D2.1: TREASURE methodology definition

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EXECUTIVE SUMMARY

D2.1 “TREASURE methodology definition” is meant to describe the activities carried out within T2.1 “TREASURE assessment methodology definition”, the project task in charge of defining an integrated evaluation methodology that is addressing the three areas of sustainability (i.e., environmental, economic and social) and the circularity one. The investigation performed has a twofold scope. On the one hand, establishing the methodologies and the indicators to be exploited for the impact and benefit assessment of the single areas of sustainability and circularity (chapter 2 and 3 included); on the other hand, investigating a methodology to integrate the single areas and provide a holistic interpretation of the assessment results (chapter 4).

§1 of D2.1 provides an introduction of the issue currently related to the Life Cycle Sustainability & Circularity Assessment (LCS&CA) and provides the scope of this deliverable together with a vision on the relation of the task and deliverable with the other project activities.

After this introduction, §2 focuses on the identification of the sustainability and circularity impact assessment methodologies to be adopted for the evaluation of the performance of TREASURE project’s activities under the triple bottom line perspective complemented with the Circular Economy (CE) vision. The chapter starts with the investigation of the consortium expertise in the development and application of sustainability and circularity assessment methodologies that allows also to identify a common vision on the topic, with indications and shared open points to be deepened, that guided the identification and the analysis of the current state of the art on the most accepted, credible, and suitable methodologies nowadays adopted by experts. Those methodologies have been then investigated by a literature review performed to better characterize and select them. The Life Cycle Sustainability Assessment (LCSA) methodologies proposed to be applied in the TREASURE context are detailed into three separate sections, the first dedicated to the environmental area, the second to the economic one and the last for the social aspects. A separate but complementary discussion on circularity aspects is also provided in a separated section. In each section, after a detailed presentation of the methodologies, reasoning concerning the application in TREASURE are also provided.

Starting from the assessment methodologies analysed in §2, D2.1 §3 is meant to identify and preliminary select the LCS&CA indicators. The identified assessment methodologies propose a large set of indicators to evaluate the Sustainability and Circularity (S&C) performances of a system, covering a wide set of areas of protection, sometimes proposing also different calculation approaches for the same impact area. Similarly to §2, §3 provides in separate sections a description of the most acknowledged and used indicators within both the academic and industrial context together with the related characterization methodologies and, when available, the calculation formulas. In each specific section, the identification of the most suitable indexes to be exploited in the TREASURE context is also performed showcasing the criteria and the reasoning behind the selection process performed.

§4 is eventually dedicated to investigate the available methodologies and procedures to aggregate the indicators within the single S&C areas and to perform an integrated LCS&CA in order to present, when needed, an overall and aggregated vision of the product and process performances for a more efficient and easier decision-making process, addressing at the same time possible communication needs to the different stakeholder involved into the TREASURE ecosystem. This chapter starts with a literature review analysis of the aggregation approaches that could be generally applied both to the single area level and at the overall LCS&CA level.

Normalization and weighting approaches, Multi-Criteria Decision Analysis (MCDA) considered as alternative methods to normalisation, integrated graphical visualisation approaches and aggregation and grouping methods are thus presented. The chapter is then presenting the application of such methodologies into the single S&C domains, always providing a preliminary vision on their application into the TREASURE context. The analysis carried out ends with a dedicated section on the methodology for the aggregation between sustainability domains best fitting the TREASURE project’s peculiarities and objectives. In this regard, responses to a questionnaire circulated among project partners with experience in sustainability have been also considered.

D2.1 is finalized by §5, where conclusions are outlined identifying strength and weakness of the proposed approach with indication of next steps to be performed in other relates tasks within the project. Eventually, §6 provