirements affect them directly. If a requirement, for example, is to increase the recycled content in the product, this information does not concern the supplier of the part (like WalterPack in this case), but the raw material supplier. It is also true that materials with recycled content should perform identically to fully petrochemical materials but may behave differently. As such, this is a matter for the part manufacturer, as the manufacturing process may be affected. The workshop also made it possible to distinguish two design approaches in line with the project, namely design for disassembly and design for recycling. For each of these approaches, suggestions for decisions to be supported by advisory were provided.

Design for disassembly:

The design-for-disassembly advisory can help in choosing the placement of boards (where to put them, how to assemble them, etc.). It can also provide guidelines on the aggregation of components to facilitate the disassembly process. Finally, it can estimate a certain level of disassemblability given a specific design. A DfD approach has been investigated in "D5.6 (Simulation of the in-mould-structural electronics prototyping process" by TNO.

Design for recycling:

In the design of the product, it might be possible (within the limits of product's functional specifications) to make design changes to increase recycling performance e.g. by making other choices in materials use, materials combinations (e.g. avoiding incompatible materials in one component, or allowing better separation through disassembly). It is necessary to know where recycling problems occur given a specific design. The advisory can give recommendations e.g., on technologies that can be used for eco-design, highlighting where material is lost, where problems occur during recycling, and providing tips to improve the design for recycling (e.g., providing information on material characteristics that can be used). It could also estimate the recyclability potential related to a specific project.

An additional aspect raised in the design and recycling-related discussion is about the use of recycled material. The car manufacturer (or the electronic component provider) could set the limit of recycling content and they often they don't want to compromise the quality of a component by increasing too much it. To change the perception of the customers, it is possible to perform test with higher recycled material content. TNO is performing experiments within the activities related to deliverable "D5.6 (Simulation of the in-mould-structural electronics prototyping process" by testing re-injected petrochemical polymers (e.g. polycarbonate) and validate the quality of the product made with reprocessed (i.e. recycled) plastic by means of injection molding.

Conclusions:

The results of the workshops, those concerning the identification of AS IS processes in the different use cases, were used as input together with the state-of-the-art study carried out in this deliverable, and together with the results obtained in T2.1, T3.1, T3.2, T3.3, T4.1, to elaborate Chapter §4, in which an overall vision of the Sustainability and Circularity Advisory framework was proposed.

4. Overall vision of the Sustainability Advisory Framework

This chapter first describes the Sustainability Advisory Framework (§4.1). The decision-making process is investigated and how the 3 use-cases, disassembly, recycling and eco-design, addressed in TREASURE, are supported by the Advisory tool.
Next, in §4.2 a proposal for integrating the Advisory tool within the TREASURE platform is described, which will be formalized in D4.9.
In the last section, §4.3, a model is proposed in order to investigate with the pilots which indicators are most suitable to evaluate their activities.

4.1. Sustainability Advisory Framework

Related to the objective of T2.2, this section defines the framework of the TREASURE advisory methodology focused on sustainability and circularity, and the related algorithms and metrics needed to provide decision support. In order to meet the objective, SUPSI has developed a methodology that can support the 3 use-cases in making decisions to implement sustainability performance improvements. Analysing the methodology, it is based on the description of the decision-making process structured in a series of decisions that can be sequential or parallel and the indication of suggestions and best practices to be implemented.
Before proceeding to the description of the methodology, it is necessary to specify that the use-cases Disassembly and Recycling will be treated together. This is due to the strong correlation between the two processes and from what emerged during the Workshops outlined in §3.

In order to describe decisions, "Decision cards," i.e., summary cards containing all the necessary information and sources, are made. Specifically, the Decision cards aims to: describe the decision to be taken, describe the object of the decision (product, single component…), provide the decision-maker profile (who is taking the decision), identify the input information needed to carry out the decisions (e.g., the mass of the raw material contained in the component under analysis), list the supporting tools and technologies (such as databases, methodologies, simulation tools, etc.), determine how AI can support the decision-making process, how the Advisory tool provides support and, finally, all the environmental, social, economic and circulatory indicators to be calculated in order to make the decision.

Starting with the description of the decision to be implemented, it is defined according to the objectives of the TREASURE project, thus supporting use-cases to implement sustainability improvements. The input information is defined according to the indicators to be calculated by the Advisory tool and the analysis to be performed by the decision-maker. The decision-maker, selected as the suitable figure with the most expertise, is not necessarily the one indicated in the Decision card. In addition, professional figures who can provide support are suggested in addition to the decision maker.
The supporting technologies and tools are defined by indicating which of those available in the TREASURE project may be useful and which others from literature provide support. Regarding support from AI, a possible use is assumed. It is not mandatory to be the one indicated and additional support from AI can be implemented. An important aspect to consider is the feasibility of implementing such proposed solutions, which will be investigated in T4.5 by investigating limitations especially related to data availability.
The last aspect related to the selection of indicators to be calculated is performed by considering the indicators and methodologies mentioned in D2.1.

To clarify the composition of Decision cards, an example of an unfilled paper is given (Figure 10

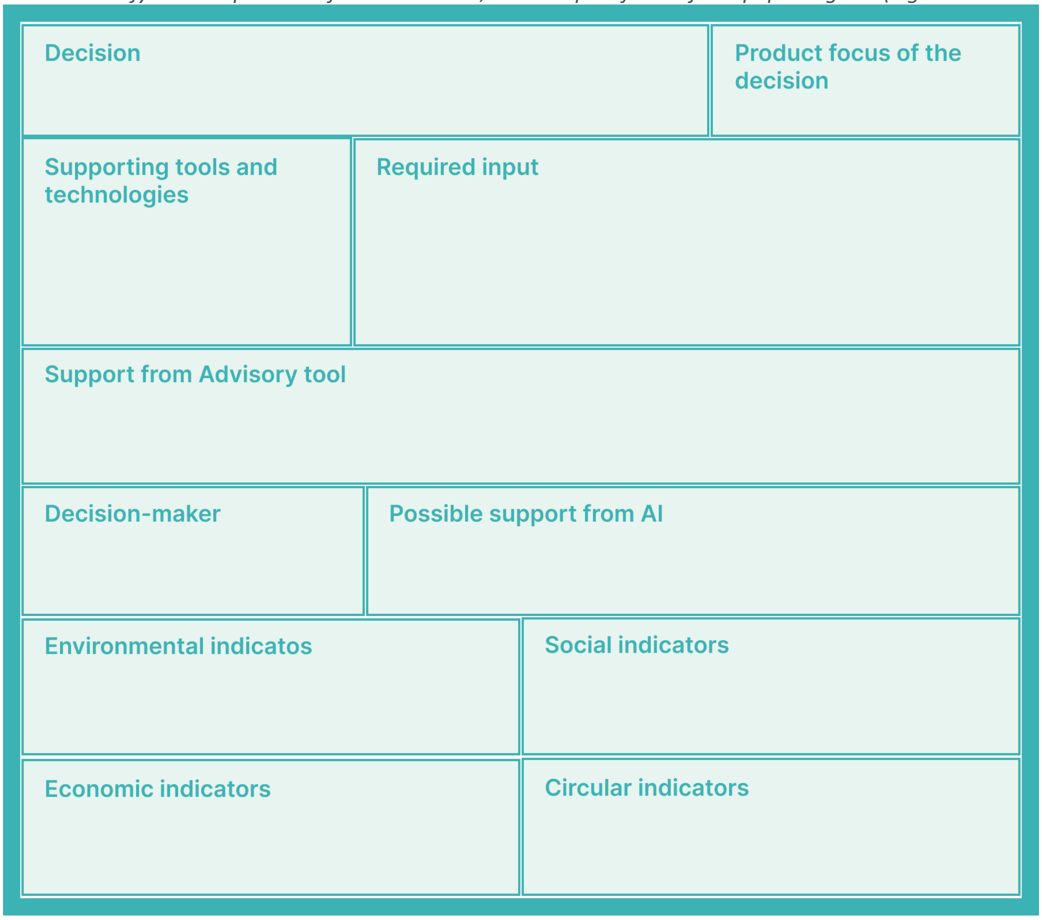

Figure 10).

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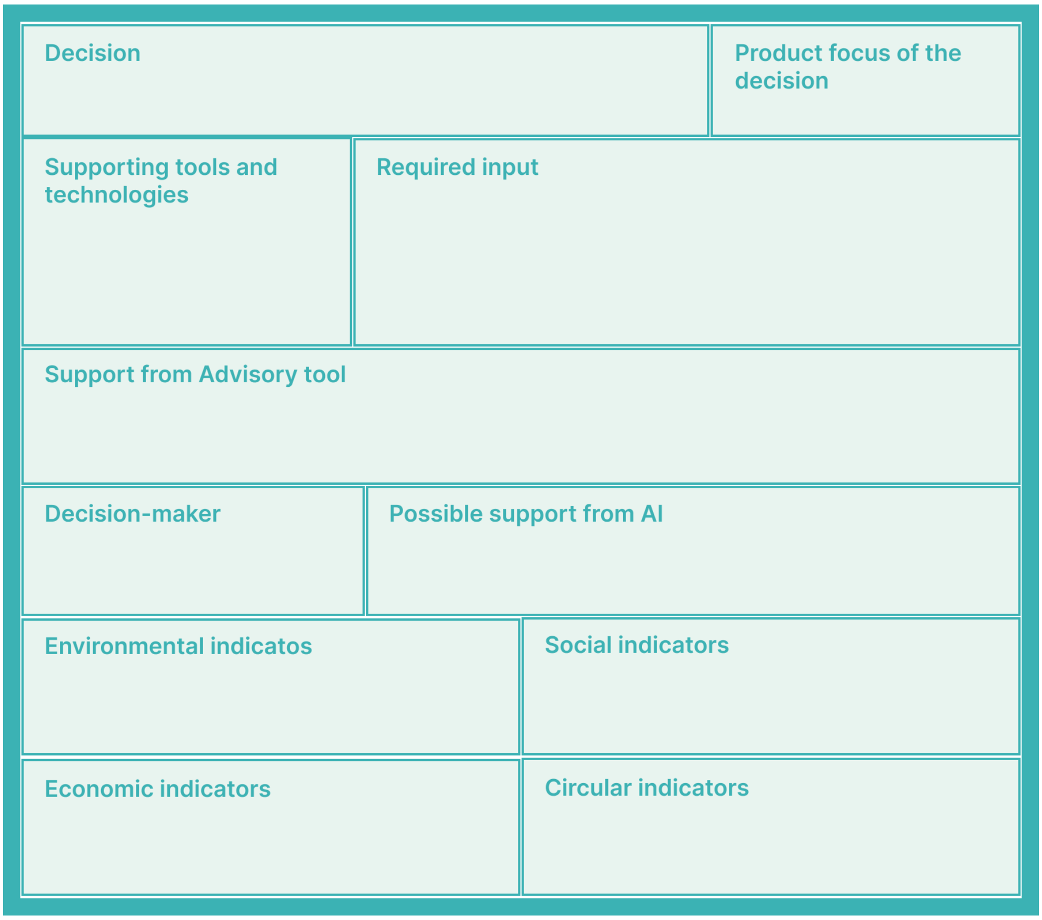

Figure 10: Example of Decision card

In order to identify from which professional figure or tool the information needed to make the decision is extracted, an "information flow" diagram is given for each decision described. Each information can be derived from 3 types of sources: from professional figures (e.g., component manufacturer, disassembler), from supporting tools (such as Sustainability tool), or from external sources (literature, web site, etc.). These sources are indicated for all Disassembly and Recycling use-cases, while for Eco-design use-case decisions an additional source of information is included: input from Disassembly and Recycling Decisions.

The addition of an information source is related to the way the 3 use-cases communicate. In fact, in addition to Decision cards and information flow, there is a section dedicated to collecting feedback. Decision-makers are expected to have the possibility to record critical issues encountered during the implementation of the processes under their responsibility. This is done particularly by the Disassembly and Recycling use-cases which provide necessary inputs to the designer in order to implement improvements to already disassembled and recycled products.

As for the eco-design use-case, it does not provide feedback to be submitted to the disassembler or recycler. Instead, the designer is able to provide useful information for decision-making, such as the mass of materials contained in the product under analysis.

The chapters below, §4.1.1 and §4.1.2, describe the advisory methodology applied to Disassembly and Recycling use-cases and Eco-design use-case.

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4.1.1 Disassembly and Recycling Advisory methodology

This section investigates how it is possible to provide advice on two use cases addressed in the TREASURE project: disassembly and recycling of materials. Disassembly and recycling represent two key steps in achieving one of the project's goals, which is to avoid waste generation and increase the rate of reintroduction of discarded materials back into the supply chain. The two use cases are treated together as they are closely related; through optimised disassembly of products, higher recycling rates of individual materials can be achieved. Implementing recycling processes requires an initial prioritization of the components to be extracted and the subsequent definition of the disassembly sequence. This aspect emerged particularly during the Disassembly and Recycling use-cases related Workshops described in §3.
To this end, a process structured in a series of sequential decisions partly related to disassembly operations and partly to recycling is described.

Investigating the role of the advisory, it can provide a ranking of the most beneficial electronic components to be extracted and provide a sort of trade-off, trying to combine the various aspects of sustainability: from a circular point of view, it is needed to recover all the materials; from an economic point of view, it is convenient to recover only the resources that, after the cost afforded to disassemble and recycle a component, can generate a profit (e.g. precious metals); from a sustainable point of view, the environmental savings of material recovery must not to be (negatively) balanced by the impacts of the recycling and disassembly processes needed to extract that material.

Regarding the decision-making process, first the selection of the Electronic Component to be removed is needed. A useful tool to exploit in the inventory is the complete overview of the vehicle (e.g., the 3D drawings and the technical sheets of the electronic components) coming from the vehicle manufacturer, showing whether Electronic Components are contained in the car, where they are and what they contain. Having a list of possible Electronic Components to be taken out of the car, they are evaluated by analysing possible disassembly and recycling processes. In this perspective, the advice for the category "Disassembly and Recycling" concerns:

- Indication of the location of electronic component in the vehicle and their contents;
- Analysis of materials contained in Electronic Component in relation to thermodynamic rarity and market value;
- Ranking of the most advantageous Electronic Component to be extracted;
- Electronic Component that should be removed first;
- Recovery rate calculation (MARAS data);
- Disassembly routes;
- Recycling routes;
- General recommendations derived from analyses already performed on other Electronic Components that have been treated in the past.

In order to provide support to the decision-making process of recycling and disassembly, a sequential decision flow (Figure 11) has been implemented where various professionals are identified as decision-makers and others are tasked with providing information. In detail, the first decision identified (Decision 0) is related to the identification of the components contained in the car to be extracted and resold as spare parts. It is referred to as Decision 0 because it is out of scope of the TREASURE project but nevertheless included since it is relevant from the point of view of sustainability. In fact, it promotes the concept of components and subassemblies reuse, a practice that is preferable to recycling in terms of sustainability because

it requires fewer transformation processes. Delving into the focus of TREASURE, Decision 1 instead identifies which Electronic Component is environmentally and economically beneficial to be extracted from the car, with a high-level perspective. So, through an analysis focused on the thermodynamic rarity of the materials contained in the various Electronic Components and the profit that can be generated from the sale of the materials, a ranking of Electronic Components is provided, leaving the final selection to the decision maker. This evaluation is performed applying the recycling rate potential derived from two possible sources: historical data held by the Advisory tool or from literature. If not available, consider the ideal recycling potential: the materials contained in the components can be fully extracted without losses and processes inefficiencies. This approach allows a rapid ranking process of a high number of components, without involving a more specific analysis of the actual recycling rate that would require the assessment of disassembly and recycling processes.
Having defined the Electronic Components to be extracted, they are examined in detail by defining in Decision 2 the most cost-effective car disassembly route to extract the selected Electronic Components and in Decision 3 the combination of disassembly route and recycling process that maximize the amount of recycled material while minimizing sustainability impacts.

An important aspect to consider is that the improvement of these end-of-life processes should be at all electronic components contained in the car.
In fact, the purpose of decision 1 is to make a selection of electronic components on which to perform the analyses of decision 2 and 3. This is not compulsory, if considered more suitable, decision 1 can be excluded and decision processes 2 and 3 can be carried out directly on all the EEE of the car.

It is necessary to specify that the flow of decisions just described must be carried out before any practical activities are initiated. The Advisory tool will be responsible for providing advisory, connecting decision-makers and collecting feedback related to critical issues and observations encountered during the fulfilment of decisions.

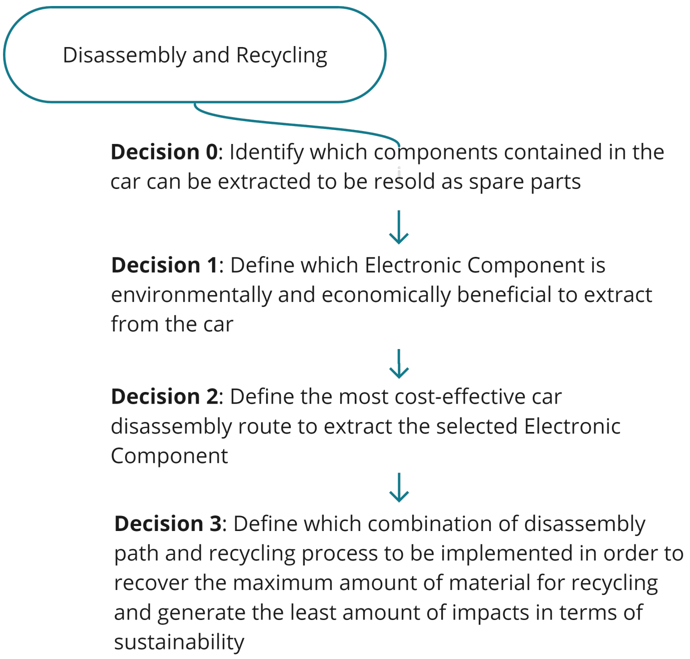

Figure 11: Decision-making flow of Disassembly and Recycling use-cases

The next sections describe each decision in detail defining the decision-making moment, the role of the decision-maker and of any supporting persons, the indicators to be used to evaluate possible decision alternatives, and the advice provided. This description is carried out via the template presented in §4.1 together with an outline of the flow of the necessary information.

Decision-making moment 0

In accordance with Figure 11, the first decision-making moment to be addressed turns out to be the definition of which components contained in the car can be extracted in order to be resold as spare parts. Decision 0 turns out to be relevant as it allows the practice of reuse to be favoured over recycling as it is more advantageous in terms of sustainability (Reike, Vermeulen, et al., 2018). This is explained by the reason that reuse involves the implementation of fewer transformation processes in order to derive the desired product than during recycling. It is necessary to specify that at this stage not only the electronic components will be considered as possible spare parts, but the car as a whole will be examined, thus also other components such as seats, headlights, etc. The professional figure identified as the decision-maker is the car disassembly manager, supported by the disassembly operator and a market analyst, i.e., a person who can determine the demand for spare parts and estimating the revenue that can be obtained.

First, it is necessary for the decision-maker to analyse the CAD model of the car and conduct an initial analysis of the contained components. In case the CAD drawing is not available or provided by the manufacturer, the component analysis is based on the decision-maker's experience.
Next, the decision-maker, with the support of the disassembly operator, will verify that all components expected are present in the car since, being a dismantled car, it may have missed or crashed parts. Knowing the composition of the car, the market analyst can proceed establishing an estimation of the market demand for the components and the revenue that can be generated, which will be calibrated according to how damaged the component under analysis is. An additional constraint to be evaluated are the possible regulations that can limit the reuse of certain components that are deemed to be critical from the security point of view (e.g. the ones related to the ABS system). With these evaluations, the decision maker, supported by the market analyst, identifies which components to extract.

For this decision, the decision template presented in §4.1 is not reported since Decision 0 is not properly the focus of the project. Apart the consideration from the circular economy point of view already presented, this decision is anyway explained since it is necessary to know which components have been resold as spare parts as some may contain PCBs and other electronic parts that will then be excluded from the subsequent decision-making moments. So, the decision-maker then has the task of recording in the Advisory platform which spare parts have been taken out of the car under analysis during phase 0.

One support that could be provided by the Advisory tool during the process of selecting parts for reuse is to indicate which spare parts have the highest demand, through algorithms that exploit AI. In fact, the tool by exploiting the data collected on the components extracted as spare parts, over time will be able to provide a characterization of the most in-demand components.

Decision-making moment 1

Analysing the decision-making flow related to disassembly and recycling processes, the next decision to be made is the definition of which Electronic Components (ECs) are environmentally and economically beneficial to extract from the car. To do this, it is necessary to clarify how the decision-making process should be approached.

First, the decision-maker, in this case the car disassembly manager, may need the support of three other figures to make the decision: a sustainability expert (e.g., the HSE manager), an accounting expert, and the disassembly operator. Support is not mandatory, but these figures are recommended as possible backups.

As a first step, the decision-maker, eventually supported by the disassembly operator, must identify all the Electronic Components in the car under analysis using the 3D drawing provided by the car manufacturer, or the MISS (Material Information Sheet System), or any other type of detailed compositional product data. Next, the two figures must perform a preliminary analysis verifying that the Electronic Components are actually in a location on the car that is reachable or still present. Indeed, since these are dismantled cars, it is possible that components are missing as they may have been crashed, or these components may have been removed to be sold as spare parts. Electronic Components not present should therefore be excluded from the decision-making process.

After identifying the Electronic Components, it is necessary to determine which one(s) is advantageous to extract from the point of view of environmental sustainability by studying the rarity of the materials contained, and from the economic point of view according to the cost-revenue relationship generated by the process. It is necessary to specify that Decision 1 is purely a screening decision, so it is not necessary that a detailed analysis be done but is only used to figure out where to focus the quantitative analysis, so a high-level study (with estimated data) can be carried out. Below all the variables considered for evaluation are first explained and then the decision-making process is described.

Starting from the economic aspect, the following quantities were determined to be included in the analysis: the revenue generated from the sale of the material extracted from the Electronic Component (Resale value indicator from D2.1) and the cost incurred to disassemble the car to extract the Electronic Component and to disassemble it. It is important to point out that the revenue is influenced by the quality of the recycling product. Being a screening phase, the quality is not considered. Concerning any evaluation in economic terms, the decision-maker may be supported by the accounting expert and also by the disassembly operator who will provide estimates of disassembly time and supporting tools.

Regarding the revenue from sale, it is necessary to know the type of materials contained in the Electronic Component and their mass, information given by the manufacturer by providing the component's technical sheet, BOMs or through to the MISS (Material Information Sheet System) presented in D4.3, which is a system containing the material composition and weight of components used in cars. Given this information, the possible revenue that can be generated from the sale of the recoverable materials through their market value is estimated by the Advisory tool. For this purpose, a fundamental support is provided by the Artificial Intelligence contained in the Advisory tool which, thanks to a database that could be developed during the use of the platform, will be able to provide an estimate of the amount of recoverable material by analysing the similarities between the Electronic Component under analysis and those studied previously. If there are no similar Electronic Components from which the value of recoverable material can be derived, 100% recovery of the amount or a percentage form literature is assumed (UNEP-IPR, 2011).

As regard to the environmental aspect, a useful indicator turns out to be the thermodynamic rarity indicator, explained in detail by (Calvo, Valero, et al., 2018a) and in D3.1 of TREASURE. This indicator allocates a physical value to raw materials in accordance with their scarcity in nature and the net energy required to extract and refine them. So, the higher the value of thermodynamic rarity, the greater the importance of recovering the material in question. Again, as with the revenue from the sale of materials, it is necessary to know the type and mass of recoverable materials since the indicator is obtained by multiplying the values of thermodynamic rarity by the mass. To make an assessment of this indicator, it is necessary to obtain the value related to the percentage of recoverable material, which as mentioned before is either provided through AI support or is estimated to be 100% or from literature. Once the value is calculated by the Advisory tool, for evaluations in environmental terms the decision-maker may be supported by the sustainability expert.

It is necessary to specify how the calculation of the above indicators is to be carried out. Therefore, the mathematical formulas of thermodynamic rarity indicator, resale value and disassembly cost in the following Table 6.

Table 6: Formula and explanation indicators used in the decision-making moment 1

Indicator	Formula
Thermodynamic rarity indicator ($R(A)$) (TREASURE D3.1 §4.2)	$R(A) = m_i * R_i$ • m_i is the mass content of a given element (A) expressed in grams; • R_i is the thermodynamic rarity (A) of the specific element expressed in $\frac{kj}{g}$.
Resale value ($RV(t)$) (TREASURE D2.1 §3.2)	$RV\ (t) =\ m_i * RV_i(t)$ • m_i is the mass content of a given element expressed in grams; • $RV_i(t)$ is the resale value of the specific element at a given time t expressed in $\frac{€}{g}$.
Labor cost (TREASURE D2.1 §3.2)	$Labor\ cost\ (C_{labor\_disassembly}) = labor\ cost\ rate\ \left[\frac{€}{min}\right] * t_{dis\_estimated}\ [min]$ • $t_{dis\_estimated}$ is the estimated disassembly time.
Energy cost (TREASURE D2.1 §3.2)	$Energy\ Cost\ (C_{energy\_disassembly}) = power\ absorbed\ [kW] * energy\ cost\ \left[\frac{€}{kWh}\right] * t_d[h]$ • $t_{dis\_estimated}$ is the estimated disassembly time.
Disassembly cost (C_d)	$C_d\ = C_{labor\_disassembly} + C_{energy\_disassembly}$

Knowing the parameters to be calculated, the following shows how the how the decision-making process should be carried out by the decision maker, focusing the analysis initially only on rarity values and economic revenue, thus leaving out costs that will come into play later.

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In fact, the decision-making process is structured in two phases:

- Step 1: identification and selection of target materials contained in the Electronic Component, thus materials with high rarity value and high economic revenue. The process is carried out for each Electronic Component;
- Step 2: economic analysis of the target materials identified in step 1, defining whether their sale is able to cover the costs incurred to extract them and allow them to generate a profits.

Starting from the first step, a set of thermodynamic rarity values expressed in $\frac{kJ}{g}$ and market quotations of certain materials expressed in $\frac{€}{g}$ is provided to clarify the meaning of the two indicators (Table 7). During the implementation of Decision 1, it is necessary for the decision-maker and his/her team to derive the thermodynamic rarity values and market quotation from external resources such as literature (Calvo, Valero, et al., 2018b) for thermodynamic rarity values), websites, or purchase prices of materials from possible buyers. Once the thermodynamic rarity values $\left[\frac{kJ}{g}\right]$ and market quotations $\left[\frac{€}{g}\right]$ are derived, they must be multiplied by the mass of each contained material and the percentage of recoverable material in order to obtain the values of the two indicators.

Table 7: Thermodynamic rarity values [kJ/g] and market quotation [€/g] of a number of minerals potentially contained in an Electronic Component

Mineral	Thermodynamic rarity values [kJ/g]	Quotation [€/g] [4]
Palladium (Pd)	2’870’013	63.98
Platinum (Pt)	2’870’013	31.50
Ruthenium (Ru)	2’870’013	17.17
Iridium (Ir)	2’870’013	133.52
Gallium (Ga)	754’828	0.67440
Gold (Au)	654’683	55.25
Indium (In)	363’918	0.30783
Rhodium (Rh)	103’087	448.28
Germanium (Ge)	24’247	1.14869
Silver (Ag)	8’937	0.67
Nickel (Ni)	758	0.02912
Copper (Cu)	348	0.00946
Zinc (Zn)	196	0.00425

Once the two indicators have been calculated for all the materials contained in each Electronic Component, the decision-maker will need support in analysing them and favouring Electronic Components that have a greater amount of materials that have a high thermodynamic rarity value and at the same time allow them to generate a high profit that can cover the costs incurred.

To do this, it is necessary to determine boundary values for the indicators of rarity and revenue, which indicate the threshold above which it is interesting to consider a material. So, for each Electronic Component only materials that simultaneously exceed both boundaries will be selected. In order to determine the threshold values for the two quantities, it is recommended

[4] https://www.legor.com/en-us/metals-quotation (11/17/2022)

to: (i) conduct a literature search in order to identify possible values or (ii) leave it to the decision maker and his/her support team to define the value according to their experience.

To help the decision maker, the advisory tool will prepare a graph for each Electronic Component mapping all the materials contained, indicating on the x-axis the economic revenue generated from the sale of the materials while on the y-axis the thermodynamic rarity. Using such a graph (Figure 12Figure 12), it will be possible to identify the most valuable materials (target materials), focusing on those located in the upper right quadrant bounded by the threshold values where the revenue and rarity are maximized.
The following is an example of a possible layout matrix realized using the unit values given in Table 7, multiplying them by the mass of material recovered. The mapped materials contained in the Electronic Component are assumed to have a mass equal to 1 g and a recovery rate of 100%. Threshold values are indicative not real values.

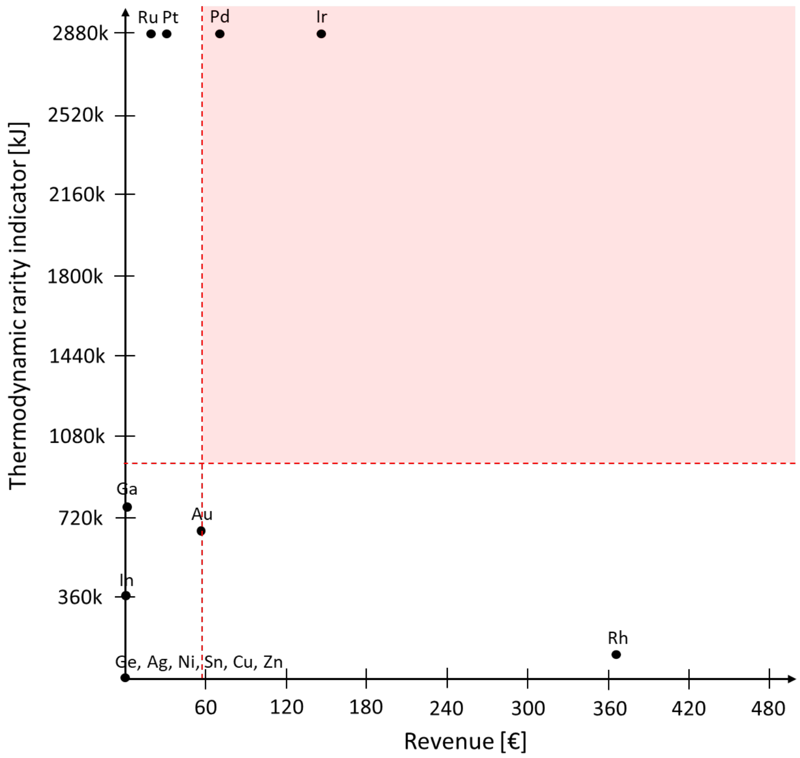

Figure 12: Layout matrix generated by the advisory tool with mapped materials in a PCB according to thermodynamic rarity indicator [kJ] and revenue [€]. The area highlighted in red represents the quadrant on which the target materials are placed.

By evaluating the figure above, the area that the decision-maker needs to examine in order to identify the target materials, which in this case are Palladium and Iridium, has been highlighted in red. During Decision 1 the graph will be made for all Electronic Components under analysis so that the decision maker can view detailed information for each one.

Once the target materials have been defined, it is possible to proceed with the second step, i.e., to analyse the target materials in detail in order to understand whether their sale allows for profit generation. To do this, it is necessary to provide an overview of each individual Electronic Component, focusing on the materials placed in the upper right quadrant, as highlighted in Figure 12, and introducing another variable, namely the cost incurred to disassemble the Electronic Component. Since Decision 1 is a preliminary stage of Electronic Component screening, cost estimation may require effort. Again, as with the percentage of recoverable

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material, AI could provide support by providing indicative cost data from analyses previously conducted on other similar Electronic Components. For those with no similarities to those already examined, the disassembly operator may provide support to the decision-maker in order to estimate the disassembly time and the accounting operator to formalize a consistent cost. It is necessary to specify that this cost is not considered in the previous step because it is a cost related to the whole Electronic Component, thus it is not allocable to the individual materials contained in it.

Having noted the value of the total cost, it is possible to derive the profit generated, obtained by subtracting the cost to disassemble the Electronic Component from the total revenue obtainable from the sale of the target materials. Following the definition of the profit, an initial selection of ECs can already be made. In fact, if the revenue from the sale does not exceed the cost incurred to recover the material, the EC will automatically be excluded from the decision-making process. This is done without considering the environmental aspect provided by the thermodynamic rarity indicator, only high rarity-high revenue materials are analysed at this stage, so the driver of the decision remains purely economic.

Excluding ECs that do not cover costs, a final ranking of Electronic Components can be made. Again, only the economic aspect is considered, preferring those that allow to generate a certain positive margin (e.g., 20 percent). The percentage just mentioned represents a hypothetical percentage; it will be up to the decision-maker to define the value of interest.

Therefore, the following ratio of revenue to total imposed cost greater equal to $1 + \%\,desired\ margin$ (in this case 1.2) is performed to obtain the ranking (Eq. 1).

$$\frac{Revenue\ from\ the\ sale\ of\ the\ target\ materials\ of\ the\ i{-}the\ PCB}{Cost\ to\ disassemble\ the\ i{-}the\ PCB\ target\ materials} \geq 1 + \%\,desired\ margin \qquad \text{Eq. 1}$$

ECs that do not meet the condition will be eliminated from the decision-making process, while those that do will be ranked from most profitable to least profitable. Having provided the ranking, it will then be up to the decision-maker to define which and how many Electronic Components to select to be extracted and subjected to the following decisions.
In conclusion, from this process it will be possible to determine which ECs will be extracted from the car, as they bring in more profit from the sale than the costs incurred to process them and allow for the recovery of rarity-relevant materials. Below the Decision card defined in §4.1 applied to Decision 1 (Figure 13Figure 13) is presented.

Decision

Define which Electronic Component is environmentally and economically beneficial to extract from the car

Product focus of the decision

EEE

Supporting tools and technologies

- MISS database.

Required input

- 3D CAD of the car:
- List of all ECs in the car and location;
- BOM of all ECs in the car;
- Mass of each material contained in the EC [g];
- Market value of each material contained in the EC [€/g];
- Labor cost and other time-based direct costs for disassembly [€/min];
- Estimated disassembly time [min];
- Percentage of recoverable material [%].

Support from Advisory tool

Creating a ranking of ECs to be disassembled and recycled.
Implementation of a visual tool for Electronic Component analysis.

Decision-maker

Car disassembly manager

Possible support from AI

The AI can provide an estimate of the percentage of recoverable materials and an estimate of disassembly cost.

Environmental indicatos

- Thermodynamic rarity indicator.

Social indicatos

Economic indicatos

- Resale value;
- Disassembly cost.

Circular indicatos

- Estimated disassembly time;
- Estimated percentage of recoverable material.

Figure 13: Disassembly and Recycling - Decision card 1

Examining the Decision card, first it is necessary to clarify what inputs are needed.
In order to activate Decision Making 1, the Advisory tool needs inputs from three sources: inputs from professional figures, inputs from supporting tools, and inputs from external sources (such as literature, websites, etc.).
Regarding inputs from professional figures, the following have been identified: car producer, electronic component producer, and disassembly operator, who will provide the data needed to examine CEs in detail and calculate indicators. For the collection of this data, AI can provide support. As mentioned before, some information provided by the disassembly operator can be obtained from the AI.

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As indicated in the introduction of §4.1, since the 3 use-cases communicate with each other, the information that the Electronic Component producer provides can also be indicated by the designer. This, however, is only feasible if the product under analysis has undergone the new-design or re-design decision-making process described in §4.1.2.
Instead, external sources provide the market values of the materials contained in the CE, the value of thermodynamic rarity, and, if necessary, the percentage of recoverable material by type. The last aspect, namely the percentage of recoverable material, as mentioned above, can be provided by the AI.

In addition to the inputs, it is necessary to define what the output information from Decision 1 can be derived. In relation to output, the last interesting aspect, which can benefit the eco-design decision making process, is the collection of feedback provided by the decision maker and the team in relation to decision 1.
In fact, they have the opportunity to communicate to the Advisory tool feedback such as the case of an analysed EC that has a high number of rare materials with high economic value but has high disassembly cost. The proposed feedback could be very useful in the re-design stages of the EC (§4.1.2.1) as it would appear as a critical issue for the designer to improve.
Another feedback could also be more detailed, i.e., the target material selected to be extracted is not extractable because it is bonded and not separable from another material. Such types of feedback could be even more detailed in the following decisions where the disassembly process is examined in depth. Thus, the decision maker and his/her team provide possible feedback on the critical issues found in the Electronic Component analysed so that improvements can be allowed to be implemented and more and more material recovery promoted.

In order to represent the flow of information, the following diagram was made (

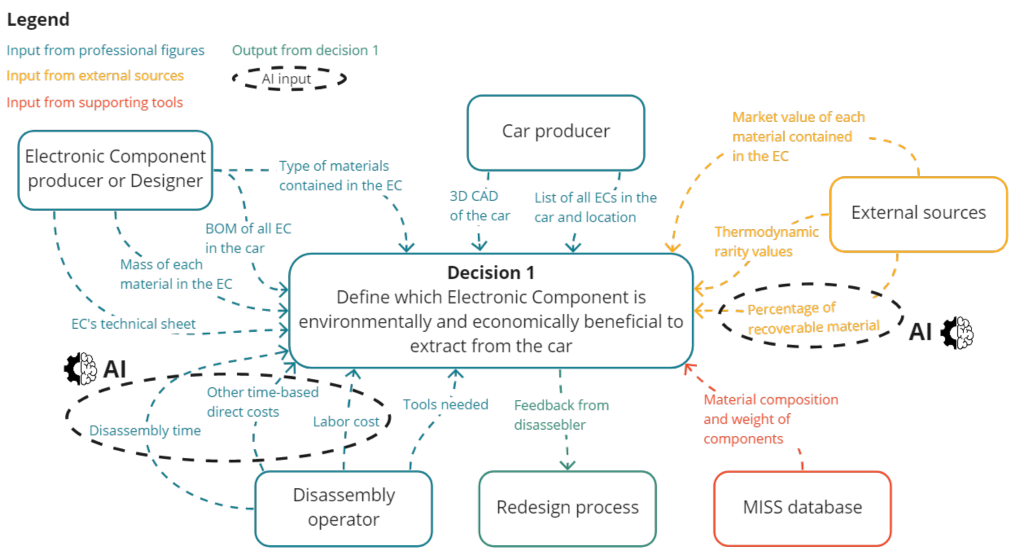

Figure 14Figure 14) where the inputs needed by the Advisory tool to trigger the decision-making process 1 were mapped out and the outputs from the decision. The legend in the figure indicates the type of input/output.

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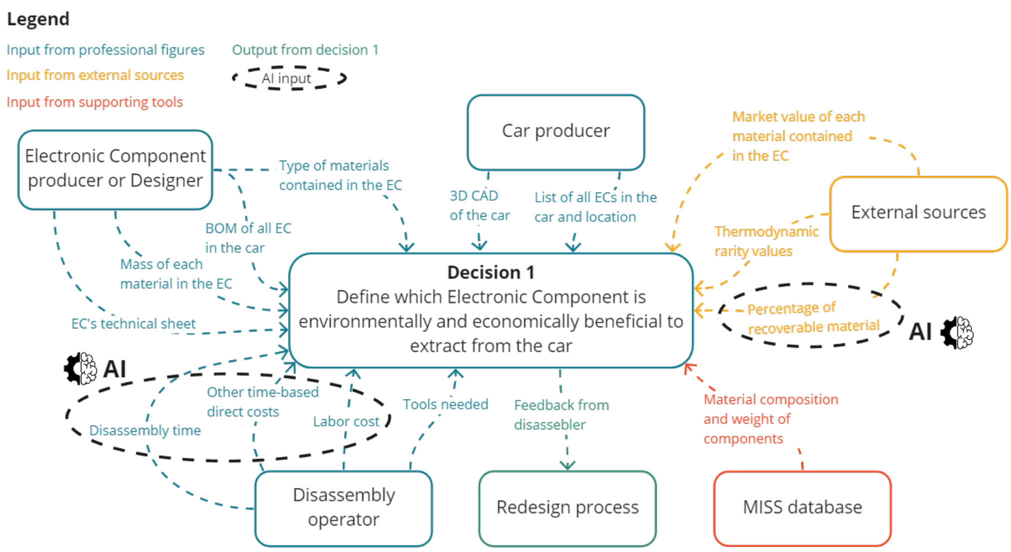

Figure 14: Disassembly and Recycling - information flow of the decision-making moment 1

Decision-making moment 2

Once the Electronic Component to be extracted have been determined, the next step is to define the passages that the disassembly operator must perform to disassemble the car in order to extract the desired EC. It is important to pay attention to this process since it must be done minimizing the effort and generating less impacts. Compared with Decision 1, which is a high-level screening decision, this decision and the following one aim to conduct a detailed assessment, thus based on calculated data. The decision maker turns out to be the car disassembly manager, who, if necessary, can be supported by the disassembly operator and by a cost expert.

In order to achieve the goal, the analytical tool developed by (Mandolini, Favi, et al., 2018b) called "time-based disassembly analysis" can support in defining the disassembly path and determine the disassembly time of a specific target component.

First, it is necessary to determine which target component(s) should be removed from the product under analysis, which turns out to be the Electronic Components(s) identified in Decision 1.

The second step is to define possible disassembly sequences for the car, with support from the disassembly operator. Given the ECs of interest, it is necessary to study the structure of the car containing them and hypothesize disassembly paths for each of them in order to extract them.

Support at this stage can be provided by the IDIS database described in D4.3, which is an advanced information system containing practical information on pre-treatment, dismantling of potentially recyclable parts, and other items mentioned in end-of-life vehicle regulations. Another tool to support this step is the design model of the car provided by the manufacturer, such as a CAD drawing, which allows the product to be analysed through features such as rotation, zoom-in, zoom-out, or the ability to hide components. It is necessary to specify that the CAD drawing of a car may not be easily shared by the manufacturer as it contains possible confidential information or trade secrets. Therefore, where there is no such possibility, the decision maker together with the disassembly operator will generate disassembly paths based

on their experience. Noting this limitation, the car manufacturer could still provide guidance on disassembling the car, for instance presenting disassembly instructions in place of the detailed car CADs drawings. It is important to specify that attention must be paid to the presence of components with special management requirements encountered during the disassembly path. The output of this phase allows determining what obstructions are present to reach each PCB and the precedence to be followed.
Focusing on the disassembly path, a relevant aspect that should not be excluded is destructive disassembly. In fact, if the decision-maker deems that the car under analysis no longer has market value except for the EC to be extracted, it is recommended to consider cutting the car close to the EC of interest in order to reduce effort and related costs.

At this point a square NxN, "level matrix" can be constructed where each row/column represents a component/subassembly of the assembly and each box expresses the relationship between components. Linking and joining elements such as screws, connectors, etc. are not counted as components in the level matrix.
This matrix allows the disassembly level of components under analysis to be mapped by entering a number explained below. First, it is necessary to clarify the meaning of disassembly level, which is the level at which one or more components/subassemblies connected to other components/subassemblies can be disassembled without any physical obstruction. In order to define it, it is necessary to follow a rule i.e., if a component A obstructs one or more components, component A is at level n, while the other components are at level n+1. Following this logic, at level 0 will be found all components that can be extracted without any precedence, while the other components in the other levels accordingly.
Having realized the matrix, it is essential to develop a precedence diagram. The precedence diagram is a visual representation that allows you to make a network diagram with the activities indicated with boxes or nodes and the dependencies between such indicated with arrows. To create it first, it is necessary to identify for each disassembly path alternative the list of steps, and then it will be possible to create a network diagram, knowing the dependencies that exist between components indicated in the level matrix.

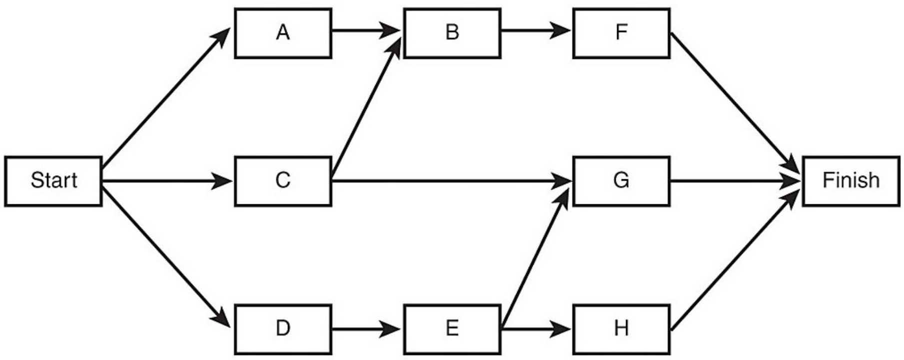

Figure 15: Example of a sequence diagram

Since this is disassembly, identifying the assembly connections, i.e., mechanical, electrical and physical connections, that there are between individual parts is critical. In fact, it is necessary that they be mapped in the flowchart, serving as a list of connections with a specific disassembly time assigned (Table 8).

Table 8: Standard disassembly times for the liaison types

Liaison class	Liaison type	Standard disassembly time [s]
Threaded	Screw	4
	Threaded rod	4
	Nut	4
Shaft-hole	Pin	3
	Linchpin	3
Rapid joint	Snap-fit	2
	Guide	3
	Dap joint	2
Piping	Rubber hose	2
	Spring Clip	4
Electric	Coaxial cable	4
	Electric plug	2
	Screw terminal	2
	Ribbon cable	2
Prevent extraction	Circlip	4
	Split pin	4
Not removable (destructive operation)	Nail or rivet	6
	Welding	10
	Adhesive	6
Motion transmission	Tang or Key	3
	Spline profile	3
Washer	Washer	2
Bearing	Bearing	5
Magnetic	Magnetic	2
Visual obstruction	Visual obstruction or contact	1

At this stage, it is necessary to take into account the condition of the liaison at the time of disassembly, such as whether it is worn, and the tools used for disassembly. In fact, depending on the condition a correction factor is applied for each liaison that can affect the disassembly time, reported by (Mandolini, Favi, et al., 2018a).
It is now possible to proceed with the next step, which is the calculation of the effective disassembly time (T_e) for all identified disassembly paths, shown in the following equation (Eq. 2):

$$T_e = T_s * \prod_k CF_k \qquad \text{Eq. 2}$$

Where T_s denotes the standard disassembly time given in Table 8 above and CF_k the correction factor of the k-th liaison property related to the chosen de-manufacturing conditions.
Due to the computational automaton, the Advisory tool will define this magnitude, which is necessary for the decision maker in order to analyse which path to select. For this purpose, the Advisory tool will calculate the total disassembly time obtained multiplying the labour rate and other time-based direct costs by the effective disassembly time. To identify costs and define their entity, the Sustainability tool developed by SUPSI can provide support. Having obtained the results of the calculation the decision maker, supported if necessary by the cost expert, can identify the path with the lowest cost.

It is necessary to specify how the calculation of the above indicators is to be carried out. Therefore, the mathematical formulas of labour cost, energy cost, service cost and effective disassembly time in the following Table 9.

Table 9: Formula and explanation indicators used in the decision-making moment 2

Indicator	Formula
Effective disassembly time ($T_{dis\_effective}$) (Mandolini, Favi, et al., 2018a)	$T_{dis\_effective} = T_s * \prod_k CF_k$ • T_s is the standard disassembly time; • CF_k is the correction factor.
Labor cost (TREASURE D2.1 §3.2)	$Labor\ cost\ (C_{labor\_disassembly}) = labor\ cost\ rate \left[\frac{€}{min}\right] * T_{dis\_effective}\ [min]$
Energy cost (TREASURE D2.1 §3.2)	$Energy\ Cost\ (C_{energy\_disasssembly}) = power\ absorbed\ [kW] * energy\ cost \left[\frac{€}{kWh}\right] * T_{dis\_effective}[h]$
Service cost (TREASURE D2.1 §3.2)	$Service\ Cost\ (C_{services\_disassembly}) = C_{lights} + C_{non-invasive\ maint.actions} + \ldots$
Disassembly cost (C_d)	$C_{disassembly} = C_{labor\_disassembly} + C_{labor\_disassembly} + C_{services\_disassembly}$

The role of AI in the advisory tool during decision making process 2 is critical in order to speed up and automate the definition of the optimal disassembly path. Having the capacity to analyse a large amount of data, it can draw on the data collected during the generation of the disassembly path of the cars previously examined by the advisory tool, and rely on the similarities with the case under analysis; therefore, if the electronic component is at, or near the same point as cars already analysed and if it is the same car model, the Advisory tool is able to recommend the optimal path compared to those already analysed. At this point it will be up to the decision-maker whether to implement the path recommended by the Advisory tool without performing the whole process just described, or to compare the one recommended by the one he/she generated. The advisory tool must have the ability to store for each car model analysed the optimal path generated and recommend it as appropriate.
Below the Decision card defined in §4.1 for Decision 2 (Figure 16Figure 16) is presented.

Decision Define the most cost-effective car disassembly route to extract the selected Electronic Component.	**Product focus of the decision** Car
Supporting tools and technologies • IDIS database; • Sustainability tool.	**Required input** • BOM of selected Electronic Component; • 3D CAD of selected EC: • Information from the manufacturer on car disassembly; • Tool needed for disassembly; • Number and type of joints; • Labor cost and other time-based direct costs for disassembly [€/min]; • Estimated disassembly time [min].
Support from Advisory tool Calculating of the disassembly time and costs required to achieve the Electronic Component. Comparison of disassembly routes already implemented and other possible ones. Advice on disassembly steps to be implemented.	
Decision-maker Car disassembly manager	**Possible support from AI** The AI through the comparison of similarities between the case under analysis and others already implemented, can suggest the optimal disassembly path among those already made.
Economic indicatos • Disassembly cost.	**Circular indicatos** • Effective disassembly time.

Figure 16: Disassembly and Recycling - Decision card 2

In accordance with the Decision card above, information needs to be provided as input to execute the decision.
To activate decision-making 2, the Advisory tool needs inputs from three sources: inputs from professional figures, inputs from supporting tools and input from AI.

Regarding inputs from professional figures, namely the car manufacturer and the car disassembler, they will have to provide the necessary data to generate disassembly path alternatives and support the definition of disassembly time. Focusing on disassembly path alternatives, an important support is input from AI, which, by analysing similarities with already disassembled products, is able to suggest pathways.
Similarly, the sustainability tool will be able to support the definition of the economic impacts of the various disassembly pathways.
In addition to the inputs, it is necessary to define what the output information (feedbacks) from Decision 2 can be derived. Focusing on the possible feedbacks that this decision-making process could record and communicate to other use cases, the car disassembler could highlight how

Electronic Components of high interest might be difficult to extract without having to disassemble much of the car. So, it could point out critical issues, i.e., ECs for which disassembly time and thus a related high cost is required. This could provide support to designers who, knowing such information, could optimize the placement of ECs by promoting a less economically impactful disassembly of the car.

In order to represent the flow of information, the following is a diagram was made below (Figure 17) where the inputs needed by the Advisory tool to trigger the decision-making process 2 were mapped out and the outputs from the decision. The legend in the figure indicates the type of input/output.

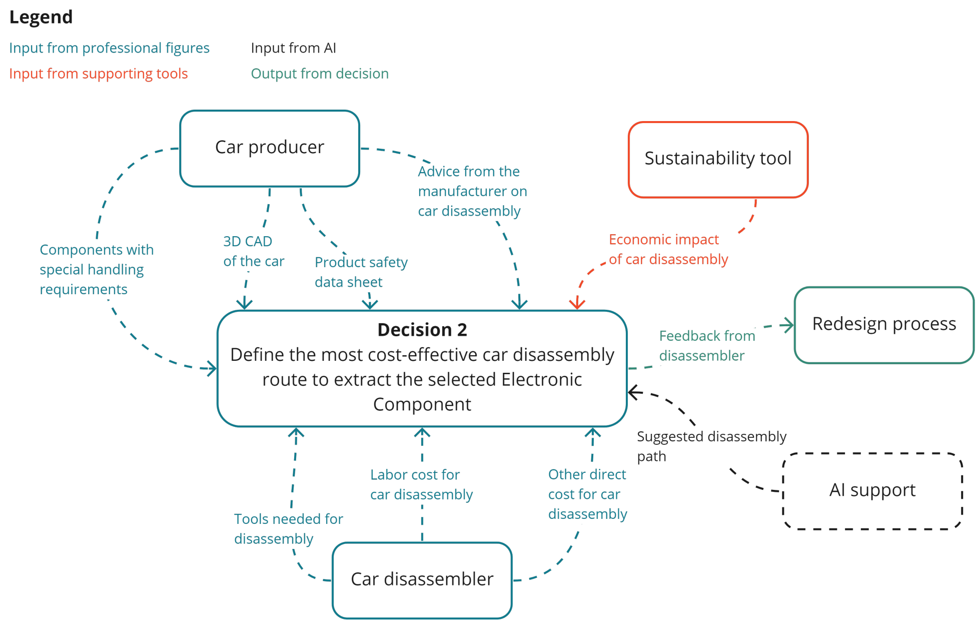

Figure 17: Disassembly and Recycling - information flow of the decision-making moment 2

Decision-making moment 3

Once the Electronic Components to be extracted have been selected and the car disassembly route defined, an analysis needs to be conducted to identify the disassembly route to extract the recyclable material contained in the EC and the most sustainable recycling process. At this stage, the decision maker is the recycling manager who, if necessary, can be supported by the operator who disassembles the Electronic Components and a sustainability expert.
Indeed, the objective of Decision 3 is to identify for which combination of disassembly path and recycling process the highest amount of recyclable material is obtained while generating the least impact in all spheres of sustainability.

Starting from the aspect of circularity, key support is provided by the tool developed by MARAS, namely the Recycling Simulation tool. Through a simulation, the decision-maker can reproduce the processes of dismantling, shredding and sorting, determining the recoverability and recycling of a product. As reported in D3.3, 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 (Product Centric approach). When desired, materials of special interest (such as ferrous metal, Critical Raw Materials (CRMs), organic, etc.) can be given special focus where required, e.g., when selecting the most optimal or most suitable recycling

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route(s) for processing the different disassembled car parts or additionally selected parts for further disassembly of the car parts.

As a result, the evaluation cases generate information on the Best Available Techniques (BAT), the industrial (and thus economically viable) recycling treatment routes and the facilities to be applied to achieve the most optimal treatment for the different car parts and recycling targets. 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 on the full metallurgical recycling infrastructures.

In relation to the TREASURE context, as far as PCBs that are contained in Electronic Components are concerned, one possible disassembly procedure to be considered is that performed by the semi-automatic PCB disassembly station located at POLIMI's I4.0Lab. It allows all components to be de-soldered from the board and sent to the recycling process. As with the disassembly route, one possible recycling route is already defined by the TREASURE project but could also be accompanied also by alternative technologies. In fact, the process turns out to be the bio-hydrometallurgical processes, which allows after the PCB has undergone the disassembly process, to recovery of valuable (critical) raw materials in order to put them back into the value chain.

Once the simulation is finished, a comparable graph will be provided, which shows the main recycling route(s) to be followed for the user-defined recycling objective. In particular, for each recycling route, recycling results are shown according to three levels of circularity:

- **Closed loop CE** (recycling into high quality products with material properties equal to original product/material);
- **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;
- **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, a Material Recycling Flower is provided for each route, showing the recycling rate for each individual material (detailed description of the tool is provided in D3.3).

Based on the recycling rate values, the value of energy recovery and in relation to the level of circularity that the decision-maker wants to implement, he/she is able to choose the best processing route(s) for the selected recycling target.

An innovative aspect of the Recycling Simulation tool is the integration of the environmental impact assessment of EoL routes. As reported in D3.3, the process simulation model developed by MARAS has been built in the industrial software platform HSC Chemistry Sim® 10, providing a professional and industrial platform for process simulation tools and recycling as well as environmental impact calculations.

As environmental impact calculations are directly linked in HSC Sim, LCA indicators and assessment on the EoL can be calculated from this.

Through the Recycling Simulation tool, it is possible to identify the best route(s) in terms of circularity, total Recycling Rate (%) of the product(s)/part(s), Recycling Rates (%) for all individual materials/elements, energy recovery (MWh/t feed or per part), exergetic and energy performance, and can provide an Eol environmental assessment. Therefore, it is necessary to

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include decision criteria related to economic and social sustainability. A supporting tool at this stage is SUPSI's Sustainability tool that can help with evaluation in all three thematic areas.
Starting with the economic impact, it is necessary to quantify the total cost of disassembly and subtract it from the sum of the revenue that can be generated from the sale of individual recyclable materials. The revenue values must be obtained as a function of the mass of material under analysis contained in the component multiplied by the specific recycling rate of that material rate obtained from the simulation performed by the Recycling simulation tool. The decision maker also makes adjustments to the economic value depending on the quality of the material obtained. In this way it is possible to obtain the profit that can be generated.
It is not enough to consider only the environmental and economic aspect, but it is necessary to introduce the social impact component. To this end, a fundamental support is provided by the Sustainability tool which, by integrating the PSILCA database, is able to estimate the social impact avoided by not extracting raw material. In fact, in addition to impacting the safety of workers who are subjected to continuous risks during extraction and refining processes and for whom it is necessary to ensure preventive measures and appropriate clothing. Another affected stakeholder is also the local community. Indeed, extraction of resources such as water, fossil fuels, and ores has an impact on the community. Social impacts must refer to the mass of recyclable material obtained by multiplying the mass of materials by the specific recycling rate of that material rate obtained from the simulation performed by the Recycling simulation tool.

In order to understand the decision-making moment in question, it is essential to analyse the necessary indicators. Below (Table 10) are the circular indicators, PEF default environmental indicators needed to define the least impactful disassembly and recycling processes while the indicator disassembly cost combined with the resale value for choosing the most cost-effective route. Finally, the social indicators that must be calculated in relation to the extraction and refining process of the mass of raw material contained in the Electronic Component under analysis.

Table 10: Formula and explanation indicators used in the decision-making moment 3

Indicator	Formula
Climate change (TREASURE D2.1 §3.2)	Radiative forcing as Global Warming Potential (GWP100) [kg $CO_{2\ eq}$]
Acidification (TREASURE D2.1 §3.2)	Accumulated Exceedance (AE) [mol H+ $_{eq}$]
Eutrophication – terrestrial (TREASURE D2.1 §3.2)	Accumulated Exceedance (AE) [mol N $_{eq}$]
Eutrophication – aquatic, fresh water (TREASURE D2.1 §3.2)	Fraction of nutrients reaching freshwater end compartment (P) [kg P $_{eq}$]
Eutrophication – aquatic, marine (TREASURE D2.1 §3.2)	Fraction of nutrients reaching marine end compartment (N) [kg N $_{eq}$]
Photochemical ozone formation, human health (TREASURE D2.1 §3.2)	Tropospheric ozone concentration increase [kg NMVOC $_{eq}$]
Ozone depletion (TREASURE D2.1 §3.2)	Ozone Depletion Potential (ODP) [kg CFC-11 $_{eq}$]
Resource use – fossils (TREASURE D2.1 §3.2)	Abiotic resource depletion – fossil fuels (ADP-fossil) [MJ]
Water use (TREASURE D2.1 §3.2)	User deprivation potential (deprivation-weighted water consumption) [m^3 world $_{eq}$]
Resource use – minerals and metals (TREASURE D2.1 §3.2)	Abiotic resource depletion (ADP ultimate reserves) [kg Sb $_{eq}$]
Land use (TREASURE D2.1 §3.2)	• Soil quality index [dimensionless (pt)] • Biotic production [kg biotic production]

	• Erosion resistance [kg soil] • Mechanical filtration [m³ water] • Groundwater replenishment [m3 groundwater]
Eco-toxicity – aquatic, fresh water (TREASURE D2.1 §3.2)	Comparative Toxic Unit for ecosystems (CTU_e) [CTU_e]
Human toxicity – non cancer (TREASURE D2.1 §3.2)	Comparative Toxic Unit for humans (CTU_h) [CTU_h]
Human toxicity – cancer (TREASURE D2.1 §3.2)	Comparative Toxic Unit for humans (CTU_h) [CTU_h]
Disassembly cost (C_d)	$C_d = t_d * \alpha$ • t_d is the estimated disassembly time; • α represents the labour rate plus other time-based direct costs.
Resale value ($RV\ (t)$) (TREASURE D2.1 §3.2)	$RV\ (t) = m_i * RV_i(t)$ • m_i is the mass content of a given element expressed in grams; • $RV_i(t)$ is the resale value of the specific element at a given time t expressed in $\frac{€}{g}$.
Total Recycling Rate (%) of the product/part	See TREASURE D3.3
Recycling Rates (%) for all individual materials/elements in the product/part	See TREASURE D3.3
Energy recovery (MWh/t feed or per part)	See TREASURE D3.3
Presence of sufficient safety measures for workers (TREASURE D2.1 §3.3.2)	$OSHA^5$ *cases per* 100,000 *employees in the sector*
Level of industrial water used (related to total withdrawal) (TREASURE D2.1 §3.3.2)	*% of total water withdrawal*
Extraction of fossil fuels (TREASURE D2.1 §3.3.2)	$tons\ per\ capita\ \left[\frac{t}{cap}\right]$
Extraction of ores (TREASURE D2.1 §3.3.2)	$tons\ per\ capita\ \left[\frac{t}{cap}\right]$

Defined the impacts in each area, the decision maker can decide whether to use the combination of circular, social, economic and environmental impacts as a criterion or to consider only one of these aspects. Depending on his choice, it will be possible to define the best route.
In the case where the decision maker feels that he or she wants to choose the route that can optimize all areas of sustainability, the advisory tool can provide a visual support tool such as the one given in §4.6 of D2.1. BASF's SEEbalance method (Kolsch, Saling, et al., 2008) makes it possible to visualise the performance of different products or processes in the 3 domains of

[5] https://osha.europa.eu/en

sustainability thanks to a 3D graphical representation (Figure 18) and can be used to evaluate alternatives.

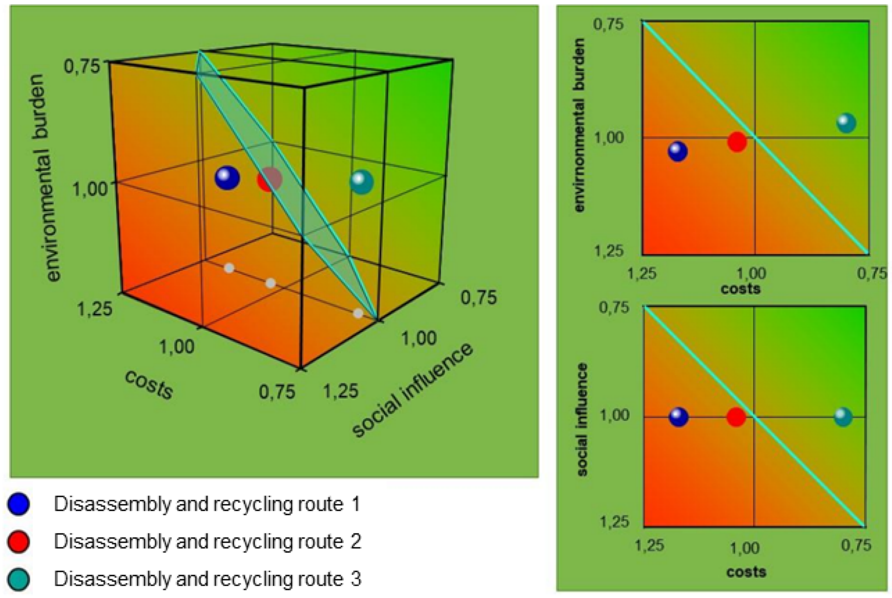

Figure 18: Three-axis graph: resale value, thermodynamic rarity indicator and avoided social impacts

Thus, the alternative with better performance in all three spheres of sustainability will be selected. In case the decision maker chooses to consider only one area of sustainability as a criterion, a ranking of routes will be provided.

Again, as with previous decisions, AI can provide support. In fact, with historical data, it is possible that similarities with previously analyzed ECs can be created and provide an indication of which are the best disassembly and recycling routes.
Known the decision-making process, below is the Decision card defined in §4.1 filled with the information related to Decision 3 (Figure 19).

Decision

Determine which combination of disassembly path and recycling process to implement in order to recover the maximum amount of material for recycling and generate the least amount of impacts in terms of sustainability

Product focus of the decision

EEE

Supporting tools and technologies

- MISS database;
- Recycling Simulation tool;
- Sustainability tool with PSILCA database.

Required input

- BOM of selected Electronic Component;
- 3D CAD of selected EC;
- Type of materials contained in the ECs;
- Mass of each material contained in the EC [g];
- Market value of each material contained in the EC [€/g];
- Thermodynamic rarity values [kJ/g];
- Labor cost and other time-based direct costs for disassembly [€/min];
- Estimated disassembly time [min];
- Information on impacts on Workers and Local Community durign virgin raw material extraction.

Support from Advisory tool

Calculation of avoided sustainability impacts of virgin feedstock extraction and refining.
Calculation of environmental impacts of disassembly and recycling processes.
Calculation of the profit that can be generated according to the percentage of recoverable materials.
Implementation of a visual tool for Electronic Component analysis in terms of circularity.
Advice on the best route for disassembly and recycling.

Decision-maker

Recycling manager

Possible support from AI

The AI through historical data, can analyze similarities with previously analyzed ECs and provide an indication of which are the best routes for disassembly and recycling.

Environmental indicatos

- 14 PEF's default midpoint indicators.

Social indicatos

- Presence of sufficient safety measures for workers;
- Level of industrial water used;
- Extraction of fossil fuels;
- Extraction of ores.

Economic indicatos

- Resale value;
- Disassembly cost.

Circular indicatos

- Estimated disassembly time;
- Total Recycling Rate;
- Recycling rate for individual materials;
- Energy recovery.

Figure 19: Disassembly and Recycling – Decision card 3

Examining the Decision sard, first it is necessary to clarify what inputs are needed.
As for previous decisions, it is necessary to specify the sources of the inputs needed to execute the decision. Three sources of input were identified: inputs from professional figures, inputs from supporting tools, inputs from external sources and input from AI.
Aanalyzing the inputs from the professional figures, namely the EC disassembler and the EC producer, who will have to provide the necessary data to generate alternatives disassembly path and alternatives recycling process. As mentioned in the introduction of §4.1, since the 3 use-

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cases communicate with each other, the information that the electronic component manufacturer provides can also be indicated by the designer. This, however, is only feasible if the product under analysis has undergone the new-design or re-design decision-making process described in §4.1.2.
Similarly, the sustainability tool will be able to support the definition of the environmental impacts of various processes, avoided social impacts thanks to the support of the PSILCA database and the profit that can be generated from the sale of recovered materials. The Recycling Simulation tool allows calculation of the % of recoverable material by type while the MISS database provides the data needed to make assessments.
Inputs from external sources, such as literature and websites, are the market value of the materials. Finally, inputs from AI, which as mentioned earlier suggests disassembly and recycling routes.
In addition to the inputs, it is necessary to define what the output information from Decision 3 can be derived. As in the previous decisions, the decision-maker and team can provide feedbacks to other use cases. In fact, as mentioned in Decision 1, they can point out critical issues encountered, such as pointing out materials with high values of recovery and market value but high social impact (high social impact is referred to as avoided social impact so the greater the value, the greater the benefit). This could help the designer during the design phase to focus their attention on these materials and prefer them over others.

In order to represent the flow of information, the following is a diagram was made below (Figure 20) where the inputs needed by the Advisory tool to trigger the decision-making process 3 were mapped out and the outputs from the decision. The legend in the figure indicates the type of input/output.

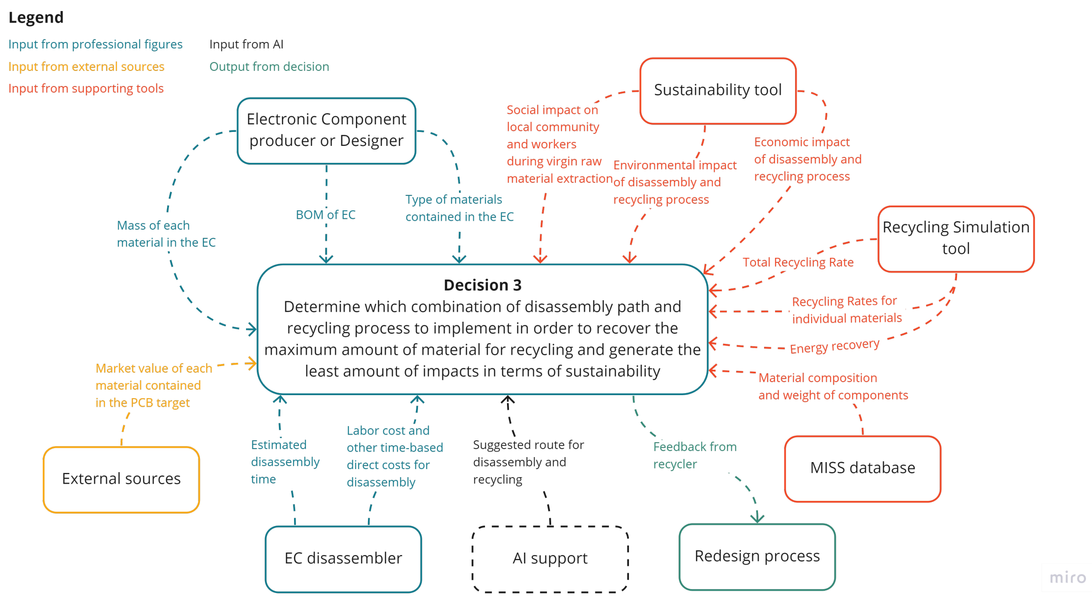

Figure 20: Disassembly and Recycling - information flow of the decision-making moment 3

4.1.2 Eco-Design Advisory methodology

This chapter explores the methodology developed in order to support the design phase of a new design that complies with eco-design principles. The goal is to guide the designer, identified as the decision-maker, to make decisions that will enable the creation of a product with high circular performance.

As mentioned in §2 the TREASURE project, in relation to eco-design use-case, focuses on the realization of Recovery-conscious Design (RSCD), specifically Recovery System-conscious Design (RSCD) which integrates design oriented toward simplifying product disassembly (Design for Disassembly (DfD)) and achieving the highest degree of recycling (Design for Recycling (DfR)). It is important to note that, knowing John Elkington's concept of the Triple Bottom Line (Elkington & Rowlands, 1999), i.e., sustainability is the intersection of three dimensions of performance: environmental, social, and economic sustainability, the three spheres are not excluded from the eco-design process.

The creation of a new product can start from two needs: improving an existing product or making a completely new one, both dictated by market needs.

For this reason, two decision processes are described:

- Redesign process: focused on the redesign of an existing product basing the improvements to be implemented on feedback gathered from disassembly and recycling use-cases;
- New design: focused on designing a new product without feedback.

Regarding the redesign process, the first subchapter describes the decision-making process consisting of five sequential steps.

In the first step the designer will have the task of analyzing the old design. To do this it has the opportunity to analyze both the feedback collected during the disassembly and recycling processes and analyze all the information collected and outputs during these processes (§4.1.1). As a result, the designer will have insight into the product's end of life, the critical issues encountered by disassemblers and recyclers to optimize the design with a view to disassembly and recycling. In the second step, the designer, thanks to the physics and recycling industry-based approach to Design for Recycling developed by MARAS (Schaik, A. van and Reuter, 2013), is able to generate specific guidelines for the product under analysis. In fact, thanks to fundamental guidelines and an iterative process supported by the Recycling simulation tool, it is able to define product-specific guidelines. Next, the guidelines can be appropriately associated with the feedback gathered from the disassembly and recycling processes. This is done since the guidelines represent the solution to the highlighted criticality. Finally, the fulfilment of the guidelines by the old design is evaluated by exploiting a method developed by (Bovea & Pérez-Belis, 2018). During this step, it is critical to give top priority to the guidelines associated with feedback. Prioritising the guidelines to be acted upon is not a compulsory step, but only recommended if necessary.

In the third step, following the evaluation of the old design, it is necessary to define the optimization actions to be applied. This can be done by leveraging both AI support and relying on the designer's experience. In the last step, a comparison between the old design and the new one is performed. The comparison, based on a set of selected indicators, is useful to the designer in order to identify for which aspects the implemented improvement actions have had a positive effect and for which further optimization is needed.

Focusing instead on the design of a new product, the designer is expected to follow the decision-making process described for re-design, excluding two steps: steps 1 and 5.
The designer can use the guidelines to realize the sustainable design, have support from AI by providing optimization suggestions, and instead evaluate the goodness of the realized design.

For both decision-making processes, Decision cards are described. There are two Decision cards, the first focusing on Design for Disassembly and the second focusing on Design for Recycling.

In the following sub-chapters, §4.1.2.1 and §4.1.2.2, the decision processes of re-design and new design are described.

4.1.2.1 Re-design decision process description

With the aim of making products that can integrate sustainability and circularity aspects, it is necessary to focus not only on the design of new products, but also on the re-design of existing products. In fact, re-design generally focuses on resolving conflicts between current product requirements, dictated by the market and strategic business goals, and previous design capabilities.
To this end, the designer must follow a different process than he or she would for a new product design, first analyzing the critical issues of the existing product, noting an improved solution, analyzing its feasibility, and implementing it by verifying that it is actually beneficial.

In accordance with the objectives of the TREASURE project, the focus on which the eco-design use-case activities is Design for Disassembly (DfD) and Design for Recycling (DfR). Therefore, two different decisions focusing on the two themes have been developed. Clearly, since they are closely related in the way that a choice made from a Design for Disassembly perspective can influence choices from a Design for Recycling perspective and vice versa, it is expected that in the Advisory tool the two decisions will be implemented simultaneously, unlike the Disassembly and Recycling use-cases.
Although the two focuses are different, the process that the designer must follow in order to make choices to realize the new design appears to be common. Before exploring the decision-making process, it is necessary to specify that the evaluations of improvements in the old design are carried out on the basis of a physics-based approach and the recycling industry (§2.2.2).

Following a state-of-the-art analysis of existing guidelines related to eco-design, those indicated by (Schaik, A. van and Reuter, 2013) were chosen. These were selected because the others reported in the literature do not specify how to achieve the goal and are purely for simple products. To solve these problems (Schaik, A. van and Reuter, 2013) have defined a physics and recycling industry-based approach to Design for Recycling for WEEE. They propose 10 design rules and guidelines derived from the simulation performed by the tool they developed, reported in §4.1.1 and detailed in D3.3.
Exploring the guidelines, they are divided into 5 fundamental and 5 derived guidelines. Focusing on the derived ones, they are called "derived" because they are obtained by applying the fundamental DfR rules and principles. As a result, a specific set of guidelines can be defined for each mix of materials and recycling systems. Recycling process simulation tools provide support as they allow to define, validate and quantifie the set of guidelines per product.
Based on the last aspect, it was possible to carry out an association of the guidelines developed by (Bovea, Pérez-Belis, et al., 2016; Bovea & Pérez-Belis, 2018) and by (Berwald, Dimitrova, et al., 2021), which were appropriately selected in order to extrapolate generic guidelines (not strictly related to a product type), to the 5 derived guidelines reported by (Schaik, A. van and Reuter, 2013). This was done in order to provide examples of possible specific guidelines.

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Through this state-of-the-art analysis, it was possible to derive specific guidelines related to the design of EEE (Berwald, Dimitrova, et al., 2021). These have been associated with certain generic DfR guidelines from (Bovea, Pérez-Belis, et al., 2016; Bovea & Pérez-Belis, 2018).

The decision-making process is structured in 4 steps described in the following paragraphs.

Step 1: Preliminary analysis of the old design

From the decision-making moments related to the Disassembly and Recycling use-cases described in §4.1.1, it was possible to highlight how the decision-makers and operators involved in these processes have the opportunity to record feedback, i.e., the critical issues found in the products/processes they analyze. The redesign process starts from this aspect, in fact, the designer interested in the redesign of a particular product, selected according to the business strategy or according to the feedback (a product with many negative feedbacks could attract the designer's attection), first has the task of analyzing all the feedbacks collected by the Advisory platform.

In addition to the critical issues collected, it is crucial that the designer can have the opportunity to analyze the data collected, calculated, and used during the choices made in the decision-making moments related to the Disassembly and Recycling use-cases and the outputs of those decisions. Specifically, in accordance with §4.1.1, from Decision Moment 1 the designer can derive information such as the BOM of the product, the mass of individual materials, the market value of materials, the value of thermodynamic rarity indicator. From Decision 2: the location of the component in the car, the disassembly route from the car to the product, estimated and effective disassembly time. From Decision 3: recycling route of the product, disassembly cost, total Recycling Rate, Recycling rate for individual materials, energy recovery and social impacts.

The information gathered in these decisions and the feedback provided are fundamental for the designer in order to provide him/her with an overview of the old design, how it was processed during end-of-life, and where criticalities were found on which to implement optimization actions.

Step 2: Generation of specific eco-design guidelines with the physics and recycling industry-based approach to Design for Recycling

Following the preliminary analysis of the old-design, it is necessary to identify the strengths and weaknesses of the existing design and assess what are the importance aspects on which to act. As previously mentioned, the approach chosen is the one developed by MARAS. Through the analysis of numerous EEE recyclates, MARAS tried to understand the relationship between design and recyclate quality. Based on the information gathered from this analysis and the expertise of MARAS, comprehensive simulation based DfR rules and guidelines have bene developed (see §2.2.2).
The first 5 guidelines are fundamental guidelines, which serve as a basis for the development of product-specific guidelines. Specific guidelines are developed by the designer through the implementation of fundamental rules and with the support of the simulator.
Regarding the 5 derived guidelines, these are reported above:

6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting.
7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials.

8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e., Metal Wheel).
9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility for easy identification (and removal) from recyclates and waste streams.
10. Be mindful of liberation of materials in design (Design for Liberation).

In order to provide an indication of possible guidelines related to these five MARAS guidelines, an association was made between them and those developed by (Bovea, Pérez-Belis, et al., 2016; Bovea & Pérez-Belis, 2018).
First, in order to facilitate the managing of the large number of guidelines from (Bovea, Pérez-Belis, et al., 2016; Bovea & Pérez-Belis, 2018), they were grouped into sets of guidelines, where each group represents the purpose expressed by those guidelines set. For instance, in DfD group "Easy to separate" from **Errore. L'origine riferimento non è stata trovata.** below, the guidelines aim at facilitating the separation of materials. The nomenclature of the groups comes partly from the state of the art, partly from D2.2 authors. In addition, the groups were associated with the two design topics, Design for Disassemby and Design for Recycling.
Exploring groups, the DfD-related guidelines are aggregated into the following groups of guidelines:

- Easy to identify;
- Easy to access;
- Easy to separate;
- Uniformity of tools.

Instead, the DfR-related guidelines are grouped into:

- Materials compatible for recycling;
- Easing disassembly;
- Product with a low environmental impact;
- Product with a low social impact;
- Product with a low economic impact.

Below (**Errore. L'origine riferimento non è stata trovata.**) are reported the guidelines related to DfD and DfR.

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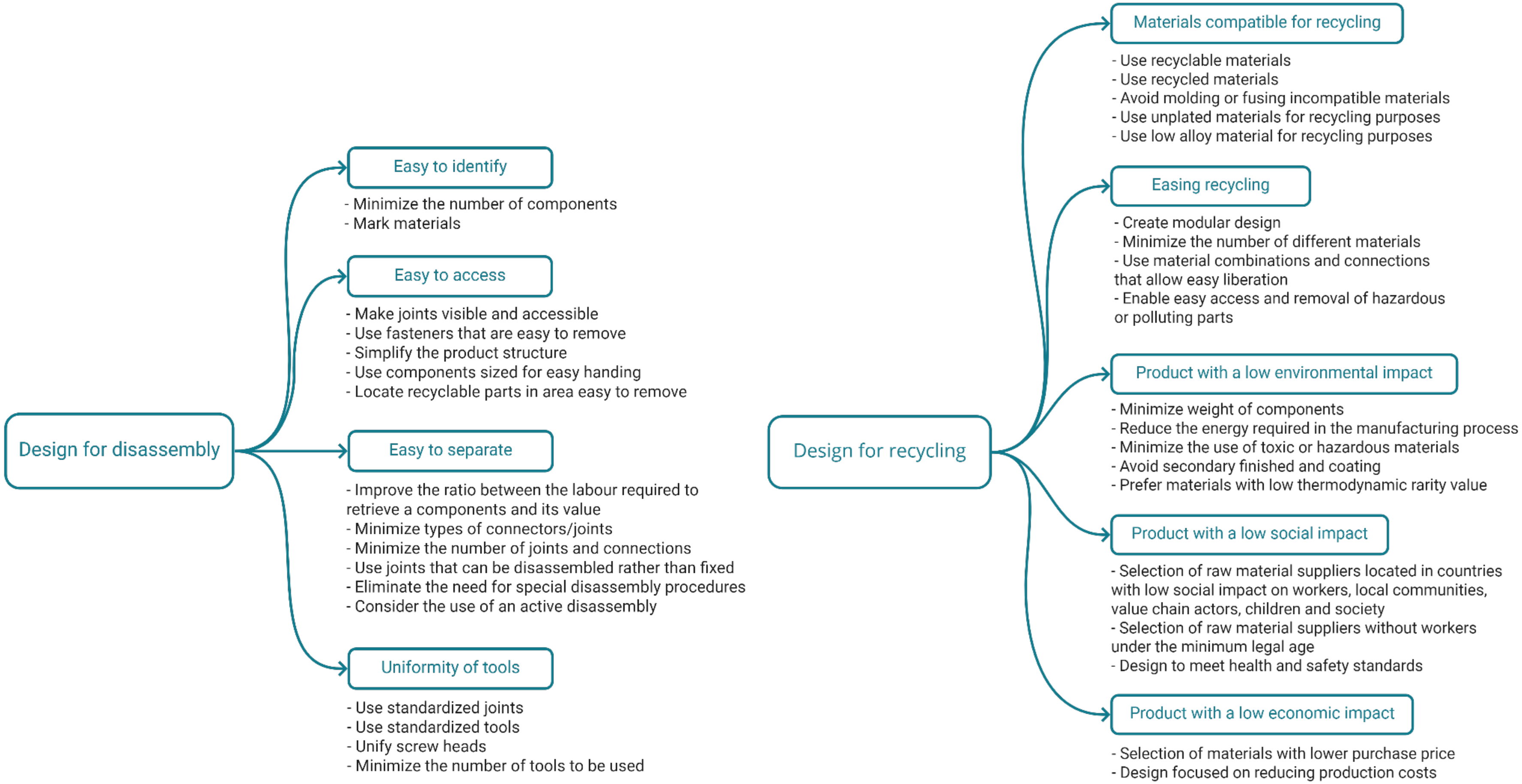

Figure 21: Guidelines for disassembly-oriented and recycling-oriented eco-design

As previously mentioned, specific WEEE-related guidelines (Berwald, Dimitrova, et al., 2021) can be linked to the guidelines for recycling-oriented eco-design on five topics:

- Material compatible for recycling: guideline "Use recycled materials";
- Easing disassembly: guideline "Use material combinations and connections that allow easy liberation";
- Easing disassembly: guideline "Enable easy access and removal of hazardous or polluting parts";
- Product with a low environmental impact: guideline "Minimize the use of toxic and hazardous materials".

The specific guidelines on WEEE are different guidelines depending on the stage of eco design development. The first group of guidelines refer to the stages from the beginning of the design to the validation of the concept (from start to concept), the second group related to the actual production of the product, thus development of functions, design and engineering of specific parts of the product, and implementation of a new structure (from concept to production).

Below (Figure 22) is the list of generic DfR guidelines shown in within addition the specific WEE-related guidelines from §2.2.2 It is recommended that when evaluating the improvement actions to be implemented related to the associated guidelines mentioned above, the guidelines related to EEE design should also be examined, so as to have more specific information on best-practice

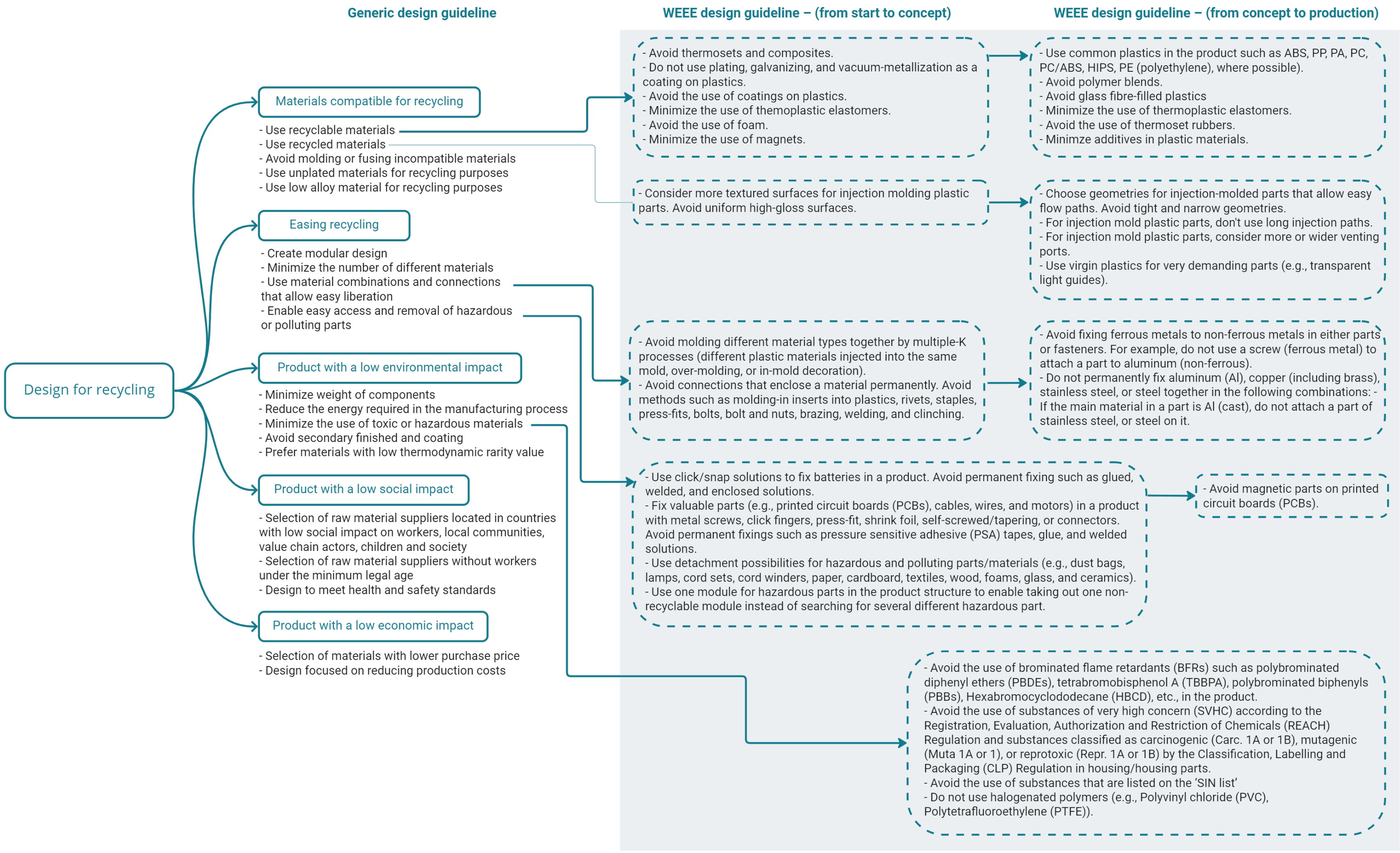

Figure 22: Generic DfR-related guidelines with associated specific WEEE-related guidelines

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Knowing the five guidelines developed by MARAS and the examples of guidelines that the designer could extrapolate from the iterative process of analysing the simulations carried out by the Recycling Simulation tool (Fundamental DfR guideline 2), the following is a table (Table 11) where the examples of guidelines are associated with the MARAS guidelines.

Table 11: Derived DfR guidelines with associated examples of specific guidelines

<table>
<tr><th>Derived DfR guideline (from MARAS)</th><th>Example of guideline from (Bovea, Pérez-Belis, et al., 2016; Bovea & Pérez-Belis, 2018)</th></tr>
<tr><td>6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting.</td><td>“Materials compatible for recycling” DfR guideline group</td></tr>
<tr><td>7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials.</td><td>“Easing recycling” DfR guideline group</td></tr>
<tr><td>8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e., Metal Wheel).</td><td rowspan="3">“Easy to identify” DfD guideline group
“Easy to access” DfD guideline group
“Easy to separate” DfD guideline group
“Uniformity of tools” DfD guideline group</td></tr>
<tr><td>9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility for easy identification (and removal) from recyclates and waste streams.</td></tr>
<tr><td>10. Be mindful of liberation of materials in design (Design for Liberation).</td></tr>
</table>

Not all the guidelines’ groups presented in Figure 21 are covered by the derived guidelines indicated by MARAS. In fact, support for the determination of guidelines in relation to environmental, social and economic sustainability is provided by SUPSI's Sustainability tool. Also by performing an iterative process of simulations on the design to be optimised, specific guidelines can be defined. On the environmental side, the Recycling Simulation tool can also provide support.

It can be observed that the guidelines could be numerous, which is why it is necessary to prioritize the designer's areas of focus. With a perspective of improvement, it would be ideal for the designer to create a re-design considering all the guidelines extrapolated, but their applicability may be limited by factors such as time, available budget, technical feasibility, etc. It is thus essential for the designer to plan the effort in order to limit resources on less problematic aspects of the product.

To this end, the first necessary action is related to the association of the feedback collected from disassembly and recycling processes with the guidelines. In fact, very often the guidelines are the solution to the criticality highlighted by the feedback. For example, taking the disassembly process into consideration, one possible feedback from the disassembler is, "Gold, identified as a material to be extracted, is un-extractable because the fasteners are irremovable." This can be associated with the disassembly-oriented guideline "Use fasteners that are easy to remove" (Figure 21**Errore. L'origine riferimento non è stata trovata.**). It is necessary to specify that each guideline can have more than one feedback associated with it. The association, which can be implemented by the designer who is the only figure with transversal skills, highlights guidelines of priority for action as they are linked to a critical issue encountered.

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It is necessary to specify that the prioritisation procedure for corrective actions is not compulsory but recommended. With a view to improvement, the designer may decide not to focus on optimising only certain aspects but to implement improvements for all guidelines.

Once the combination has been made, it is first necessary to evaluate the individual guidelines and then to obtain an evaluation by guideline group. For this purpose, a qualitative method developed by (Bovea & Pérez-Belis, 2018), was found to be suitable, which allows to define how well the product being designed meets a given guideline. In order to make the methodology less qualitative and more in line with the objective of the eco-design advisory, all evaluations below, i.e., the definition of the two criteria explained below, must be carried out according to the results obtained from the simulations performed by the Recycling Simulation tool and by the Sustainability tool.

Specifically, the methodology is based on two evaluation criteria which are:

1. **Margin of improvement (MI)**: compliance of the circular design guideline can be assessed with this criterion. In fact, it highlights how much improvement is needed in product design in order to comply with the guideline. For this purpose, the designer during the analysis of this criterion will have to carry out a semi-qualitative evaluation by indicating a value from 1 to 3. The value 3 means that the product does not meet the design guideline, so there is a high room for improvement. In case it is 2, it means that the product slightly meets the design guideline and the room for improvement is medium. Whereas, if the indicated value is 1, the product completely meets the guideline and the margin for improvement is small.
   The following is a table indicating the values that can be associated with the margin for improvement and attached description (Table 12Table 12).

Table 12: Assessment of the Margin of Improvement (MI) criterion

Grede of MI	Description
High (3)	The circular design guideline is not presented or is very slightly met in the product design. So the MI of that aspect will be high.
Medium (2)	The circular design guideline is fairly met in the product design. So the MI of that aspect will be medium.
Low (1)	The circular design guideline is fully met in the product design. So the MI of that aspect will be low.

2. **Relevance (R)**: the relevance criterion allows to assess what is the impact of guideline implementation in product characteristics. In fact, satisfaction of a guideline can generate effects on product features, life span, durability, performance, etc.
   Therefore, in accordance with Table 13, relevance is assessed in 3 grades and is associated with the specific guideline. Grade 3, thus high, is indicated when the importance of incorporating the aspects included in that group is essential when considering function, durability, durability, performance, etc. On the other hand, when the importance of incorporating those guidelines is medium, the grade 2 is given and finally, relevance is 1 if the importance of incorporating is low.

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Table 13: Assessment of the Relevance (R) criterion

Grede of R	Description
High (3)	The significance of incorporating the aspects considered in this circular design guidelines will be high when taking into acocunt the functions, life span, durability, performance, etc., of the product.
Medium (2)	The significance of incorporating the aspects considered in this circular design guidelines will be medium when taking into acocunt the functions, life span, durability, performance, etc., of the product.
Low (1)	The significance of incorporating the aspects considered in this circular design guidelines will be low when taking into acocunt the functions, life span, durability, performance, etc., of the product.

As previously mentioned, the feedback collected appropriately associated with the guidelines represents a priority of action. All guidelines with associated feedback are given the maximum value of Margin of Improvement (equal to 3) and Relevance (equal to 3).
So, the designer has the task of defining the Margin of Improvement and the Relevance of each guideline, thus enabling the definition of the level of improvement of the product circularity and the identification of which guidelines are least satisfied by the design and the related motivation. To obtain the Level of Circularity Improvement (LCI), the multiplication between the MI value of the guideline under analysis and the R value of the associated guideline group is carried out. So, the LCI can take a value ranging from 1 to 9, where 1 occurs in the case where the guideline is met by the design and the importance of incorporating it into the product is low considering functions, life span, durability, performance, etc. of the product, while 9 when the guideline is not met and it is a priority to incorporate it into the product.

To clarify, the model referring to the DfR guidelines from MARAS is given below (Table 14Table 14).

Table 14: Template to calculate the level of circularity improvement for each product design

Circular desing guideline	Degree of Margin of Improvement	Degree of Relevance	Level of Ciruclarity Improvement
6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting.	$MI_{1.1}$	R_1	$MI_{1.1} * R_1$
7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials.	$MI_{2.1}$	R_2	$MI_{2.1} * R_2$
8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e., Metal Wheel).	$MI_{3.1}$	R_3	$MI_{3.1} * R_3$
9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility for easy identification (and removal) from recyclates and waste streams.	$MI_{4.1}$	R_4	$MI_{4.1} * R_4$
10. Be mindful of liberation of materials in design (Design for Liberation).	$MI_{5.1}$	R_5	$MI_{5.1} * R_5$

Once the evaluation has been made, a graphical tool can be exploited in order to help the designer to identify the least performing guidelines from the product.
Two Radar graphs are therefore constructed: one representing the improvement level scores of each guidelines.
Below (Figure 23) is an explanatory example of a Radar chart representing unreal Levels of Circularity Improvement values for the 5 Derived DfR guidelines developed by MARAS.

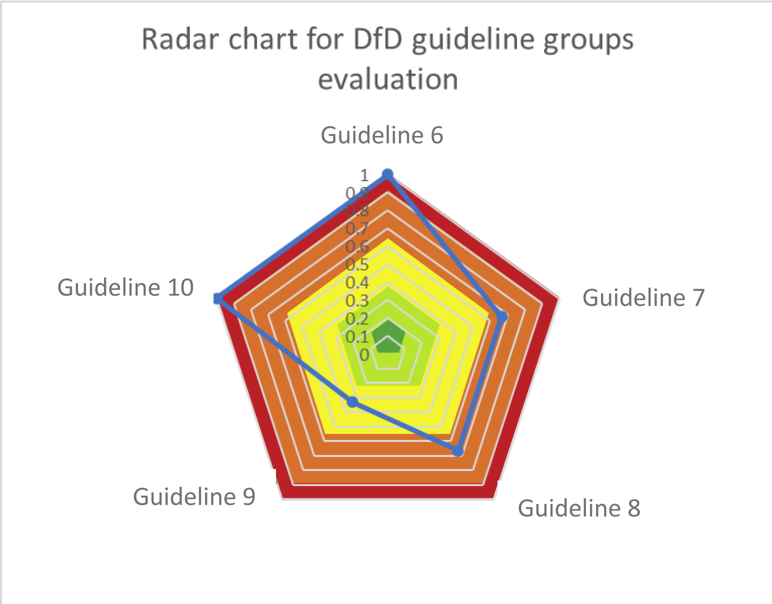

Figure 23: Radar chart for evaluation of guidelines

It is possible to see that there are differently colored areas in the graph. This is meant to facilitate the identification in the Radar chart of the most urgent circular design guideline to incorporate the into the product design. For this purpose Table 15*Figure 16: Disassembly and Recycling - Decision card 2* associates a different color depending on the "Level of Circular Improvement" value.

Table 15: Colour grades to identify the level of circularity improvement for each circular design guidelines group

		Margin of improvement (MI)		
		Low (1)	Medium (2)	High (3)
Relevance (R)	Low (1)	1 VERY LOW	2 LOW	3 MODERATE
	Medium (2)	2 LOW	4 MODERATE	6 IMPORTANT
	High (3)	3 MODERATE	6 IMPORTANT	9 VERY IMPORTANT

As already said, the Level of Circularity Improvement can assume a value from 1 to 9. If the Level of Circularity Improvement is equal to 1 (from Table 15 "VERY LOW", deep green), no improvement actions are necessary because the product already meets the guideline and it is of low Relevance. Instead, in the case where it takes value equal to 2 (from Table 15 "LOW", green), no special improvement actions are needed. When the Level of Circularity Improvement is "MODERATE" (3 and 4 values, yellow), effort is needed to incoporate the guideline into the product design, while when "IMPORTANT" (6 value, light brown) product redesign is compulsory in order to incorporate the guideline. If it is compulsory and urgent redesing the product then "VERY IMPORTANT" (9 value, brown) is indicated.

With the support of the Radar chart, the designer can easily identify which guideline is very important to focus on.

Step 3: Generation of the new design supported by the advisory

Following the identification of the strengths and weaknesses of the old design, it is possible to provide detailed advice on how to implement the new optimized design. In fact, thanks to the evaluation of compliance with the guidelines implemented in step 2, it is possible to identify corrective actions from an eco-design perspective. Fundamental support in this phase of defining improvements is provided by Artificial Intelligence technologies. In the development of the AI advisor in T4.5, for example, the use of fuzzy rules models to link automotive design to the calculation of the recycling rate will be evaluated (Antoinette van Schaik & Reuter, 2007). Fuzzy logic is often used for complex adaptive applications such as artificial neural networks for decision support. The quality of recyclates and the recycling rate of a product depend on the liberation of materials after shredding and are largely influenced by the design of the product itself. Since the complex system models for predicting recycling rates of new cars are too complex to be linked directly to CAD, due to the complexity of the liberation process, a fuzzy rule modelling approach was developed to overcome this problem through an interface between complex system models and automotive design tools. The approach considers combinations of materials and how they are assembled at the design level, in relation to the composition of the particles and the degree of liberation obtainable after shredding. Fuzzy models are also easily integrated into LCA tools, helping to provide key information about the end-of-life performance of products, including (i) the physics and thermodynamics of separation processes, (ii) the quality of recyclates as a function of physical design choices, and (iii) the calculation of recycling rates on a statistical basis. The different components of the vehicle after shredding are categorised through the parameters of particle size distribution, mineral composition, the degree of liberation after shredding, and to the major mineral present. Together they constitute the input, i.e. the mineral/particle size/liberation class distribution matrix. The defined intermediate fluxes are described in the model for each of the different materials or ‘minerals’ as a normalised discrete distribution of particle size (p = 1-5) and release class (with all possible binary, ternary, etc. combinations of materials in a particle), for each stage of the recycling mass flow in Figure 24 **Errore. L'origine riferimento non è stata trovata.**shown.

Mineral class	Particle size class	Liberation class						
		L11	L12	L13	L21	L22	L23	L31
A	p1	0.003	0.003	0.003	0.006	0.003	0.003	0.009
A	p2	0.0015	0.0015	0.0015	0.006	0.0045	0.003	0.012
A	p3	0.00001	0.00001	0.00001	0.004	0.003	0.002	0.011
A	p4	0.00001	0.00001	0.00001	0.001	0.001	0.002	0.006
A	p5	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.01
B	p1	0.003	0.003	0.003	0.006	0.003	0.003	0.009
B	p2	0.0015	0.0015	0.0015	0.006	0.0045	0.003	0.012
B	p3	0.00001	0.00001	0.00001	0.004	0.003	0.002	0.011
B	p4	0.00001	0.00001	0.00001	0.001	0.001	0.002	0.006
B	p5	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.01
...	...	...	...	...	...	...	...	...
L	p1	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
L	p2	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
L	p3	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
L	p4	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
L	p5	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001

Figure 24: Example of mineral/particle size/liberation class distribution matrix $L^{m,p,l}$ for the car after shredding (liberation matrix)

From this classification, three different release classes are defined, representing the degree of release (LC1 represents very impure particles and LC3 represents pure particles, i.e. 100 per cent purity of its principal mineral element). The method also provides a liberation matrix that presents the elemental composition of the unreleased particles, from which the elemental composition of the car can be derived. This matrix describes the elemental composition of the mineral classes for each liberation class. An example of this matrix is shown in Figure 30 reveal the influence of the design, i.e. material design, i.e. material combinations and connection types, on the release behaviour and thus on the maximum achievable recycling quality (intermediate) products. Moreover, these figures illustrate the necessity as well as the complexity of describing the liberation behaviour and capturing the composition of the liberation classes in relation to product design in a fundamental model for the recycling of modern complex consumer goods such as passenger vehicles The data for these matrices (Figure 24 and Figure 25) were obtained from an extensive data collection on crushing and recycling plants.

Mineral	Liberation class	Element											
		a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*
A	L11	0.6	0	0	0	0	0	0	0	0	0	0.4	0
A	L12	0.6	0	0	0	0	0	0.4	0	0	0	0	0
A	L13	0.6	0	0	0	0	0	0.2	0	0	0.2	0	0
A	L21	0.8	0	0	0	0	0	0	0	0	0	0.2	0
A	L22	0.8	0	0	0	0	0	0.2	0	0	0	0	0
A	L23	0.8	0	0.1	0	0	0	0.1	0	0	0	0	0
A	L31	1	0	0	0	0	0	0	0	0	0	0	0
B	L11	0	0.6	0	0	0	0	0	0	0	0	0.4	0
B	L12	0	0.6	0	0	0	0	0.4	0	0	0	0	0
B	L13	0	0.6	0	0	0	0	0.2	0	0	0.2	0	0
B	L21	0	0.8	0	0	0	0	0	0	0	0	0.2	0
B	L22	0	0.8	0	0	0	0	0.2	0	0	0	0	0
B	L23	0	0.8	0.1	0	0	0	0.1	0	0	0	0	0
B	L31	0	1	0	0	0	0	0	0	0	0	0	0
C	L11	0	0	0.6	0	0	0	0	0	0	0	0.4	0
C	L12	0	0	0.6	0	0	0	0	0	0	0	0	0.4
C	L13	0	0	0.6	0	0	0	0.2	0.2	0	0	0	0
C	L21	0	0	0.8	0	0	0	0	0	0	0	0.2	0
C	L22	0	0	0.8	0	0	0	0	0	0	0		0.2
C	L23	0	0	0.8	0	0	0	0.1	0.1	0	0	0	0
C	L31	0	0	1	0	0	0	0	0	0	0	0	0
D	L11	0	0	0	0.6	0	0	0.4	0	0	0	0	0
D	L12	0	0	0	0.6	0	0	0	0	0	0.4	0	0
D	L13	0	0	0	0.6	0	0	0	0.4	0	0	0	0
D	L21	0	0	0	0.8	0	0	0.2	0	0	0	0	0
D	L22	0	0	0	0.8	0	0	0	0	0	0.2	0	0
D	L23	0	0	0	0.8	0	0	0	0.2	0	0	0	0
D	L31	0	0	0	1	0	0	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	0.7

Figure 25: Example of composition distribution matrix

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CAD must provide the list of materials and parts, their weights, including the joints used to connect the various materials in the different parts of the car. The liberation behaviour of the different joint/connection types has been defined based on heuristic rules, which link each individual joint/connection type to a characteristic liberation behaviour. The material input types, joint types, liberation behaviour types, material combination types and composition types were defined (see Figure 26, Figure 27, and Figure 28).

Elements (k)		Type 1	Type 2	Type 3	Type 4	Type 5
Material input types – composition in (%)						
A	Al cast	8	10	**30**	**25**	8
B	Al wrought	1	1.5	**30**	**25**	1
C	Copper	2	3	1	1	1
D	Glass	3.5	4	3	3	3
E	Mg	0.4	0.7	**5**	**5**	0.5
F	Organics non-plastic	3	4	2	2	**10**
G	PP	6	8	4	4	**50**
H	PVC	2	3	1	1	1
I	Rest	*0.4*	*1.7*	*0.4*	*0.4*	*1.9*
J	Rubber	3.5	4	3.5	3.5	3.5
K	Steel	**70**	**60**	20	30	20
L	Zinc	0.2	0.1	0.1	0.1	0.1
Total		100	100	100	100	100

Figure 26: Composition of the defined material input types

Joint types	Connection/ joint	Liberation characteristic	Liberation behaviour type	Liberation matrix
Type B	Bolting/ riveting	High randomness	High	$L^{m,p,l}$ with high mass in LC3
Type A	Adhesive/ gluing	Low randomness	Low	$L^{m,p,l}$ with high mass in LC1
Type W	Welding	Medium randomness	Medium	$L^{m,p,l}$ with high mass in LC2
Type I	Insertion	Medium randomness	Medium	$L^{m,p,l}$ with high mass in LC2
Type S	Surface (coating/ painting)	Low randomness	Low	$L^{m,p,l}$ with high mass in LC1

Figure 27: Defined joint/connection types with their specific liberation behaviour

Defined material combination types in relation to the composition distribution matrix $C^{m,k,l}$

Material combination types	Characteristics	Output = composition distribution matrix $C^{m,k,l}$
Combination type 2	2 materials connected	Composition matrix type 2
Combination type 2/3	2/3 materials connected	Composition matrix type 2/3
Combination type 3	3 materials connected	Composition matrix type 3

Figure 28: Defined material combination types in relation to the composition distribution matrix

The liberation is then determined by a unique set of parameters that are the combination of the input material type, the liberation type, and the composition distribution type. Together with the composition distribution matrix, they form the input of the recycling optimisation model, which predicts the recycling/recovery rate of the project. Figure 29 gives a summary of the fuzzy variables and their respective membership functions.

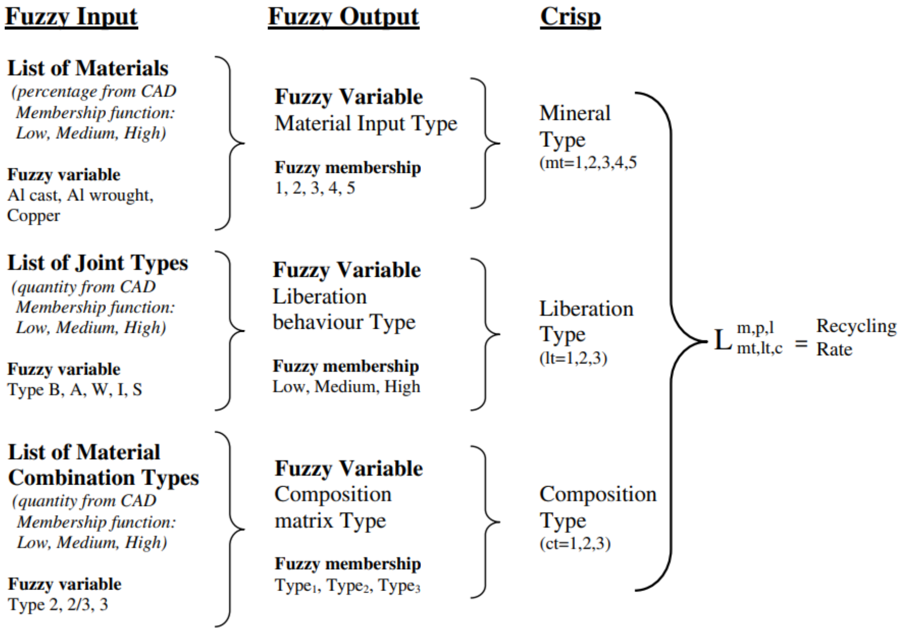

Figure 29 Definition of the fuzzy sets and membership functions for the fuzzy rule-based liberation model

Several fuzzy rule models were defined to transform a series of inputs (materials, joints and material combinations) into different categories, the combination of which determines the composition and degree of particle and flux liberation after shredding:

- Fuzzy rule model 1 – classification of list materials into material input types. Fuzzy rule modelling has been applied to classify any given (future) design expressed as a 'list of materials' as defined in Figure 26.
- Fuzzy rule model 2 – transition of quantity/occurrence of joint types into liberation behaviour types. A fuzzy model has been defined transforming the distribution of the occurrence of the various joint types shown in Figure 26 into corresponding liberation types.
- Fuzzy rule model 3 – transition of occurrence/quantity of material combinations to composition distribution types. A fuzzy rule model has been defined that predicts the composition matrix based on the occurrence and combination of the different material combination types.

These combinations of these tree fuzzy rule models describe the fuzzy rule liberation and permit to estimate the recycling/recovery rate. Therefore, the output of the fuzzy liberation model is a three-dimensional matrix with an index of mt, lt and ct, which provides a corresponding recycling/recovery rate for the fuzzy design input as defined by the fuzzy rule-based models above. Where:

- mt = material input type, result of fuzzy set liberation model 1,
- lt = liberation behaviour type, result of fuzzy set liberation model 2, and
- ct = composition matrix type, result of fuzzy set liberation model 3.

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The proposed fuzzy models can link to recycling simulations and design tools (CAD). Fuzzy rule models predict (on a heuristic basis) release behaviour as a function of material choices, connections and joints defined in the product design, thus predicting recycled quality and recycling rate as a function of unique, design-dependent particle composition and degree of liberation after shredding. This fuzzy approach allows linking fundamental recycling models to environmental life cycle assessment (LCA) tools/software to provide a fundamental and efficient basis for recycling calculations. Fuzzy models provide an efficient and user-friendly fundamental/technological basis for Design for Recycling guidelines, including the influence of material combinations and connections, release, particle size and physical/chemical/thermodynamic process efficiency on the quality of recyclates and the maximum achievable recycling rate.

As an alternative to using fuzzy rule models, the work developed by (Dostatni, 2018) (§2.2.2) can be evaluated, a system based on decentralized Artificial intelligence, or agent-based technology able to provide significant support, especially in indicating suggestions in order to increase guideline satisfaction.
Exploring the functionalities of the agent-based technology, changes need to be made to those described by (Dostatni, 2018) in order to make them suitable for meeting DfD and DfR criteria. The following are the target functionalities we purpose:

1. Analyse the structure of the product;
2. Automatically calculate and update the weight of product components;
3. Calculate statistics and indicators related Design for Disassembly and Design for Recycling guidelines for the component under analysis;
4. Detecting changes in indicators related to the guidelines;
5. Detection and indication of components that are part of non-disassembly joints and are incompatible with each other;
6. Detection and indication of the use of hazardous materials;
7. Generation of numerical lists of materials and types of joints used;
8. Automatic generation of suggestions and recommended changes with a view to disassembly and recycling, aimed at improving the parameters of the designed product;
9. Generation of lists and reports.

It is important to point out that the AI-based system needs to have indicators associated with the guidelines in order to assess their satisfaction, detect any changes in values, and propose improvements. Thanks to the suggestions provided by AI and the designer's experience, a new design can be generated that is improved over the previous one.

Step 4: Comparison amongst the new design and the old one

Through an initial process of identifying the strengths and weaknesses of the old design, followed by defining the optimization and generation actions of a new design a comparison between new and old design needs to be made. Step 4 is useful in order to highlight how the differences between the two designs impact a series of indicators. In case the new design implemented is optimized, the indicators will take on improved values.

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Some possible indicators for comparison are shown below:

- Total Recycling rate (from D3.3);
- Recycling rate of all individual materials (from D3.3);
- Energy recovery (from D3.3);
- Economic performance (from Sustainability tool);
- Social performance (from Sustainability tool);
- Environmental performance (from Sustainability tool).

If necessary, the designer may decide to include other indicators for comparison. Comparing indicator values for new and old design, the designer can identify against which indicators there has been actual improvement and for which further improvement actions are needed.

Describing the redesign decision-making process, as done in §4.1.1, the decision sheet shown below is made. The decision identified is the definition of a product design that promotes disassembly and recycling. The figure identified as the decide-maker is the Designer.
Indeed, it is able, with the support of the supporting tool riported in the Decision card and thanks to the guidelines, to realize a redesign of a product with a simplified structure, with materials that are easily identifiable, accessible and separable and and increase the recycling rate and energy recovery.
As described earlier, Decision card is shown below (Figure 30Figure 30Figure 30Figure 30).

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Decision	Product focus of the decision
Defining product design from a disassembly and recycling perspective	EEE

Supporting tools and technologies	Required input
• Recycling Simulation tool; • Sustainability tool; • Eco-design guidelines; • Methodology for assessing the Level of Circularity Improvement; • Radar chart • AI-based technology.	• Feedback from disassembly and recycling process; • BOM of selected component; • 3D CAD of the selected component; • Mass of each material contained in the component [g]; • Location of the component in the car; • Disassembly route from the car to the product; • Recycling route of the component; • Disassembly time [min]; • Number and type of tools used for disassembly; • Dissassembly cost [€]; • Number and type of toxic materials; • Thermodynamic rarity value of each material [kJ/g]; • Recycling rate; • Energy recovery.

Support from Advisory tool
Collection of feedback from disassembly process. Support in defining weaknesses related to disassembly of old design. Provide suggestions in order to realize a product that facilitates the disassembly and recycling operation. Comparison of old and new design.

Decision-maker	Possible support from AI
Designer	A system based on AI could help identify those responsible for unexceptional performance values and suggest corrective actions based on predetermined criteria.

Environmental indicators	Social indicators
• Environmental performance.	• Social performance.

Economic indicators	Circular indicators
• Economic performance.	• Total Recycling rate; • Recycling rate of all individual materials; • Energy recovery

Figure 30: Eco-design – Decision card

Analyzing the content, the focus of the decision is EEE, Electric and Electronic Equipment. The decision maker through the inputs represented by the feedback and information gathered from the disassembly and recycling process already performed to the old design, thanks to the supporting tools such as Recycling Simulation tool, Sustainability tool etc., through the advisory tool can implement corrective actions for the new design.

The indicators shown are those indicated for comparison between new and old design..

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To clarify the sources of these inputs needed by the advisory tool to activate decision-making moment, a diagram (Figure 31Figure 31) was made. In this diagram there are three type of input, indicated in the legend, which are:input from Disassembly and Recycling decisions, input from AI anche input from supporting tools.

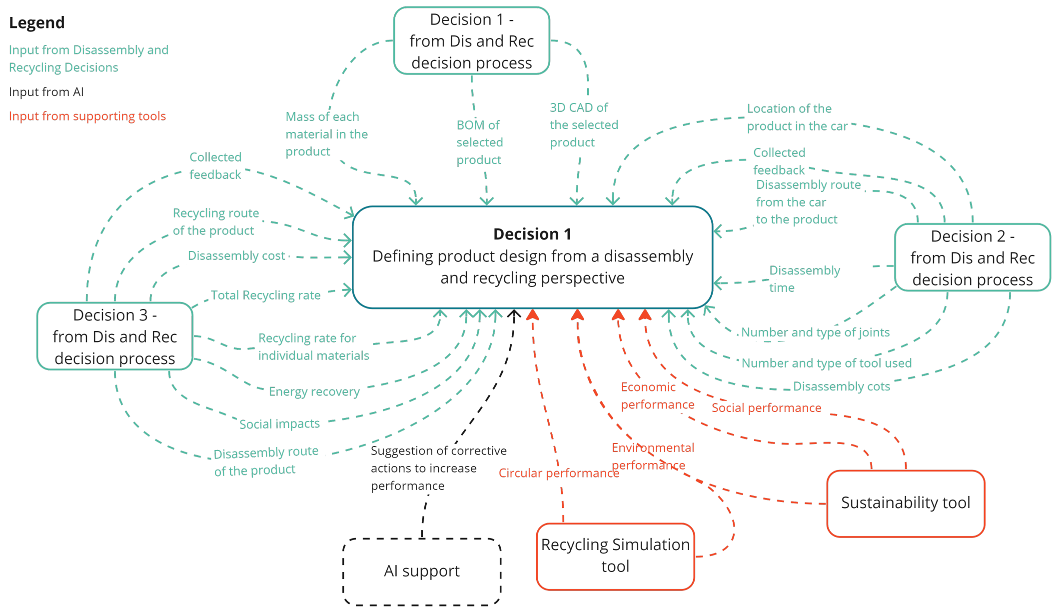

Figure 31: Re-design - information flow of the decision-making moment

4.1.2.2 New design decision process description

When designing a new design, thus a new product/component that does not exist, the process to be followed may be different from re-design. The rationale is that the implementation of a completely new product does not allow the process described above (§4.1.2.1) to be followed because there is no benchmark.

For this reason, the implementation of the new design is expected to follow only a part of the steps described in the re-design process, excluding Steps 1 and 4.
The first step to be followed i.e., "Step 2: Generation of specific eco-design guidelines with the physics and recycling industry-based approach to Design for Recycling " from §4.1.2.1, in the case of the new design remain the same. The only variation concerns the prioritisation phase of the guidelines on which to act, which, as there is no old reference design, cannot be implemented.
The second step, which is the last, from the re-design process: "Step 3: Generation of the new design supported by the advisory", remains unchanged. In that step, an iterative process is followed where the designer applies point changes to the design, he/she is making in order to optimize it.

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4.2. Sustainability Advisory integration into the TREASURE platform

This chapter contains proposed Dashboards to be presented to the decision-makers of the three use-cases to advise them during the decision-making process. These are to be integrated into the TREASURE platform and their formalization and integration will be investigated in detail in D4.9.

For the creation of the dashboards, the decision-making processes described in §4 were analyzed and different Dashboards were created depending on the professional figure identified as the decision-maker. So, for the three decision makers, i.e., car disassembly manager (dismantler), recycling manager (recycler), and designer, their decisions were grouped into a single Dashboard. Consequently, unlike the decision-making process, the use-cases Disassembly and Recycling are not treated together.

In the following sections, the Dashboards related to the 3 modules are given. Two dashboards are made for eco-design depending on whether it is re-design or new design process.

4.2.1 *Advisory tool dashboard for the disassembly module*

This section shows the proposed Advisory tool dashboard related to the Disassembly module (Figure 32). The areas highlighted in red are the areas editable by the decision-maker. Figure 33 shows the pop-ups related to Decision 1 and 2, respectively.

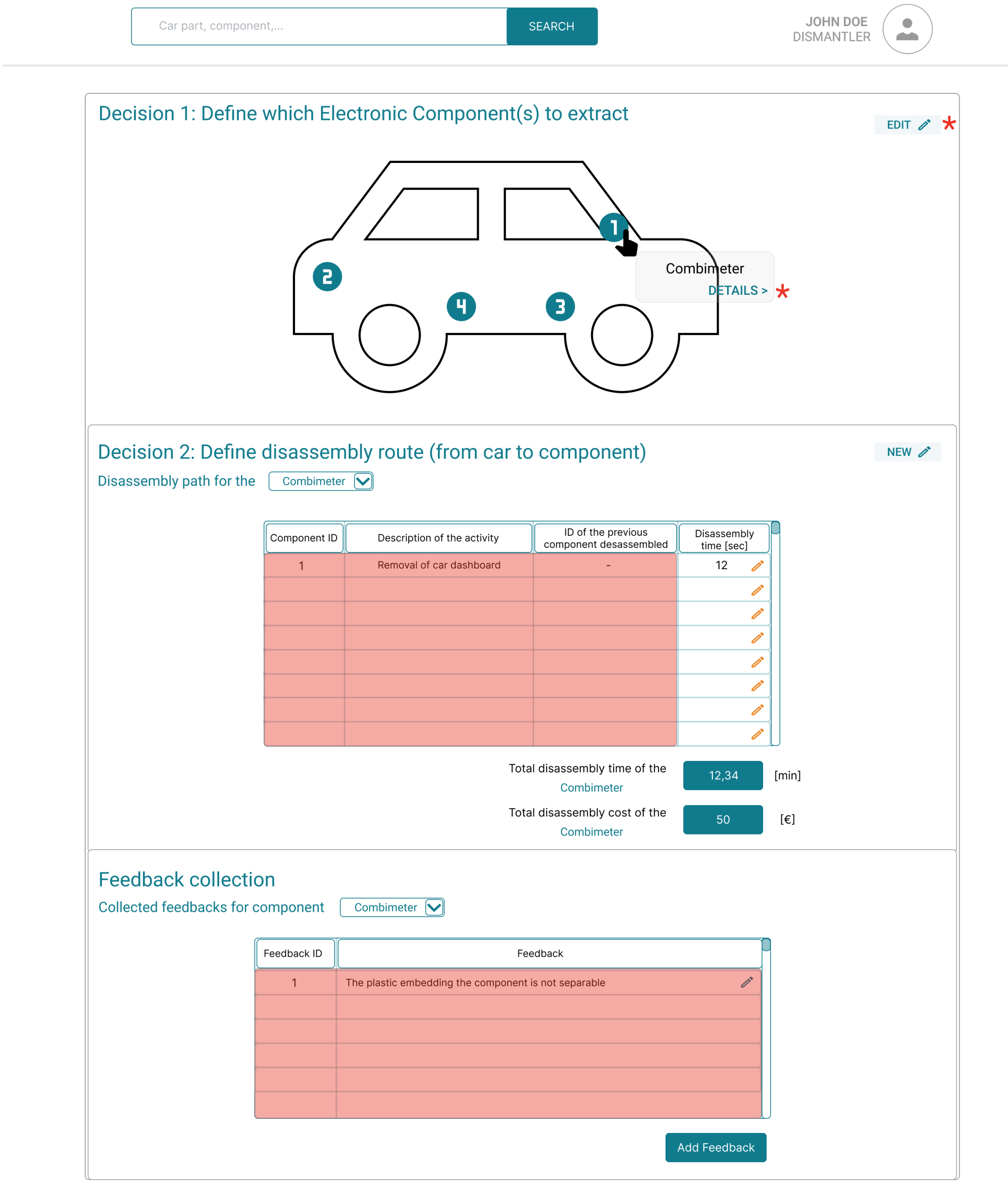

Figure 32: Advisory tool dashboard – Disassembly process

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POP-UP

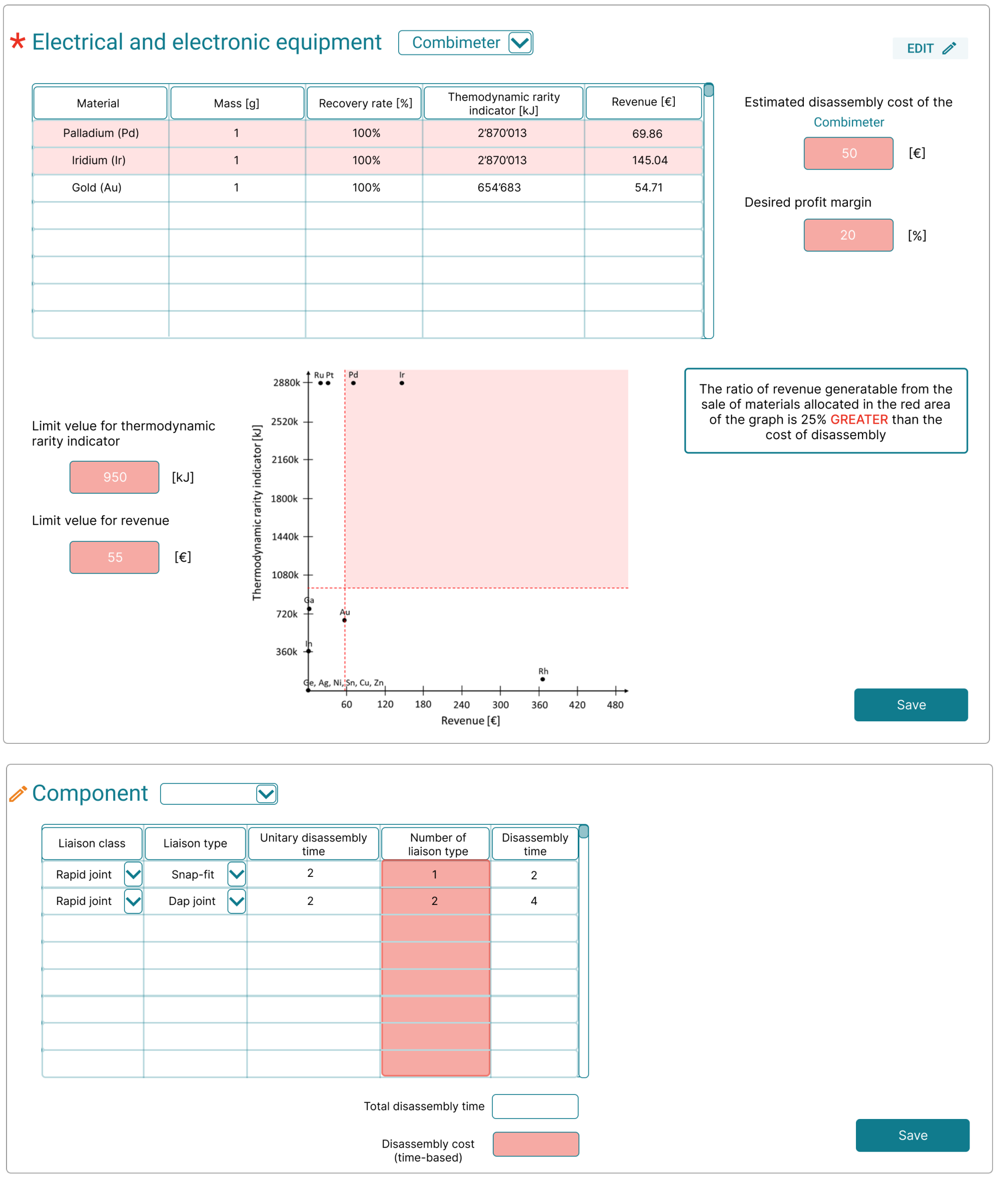

Figure 33: Advisory tool dashboard – Disassembly process (pop-up)

First, it is necessary to identify which component among those contained in the car model under analysis to extract (Figure 33, section "Decision 1: Define which Electronic Component(s) to extract"). Two different scenarios can arise during this decision. In the first scenario, the car model to be disassembled has already been previously analyzed by the Advisory tool and disassembled. In this case, once the decision-maker has selected the car model, a 2D drawing of the car is automatically displayed with the EEEs to be extracted indicated. These are presented already classified, with associated a number representing the priority of extraction from the car. For each classified EEE the decision-maker, approaching the pointer, can crush the "Details" button opening a pop-up containing a table indicating the component's materials, mass [g], Recovery rate [%], Thermodynamic Rarity indicator [kJ] and revenue [€] and, outside the table, the total cost to extract the component from the car. Since this is the case where the component has already been disassembled by another decision-maker, all the data needed to make the ranking will already be filled in. The values contained in the table are unchanged from disassembler to disassembler as they are related to the type of materials contained in the EEE

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under analysis, while the disassembly cost, the desired profit margin and the Thermodynamic rarity value and revenue thresholds may vary. Therefore, freedom is left to the decision-maker to enter the most appropriate values.
In the second scenario, on the other hand, the car under analysis has never undergone the disassembly process supported by the Advisory tool. Therefore, the decision-maker by pressing the "Edit" button opens the pop-up mentioned in the previous scenario and can enter the necessary data to realize the ranking. The disassembly manager, using the drop-down menu provided, selects all the Electronic Components contained in the car one at a time, and the data in the table will be filled in automatically by the tool. For each component, however, he/she must have to enter the disassembly cost. As for the desired profit margin and the limiting values of Thermodynamic rarity value and revenue, these will have to be entered but only once; therefore, once entered for a component they cannot be changed. So, the values cannot vary from one EEE to another, as it would compromise comparability between components. Having performed this operation, the decision maker will be able to view the 2D drawing of the car with the classified components.

Knowing the priority of component extraction, the decision-maker is able to define the disassembly route to be followed (Figure 33, section "Decision 2: Define disassembly route (from car to component)"). Also, during this decision as in the previous one, the tool can provide support. In fact, in case other disassembler(s) have already implemented a disassembly route for that component, when the decision-maker selects the component, the tool is able to propose as a route to follow the one with the best performance (i.e., lowest disassembly cost) among those already implemented.
At this point the decision-maker has the option of following the recommended path or making a new one. In case he wants to make a new one, the disassembly manager by pressing the button "New" can fill in a table indicating: description of the task, predecessor and disassembly time for each component to be extracted before reaching the one of interest.
Since this is a decision process, the disassembly time must be estimated. In fact, pressing the "pen" icon in the "Disassembly time" column of the Decision 2 table, opens a pop-up where the decision-maker enters: liaison class, liaison type, and the number of liaison type. In addition, the disassembly manager must enter the disassembly cost based on time. So, for each component to be extracted before arriving at the desired component, the time-based disassembly cost is estimated, which varies depending on the number and type of joints to be removed.
Once the new disassembly path is realized, it is the tool that will make a comparison and define which is the best path to follow.
In the last section of the Dashboard the opportunity is left for the decision maker to enter feedback, recording any critical issues encountered.

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4.2.2 *Advisory tool dashboard for recycling module*

The following is the proposed Advisory tool dashboard related to the Recycling module (Figure 34). The sections highlighted in red are the sections editable by the decision-maker.
Figure 35 shows the pop-up related to the table in Decision 3.

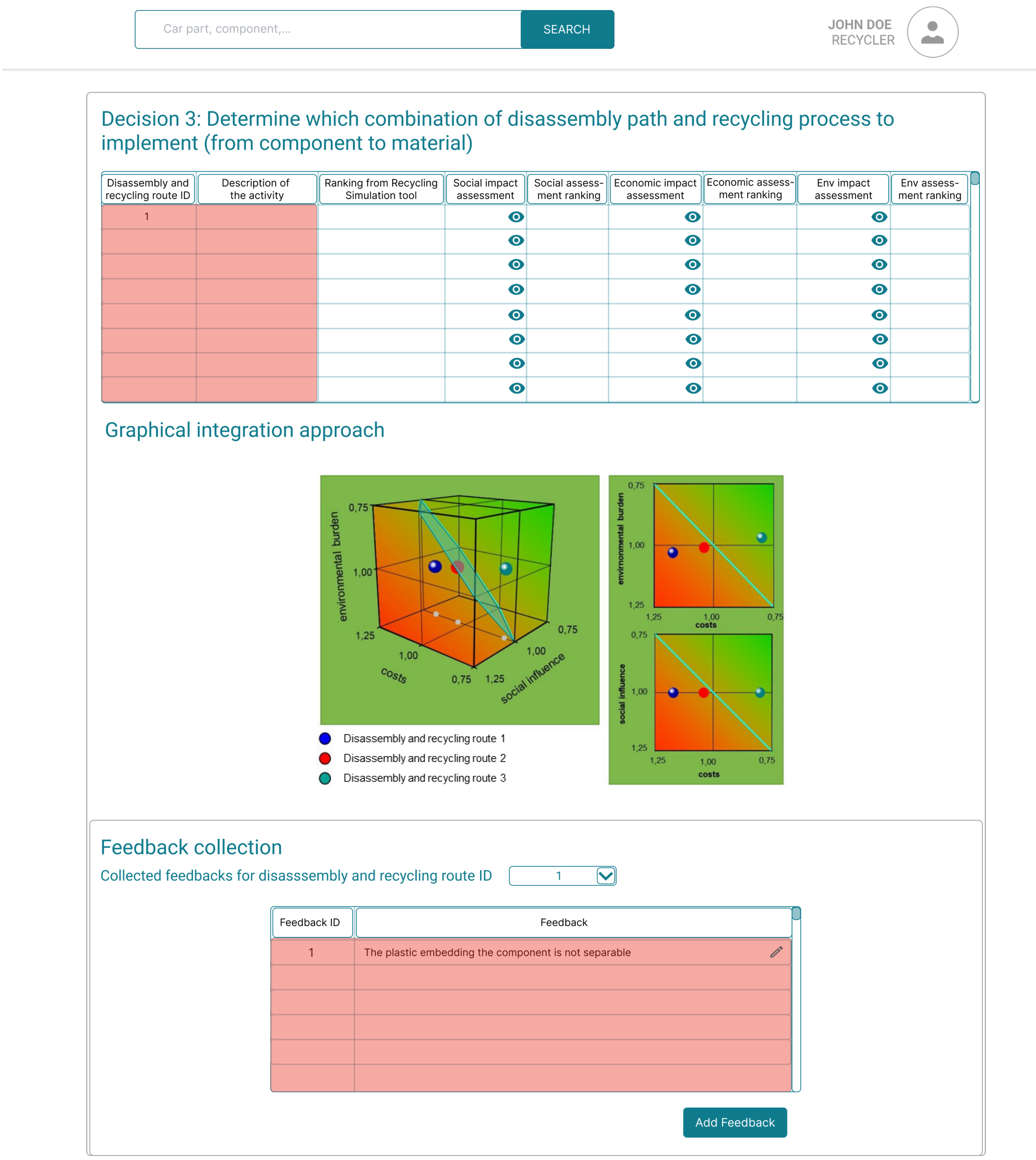

Figure 34: Advisory tool dashboard – Recycling process

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POP-UP

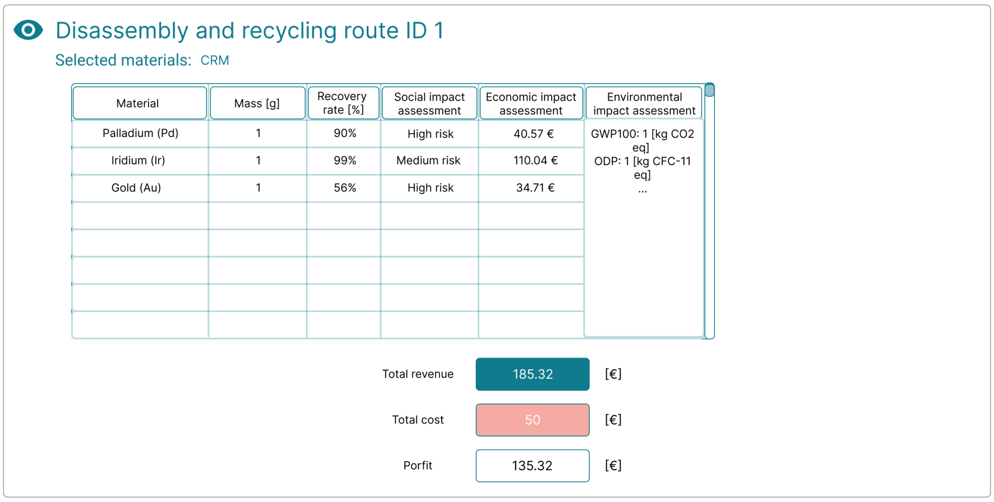

Figure 35: Advisory tool dashboard – Recycling process (pop-up)

In order to determine which combination of disassembly path and recycling process to implement, a ranking of the various combinations in all areas of sustainability is made (Figure 35, section "Decision 3: Determine which combination of disassembly path and recycling process to implement (from component to material)"). With the support of the Recycling Simulation tool, the decision-maker simulates a number of pathway combinations, and a ranking is generated based on maximizing the percentage of material recovered. In the dashboard, in addition to this ranking, 3 others are made according to social, environmental and economic impacts. The decision-maker can examine the detail of the impacts generated in the different areas by each combination by pressing in the Decision 3 table the "eye" icon *t*hat opens a pop-up. The pop-up shows a table containing all the materials selected to be extracted, the*ir* mass, the recovery rate of each material calculated by the Recycling Simulation tool, the social impact of each material derived from the PSILCA database, the economic assessment obtained by subtracting the costs incurred for the entire process, which must be entered by the decision-maker, from the sum of the revenues that can be generated from the sale of the individual materials, and finally the environmental impact of the entire route.
The recycler has the option of selecting the best route according to one aspect of sustainability or considering all of them. In case he/she wants to consider all areas of sustainability, a graph is provided that can represent the impacts generated in all areas.

In the last section of the Dashboard, the opportunity is left for the decision-maker to enter feedback, recording critical issues encountered.

4.2.3 Advisory tool dashboard for eco-design module

This section describes the proposed dashboard related to the advisory provided to the Eco-design module. The first is the dashboard that enables the decision-making process related to the re-design of a product already analyzed by the Advisory tool during the Disassembly and Recycling processes, the second concerning the design of a new product. Both are developed according to the decision-making process described in §4.1.2.

Advisory tool dashboard – Re-design process

The following is the proposed Advisory tool dashboard related to the re-design process (Figure 36). The sections highlighted in red are the sections editable by the decision-maker.
Figure 37 shows the pop-up related to the step 2.

Figure 36: Advisory tool dashboard – Re-design process

* POP-UP

Eco-design guideline	Associated feedback	Margin of improvement (MI)	Relevance (R)	Level of Circularity Improvement

Figure 37: Advisory tool dashboard – Re-design process (pop-up)

In order to carry out the process of re-designing a product, it is necessary for the designer, as the decision maker, to define which EEE to subject to optimization in terms of sustainability. The product may be chosen based on the competitive needs of the company/organization or based on feedback gathered from disassembly and recycling processes.

Once the EEE is chosen, the Advisory tool allows the decision-maker to view the 2D drawing of the component with the feedback gathered from the disassembly and recycling processes indicated. The feedbacks are reported in the component drawing by means of "danger signs" that, in case the designer approaches with the pointer, display a message containing the feedback.

To realize product re-design, the designer may also need data, other than feedback, collected during the disassembly and recycling processes. For this, two buttons indicated as "Go to Disassembly" and "Go to Recycling" are introduced, which refer the decision-maker to the Advisory interfaces of the two processes, enabling him to find information such as disassembly time, tools used, etc.

Knowing the critical issues of old design, in accordance with step 2 of the decision-making process, the designer must determine the eco-design guidelines.

The guideline generation phase remains a process below the advisory tool as it requires the support of numerous tools. Therefore, once defined, via an "Edit" button, the designer is sent back to a pop-up where he or she must enter the guidelines and has the possibility to evaluates the product's compliance to the guidelines according to two criteria: Margin of Improvement (MI) and Relevance (R), which values are multiplied by the tool in order to obtain the Level of Circularity Improvement. From this evaluation, a Radar graph is generated, which allows the designer to identify for which guidelines it is a priority to act.

At this point the designer has to carry out the re-design. To do so, he/she is supported by AI, which is able to provide suggestions to be applied to the old design, depending on the criticality. In addition to AI, the decision maker's skills enable him or her to identify other possible optimizations.

At this stage, through a drop-down menu, the designer can choose for which guideline to show the suggestions provided by the AI or record others made by him/her by pressing the "Edit" button. The designer can choose whether to generate suggestions only for guidelines that, according to Radar graphs, are not satisfied by the old design.

In the last part of the Dashboard, the designer can make a comparison between the old design and the new optimized design. This is done based on the indicators described in step 5 (§4.1.2.1).

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Advisory tool dashboard – New-design process

As indicated in §4.1.2.1, the decision-making process for new design results the same as that developed for re-design, excluding steps 1 and 4. Below is the proposed Advisory tool dashboard related to the new design process (Figure 38). The sections highlighted in red are the sections editable by the decision maker.

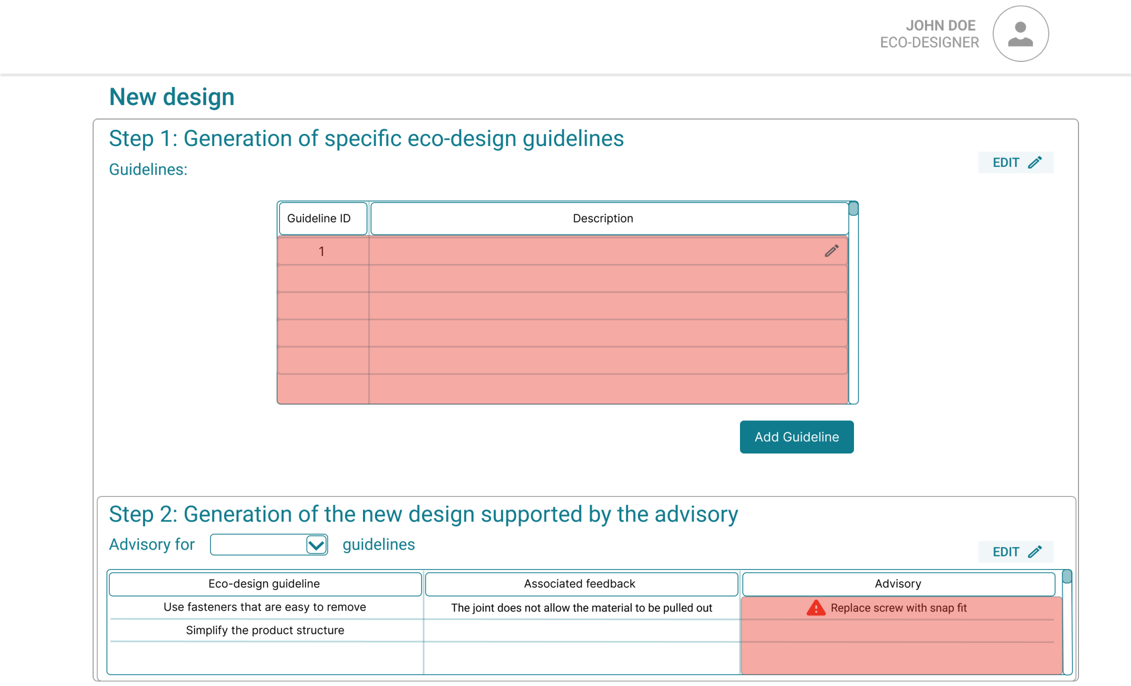

Figure 38: Advisory tool dashboard – New design process

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4.3 Survey design for Advisory Framework validation

In this chapter, a survey model is proposed that can be used in subsequent development tasks (T4.1, T4.5, etc.) to investigate with pilots the sustainability indicators they are interested in and to investigate the need for aggregation. This survey can also be taken up in T3.4, the task which among other things deals with integrating the indicators developed in WP2. Indeed, the analyses conducted in D2.1 identified several sustainability and circularity indicators and aggregation methods relevant to the TREASURE context. Table 16***Errore. L'origine riferimento non è stata trovata.*** contains a set of questions and methods to be used for the subsequent selection of indicators by involving the users of the advisory service. In accordance with the workshop presented in Chapter 3, the possible target groups for this survey are thus:

- **Disassembly:** Depending on the development needs, this survey can be compiled by POLLINI as user of the advisory service, by POLIMI and UNIZAR as technology providers and by SEAT as collaborator.
- **Recycling:** Based on development needs, this survey can be compiled by ILLSA as advisory user, by UNIVAQ as technology providers and by TXT, SEAT and MARAS as collaborators.
- **Eco-Design:** Depending on development needs, this survey can be filled out by Walter Pack and EuroLCDs as advisory users, by TNO as technology provider and by SEAT as collaborators.

Table 16: Survey to investigate advisory indicators and aggregation requirements with pilots.

General questions for pilot and
Selection of output information
1. Given the following indicator categories lists (divided by environmental and social areas), which of these could be of interest to you and to be shown as output information? If no common consensus is reached and selection or prioritization are needed to answer this question, the Analytical Hierarchy Process (AHP) can be employed. The method is described in D2.1 and an example of its use is given under this table. Indicator categories list. **Environmental Indicators (source PEF)**: • **Climate change**: capacity of a greenhouse gas to influence radiative forcing; • **Ozone depletion**: it accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substance; • **Eco-toxicity for aquatic fresh water:** it addresses the toxic impacts on an ecosystem which damage individual species and change the structure and function of the ecosystem; • **Human toxicity – cancer effects**: it accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to cancer**;** • **Human toxicity – non-cancer effects**: it accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation or penetration related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionizing radiation;

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- **Particulate Matter/Respiratory Inorganics**: it accounts for the adverse health effects on human health caused by emissions of Particulate Matter (PM) and its precursors;
- **Ionizing Radiation – human health effects**: it accounts for the adverse health effects on human health caused by radioactive releases;
- **Photochemical Ozone formation**: it accounts for the formation of ozone at the ground level of the troposphere;
- **Acidification**: it measures the impacts due to acidifying substances in the environment;
- **Eutrophication – terrestrial & aquatic**: is measured directly by analyzing nutrients, or indirectly by analyzing processes that are caused by or are related to nutrient inputs such as algal growth, dissolved oxygen and water transparency.
- **Resource Depletion – water & mineral**: it addresses use of natural resources, either renewable or non-renewable, biotic or abiotic;
- **Land Transformation**: it considers the extent of changes in land properties and the area affected;
- **Nuclear waste** (PV panel case): it covers the releases of radioactive substances from nuclear (and partly other) facilities and mines during their operation.

Social Indicators categories (Source UNEP):

*These **indicator categories** are related to the stakeholders one wants to safeguard (Workers, Value Chain Actors, society, Consumers, Local Community, and Children).*

Worker

- Fair salary
- Working hours per employee
- Equal opportunities / discrimination (gender balance)
- Health and Safety (accidents at workplace, air and water pollution, safety measures, violations of mandatory standards, assessment of consumers health and safety)
- Social benefits, legal issues
- Freedom of Association and Collective Bargaining

Value chain actors

- Fair competition
- Corruption
- Promoting social responsibility

Society

- Public Commitment to Sustainability Issues
- Contribution to Economic Development
- Poverty alleviation
- Corruption
- Technology Development

Consumer

- Health and safety
- Feedback Mechanism
- Consumer Privacy
- Transparency
- End-of-Life Responsability

Local Community

- Delocalization and Migration
- Community Engagement
- Cultural Heritage
- Respect of Indigenous Rights
- Local Employment
- Access to Immaterial Resources
- Access to Material Resources
- Safe and Healthy Living Conditions
- Secure Living Conditions
- GHG Footprints
- Environmental Footprints
- Labor Footprints

Children

- Education provided in the local community
- Health issues for children as consumers
- Children concerns regarding marketing practices

Please, insert your answer here

Environmental, please indicate the selected indicators.

Social, please indicate the selected indicators.

2. In relation to the economic part, do you think that the use of financial indicators (such as those listed below) are useful for your decision-making process? If yes, which ones would you select and why?

- **Net Profit Margin** (NPM): measures how much net income or profit is generated as a percentage of revenue;
- **Return of Sale** (ROS): evaluates a company's operational efficiency;
- **Return On Investment** (ROI): to evaluate the efficiency or profitability of an investment or to compare the efficiency of a number of different investments;
- **Net Present Value** (NPV): represent the difference between today's value of the expected cash flows and today's value of invested cash;
- **Payback time (PT):** determine how long it takes to recover the initial costs associated with an investment.

Please, insert your answer here

3. In relation to the economic part, do you think that the use of externalities analysis (definition below) is useful for your decision-making process? Why?

Externalities analysis definition: *events that are effects of the anthropic activities in the ecosystem, thus on the natural (i.e., environment) system out of the analysed system boundaries. These include costs such as future waste management cost, emission controls cost or environmental taxes and/or subsidies. E.g.: Eco-costs of global warming = 0.116 €/kg CO2 equivalent.*

Please, insert your answer here

4. Considering each single area of sustainability, and the related indicators you have selected in Question 3, would you prefer to see the value of each indicator, an aggregated result, or a combination of these options?

E.g. on the environmental area: *- Single values: GWP = 3.5 eq. kg CO2 – Acidification = 0.023 eq. kg SO2…* *- Aggregated result (built via normalization and weighting of the environmental indicators selected) : Impact Indicator = 0.33 points* *- Combination of the previous options: GWP = 3.5 eq. kg CO2 – Impact Indicator = 0.33 points*
Please, insert your answer here **Environmental**, please indicate the aggregation option for this area. **Economic**, please indicate the aggregation option for this area. **Social**, please indicate the aggregation option for this area.
5. In addition to the aggregation options on the single sustainability area identified in Question 6, are you interested to have a general aggregated indicator that summarized all the three areas of sustainability (and circularity)?
Please, insert your answer here

An example of the use of AHP to answer question 1 in Table 16***Errore. L'origine riferimento non è stata trovata.*** **Errore. L'origine riferimento non è stata trovata.** is given here.

There are many social indicators and due to different needs, such need for automatic calculation, aggregation, calculation of impacts and considering the specific needs of a use case; it may be useful to find a selection compromise or a prioritization method. The AHP can be useful here to guide decisions considering the opinions of all participants. Figure 39 shows an example application in which participants were asked to compare the stakeholders to be safeguarded in order to identify the priority of each stakeholder with a democratic method, as it is inclusive of all participants' opinions. In the example, the Consumers stakeholder was the one that received the most consensus.

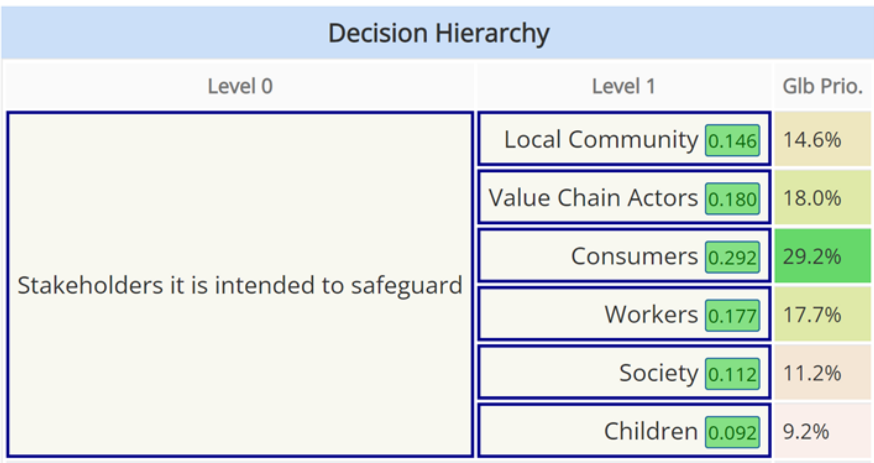

Figure 39: Example of using AHP to prioritise the Stakeholders to be safeguarded.

An AHP was then repeated asking the same participants to evaluate the impact categories associated with the Consumers stakeholder this time. Figure 40 shows the results obtained, from which it can be seen that the Health and Safety category exceeds the others.

Decision Hierarchy

Level 0	Level 1		Glb Prio.
Consumer impact categories	Health and safety	0.302	30.2%
	Feedback mechanism	0.122	12.2%
	Consumer privacy	0.190	19.0%
	Transparency	0.157	15.7%
	End-of-life responsibility	0.228	22.8%

Figure 40: Example of using AHP to prioritise the impact categories associated to the Consumer Stakeholder.

The outcomes of the AHP application just presented were used to select the stakeholder to be safeguarded, and to assign different weights to the impact categories. In practice, once the social indicators associated with each impact category were obtained, it was then possible to redistribute the weights, assigning higher weights to the categories that received more votes in the AHP. In this way, the resulting social assessment turned out to be more representative of the case study under examination.

In TREASURE the AHP could be used for a similar purpose or could also be extended to other areas of sustainability, such as the environmental area. One possible use in this regard could be the selection of environmental indicators presented in question 1 of the survey in **Errore. L'origine riferimento non è stata trovata.**.

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5. Conclusion

For the realisation of the Sustainability and Circularity Advisory methodology, it was first necessary to perform a state-of-the-art analysis. The objective was to create a knowledge base by analysing the methodologies and tools, AI-based and not, developed to support decision-making processes during two phases of a product's life cycle: end-of-life (focusing on disassembly and recycling) and design. For the analysis of end-of-life technologies, focused research was carried out on e-waste, while for the design phase, overall and later more targeted research was conducted.

Focusing on end-of-life, several technologies have been realised, such as the study conducted by (Gundupalli, Hait, et al., 2018), which developed a robotic manipulator is adopted for the automated classification of metallic fractions (MF) and non-metallic fractions (NMF) from e-waste. Another similar example of application exploiting AI to process e-waste is presented by (Tehrani & Karbasi, 2017), which allows to identify and separate different types of e-waste plastics (e-plastics). A further innovative technology developed in the "WEEE ID" (WEEE Identification) project, i.e., an intelligent, automated sorting equipment for used electronics' segregation and grading.

This investigation revealed that existing technologies are focused on the classification and sorting phase of the materials contained in e-waste. Furthermore, the sustainability performance is evaluated only downstream the technical and the functional requirements. A step forward to a global approach is the one adopted by MARAS through HSC Sim software simulation. It allows analysing and processing the chemical composition of the components and subcomponents of products, to calculate recycling and recovery rates from product level till elementary level, optimizing recycling processing flowsheet architectures related to an improved disassembly strategy.

For the design phase, research focused on Sustainability-conscious Design methodologies and tools and Recovery-conscious Design methodologies and tools. Regarding Sustainability-conscious Design methodologies, several tools were identified, divided into analysis tool, comparison tool, and prescription tool. For Recovery-conscious Design (RCD), i.e., design focused on maximizing and optimizing product recoverability, several tools have emerged. An interesting method is the one proposed by (Mathieux, Froelich, et al., 2008), called ReSICLED, which allows the design team to quantitatively assess the recoverability of a product according to a number of different scenarios and different recoverability criteria, such as weight criterion, economic criterion and environmental criterion. Another approach for evaluating and managing the EoL of products at the design stage is developed by (Favi, Germani, et al., 2017). The goal of the design methodology is to improve product sustainability by increasing the percentage of components with a closed life cycle by encouraging reuse, remanufacturing and recycling scenarios through the evaluation of the most convenient EoL scenarios for product components, considering both environmental and economic aspects. The method developed by (Dostatni, 2018), which, by implementing a system based on decentralised artificial intelligence or agent technology, makes it possible to analyse the structure of the product, detect variations in pre-set parameters, highlight those responsible for such variations and/or unacceptable values, suggest changes and signal the use of hazardous materials.

The methods and guidelines described and analysed in the state of the art, however, present rules that are too superficial to handle the DfR of complex products such as automotive products, as they are not based on a physical technological basis that can quantitatively identify recycling problems and take metallurgical processing into account. The design approach for WEEE recycling developed by Van Schaik and Reuter (Schaik, A. van and Reuter, 2013), is quantitative, considers multi-material complexities, and the connections between materials and industrial performance of the complete recycling processes involving disassembly, shredding/liberation, sorting and metallurgical processing. The 10 design rules and guidelines proposed in this method have thus been selected to propose an advisory methodology for DfR. It is also proposed to use the Metal Wheel developed by Reuter and Van Schaik as a quality tool for DfR and to guide the selection of the most suitable recycling processes in view of modular product recycling. Modular recycling through a combination of modular design (reparability-oriented) and disassembly-oriented modular recycling proved to be the most favourable approach to optimise the recycling and recovery of both basic and minor elements/metals from complex WEEE products.

The other methods were not definitively rejected but were considered in the development of a second screening methodology that can be applied by a car manufacturer or a component manufacturer when it is not possible to carry out a simulation.

Before proceeding to the realisation of the methodology, it was necessary to conduct workshops with the project pilots, in order to map the AS IS scenario of each use case, i.e., Disassembly, Recycling and eco-design, to identify critical issues, processes, and decisions to be supported.

One of the main conclusions reached after the workshops on disassembly and recycling was that these two use cases are intrinsically linked and therefore the sustainability and circularity advisory tool should support these two use cases together. The workshop on eco-design also made it possible to highlight the main critical issues and allowed initial ideas for support that this use case can receive from advisory. It also emerged that this use case more than others needs advisory services and that two approaches to decision support are needed, one oriented towards redesign and one towards new design. The analysis of the state of the art, together with the critical issues and the decision-making moments that emerged from the workshops, and the results obtained in T2.1, T3.1, T3.2, T3.3, T4.1, enabled the realization of the advisory methodology.

The Sustainability and Circularity Advisory tool aims to provide advice on sustainability and circularity, using algorithms and metrics needed to provide decision support. The methodology developed consists of 2 distinct decision flows: the decision flow dedicated to disassembly and recycling processes and the decision flow related to design. Disassembly and recycling use are treated together as they are closely related; through optimised disassembly of products, higher recycling rates of individual materials can be achieved.
Regarding the decision flow related to the disassembly and recycling processes, this is sequential, structured in a series of decisions that the decision-makers must carry out accordingly. The first decision, named “Decision 0”, has the objective of identifying which components contained in the car can be extracted to be resold as spare parts.

The professional figure identified as the decision-maker is the car disassembly manager who, with the support of the disassembly operator, will first of all check that all the intended components are present in the car. Next, the decision-maker performs a market analysis by identifying the market value of saleable components and, in accordance with legislation that may restrict the reuse of certain components, identifies which one to extract.

Although it is not a focus decision of the Project, it turns out to be relevant as it allows the practice of reuse to be favoured over recycling as it is more advantageous in terms of sustainability.

Following the decision flow, Decision 1 allows to define which Electronic Components (ECs) are environmentally and economically beneficial to extract from the car. The figure identified as decision-maker is the car disassembly manager who, firstly, must identify the target materials contained in each Electronic Component in the car, thus materials with high rarity value and high economic revenue. To do so, the decision-maker must establish rarity and economic revenue thresholds and the consulting tool will prepare a graph for each Electronic Component by mapping all the materials contained, indicating on the x-axis the economic revenue generated by the sale of materials and on the y-axis the thermodynamic rarity. Next, the decision maker must perform an economic analysis of the previously identified target materials, defining whether their sale is able to cover the costs incurred for extraction and generate a profit. Once a desired profit margin has been defined, a ranking of the analysed electronic components against those that most exceed the desired margin is generated. It will then be up to the decision-maker to define which and how many Electronic Components to select to be extracted and subjected to the following decisions.
Once the Electronic Component to be extracted have been determined, the next step is to define the passages that the disassembly operator must perform to disassemble the car in order to extract the desired EC.

Decision 2 addresses the detailed definition of the most convenient disassembly path for extracting the electronic components selected by Decision 1. The identification of the optimal path and the estimation of disassembly times is obtained with the support of the analytical tool developed by (Mandolini, Favi, et al., 2018b), and with the support of the disassembly operator. The complete list of Decision 2 inputs can be found in Chapter 4.1. An association matrix between components, joining systems, and disassembly time estimates is generated. Dependencies are then calculated, a precedence sequence is proposed, actual disassembly times are calculated, and an estimate of different cost items is made. The decision maker supported by a cost expert now has the necessary elements to define the most convenient car disassembly route to extract the selected electronic component. The format of the output information from Decision 2 are discussed in the dashboard proposals presented in Chapter 4.2. The advisory will keep track of the processed data history to refine estimates of disassembly times, costs, and precedences in future iterations.

Decision 3 identified and supported is taken by the recycling manager and concerns the identification of the disassembly and recycling route to maximise the extraction of the material to be recycled contained in the previously removed component while minimising sustainability impacts. This decision is supported by the MARAS Recycling Simulation tool (developed in the industrial software platform HSC Chemistry Sim® 10), through which the decision-maker reproduces the disassembly, shredding and sorting processes and obtains the energy recovery, exergetic and energy performance, EoI environmental assessment, and recycling rates of metals according to different metallurgical recycling processes. It is necessary to include all modules, materials, component compounds and the recycling goal in the simulation. Subsequently, the simulation generates the Best Available Techniques (BAT) associated with the recycling routes and related plants, suggesting the optimal treatment options. Among the disassembly and recycling options, the semi-automatic PCB disassembly station located at POLIMI's I4.0Lab, and

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the bio-hydrometallurgical recycling process will also be available and evaluated. The simulation generates a graph comparing the recycling routes by evaluating them on three levels of circularity (closed loop CE; open loop CE to be processed into closed loop CE; and open loop CE). Economic and social sustainability assessments will instead be covered by the SUPSI Sustainability tool. The economic impact is calculated by subtracting the total cost of disassembly and recycling from the sum of the estimated revenues from the sale of the recovered materials. The decision-maker makes adjustments to the economic value according to the quality of the material he or she has managed to obtain. The social impacts avoided as a consequence of recycling concern the missed extraction of raw materials and are calculated by the PSILCA database integrated in the SUPSI sustainability platform. Impact categories for stakeholder workers and local communities are assessed, such as job security, water, fossil fuel and mineral extraction. The input indicators for the assessments include the circular and environmental indicators listed in Chapter 4.1 and can be used at the discretion of the decision maker. Other necessary inputs and their respective sources have also been specified. If the decision-maker decides to choose the path that optimises all areas of sustainability, the advisory tool can provide visual support, such as BASF's SEEbalance method (Kolsch, Saling, et al., 2008), which allows visualisation of the performance of different processes in the 3 areas of sustainability using a 3D graphical representation. If the decision maker chooses to consider only one sustainability area as a criterion, a ranking of the paths will be provided. Other format of the output information from Decision 3 are discussed in the dashboard proposals presented in Chapter 4.2. AI can provide support by exploiting the data history and the various iterations by finding similarities with previously analysed recycling routes and making suggestions on the best disassembly and recycling routes.

The advisory in the eco-design supports two different decision-making processes, namely re-design and new design. Re-design is envisaged when a starting design is available and when the old product has already gone through the disassembly and recycling processes, i.e., the stages in which the product has already been analysed by the advisory tool. The first step of re-design is the analysis of the old design by observing feedback from disassemblers and recyclers and looking at the results of disassembly and recycling decisions. In the second step, product-specific guidelines are developed using the approach developed by MARAS, following an iterative process of the simulation tool and the fundamental guidelines (i.e., the first five). Once the guidelines are defined, you go to see how well the old design meets them using the radar chart approach. Weaknesses identified in this way can be taken as a starting point for re-design optimisation. Step 3 involves AI support through which the designer can receive advice for the new design. In step 4, the old design and the new design are compared using circularity and sustainability indicators. The new design does not include step 1 and step 4 as there is no benchmark.

6. Abbreviations

AE	Accumulated Exceedance
AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
BAT	Best Available Technique
BFRs	Brominated Flame Retardants
BoL	Beginning of Life
BOM	Bill Of Materials
CE	Circular Economy
CRM	Critical Raw Material
CTU	Comparative Toxic Unit
DCD	Dismantling-conscious Design
DES	Discrete Event Simulation
DfD	Design for Disassembly
DfR	Design for Recycling
DRCD	Dismantling for Recovery-conscious Design
ECs	Electronic Components
EEE	Electrical and Electronic Equipment
ELSEM	EoL Scenario Evaluation Method
EoL	End of Life
EOL	End Of Life
ERPA	Environmentally Responsible Product Assessment Matrix
HBCD	Hexabromocyclododecane
IMSE	In-Mold Structural Electronics
KETs	Key Enable Technologies
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LCI	Level of Circularity Improvement
LCS&CA	Life Cycle Sustainability & Circularity Assessment
LCS&CAd	Life Cycle Sustainability & Circularity Advisory
LWIR	Long Wave Infrared Range
MFs	Metallic Fractions
MI	Margin of Improvement
MISS	Material Information Sheet System
NMFs	Non-metallic Fractions
NPM	Net Profit Margin
NPV	Net Present Value
ODP	Ozone Depletion Potential
PA/ABS	Polyamide/Acrylonitrile Butadiene Styrene)
PBBs	polybrominated biphenyls
PBDEs	PolyBrominated Diphenyl Ethers
PC/PBT	Polycarbonate/Polybutylene Terephthalate)
PCB	Printed Circuit Board
PCBs	Printed Circuit Boards
PEF	Product Environmental Footprint
PET/PBT	PolyEthylene Terephthalate/PolyButylene Terephthalate
PM	Particulate Matter
POM/ABS	POlyoxyMethylene/Acrylonitrile Butadiene Styrene
PPE/PS	PolyPhenol Ether/PolyStyrene

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PSA	Pressure Sensitive Adhesive
PSILCA	Product Social Impact Life Cycle Assessment
PSILCA	Product Social Impact Life Cycle Assessment
PT	Payback time
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
RCD	Recovery Conscious Design
RCD	Recovery-conscious Design
RI	Recycling Index
ROI	Return Of Investment
ROI	Return On Investment
ROS	Return of Sale
RSCD	Recovery System-conscious Design
RV	Resale Value
RWD	Recycling with disassembly
RWOD	Recycling without disassembly
SCD	Shredding-conscious Design
SEBS	Styrol-Ethylen-Butylen-Styrol
SMD	Surface Mount Device
SVM	Support Vector Machine
TBBPA	Tetrabromobisphenol A
TBS	Technical Building Services
TPE	Thermo Plastic Elastomers
UNEP	United Nations Environment Programme
UNEP	United Nations Environment Programme
WEEE	Waste Electrical Electronic Equipment

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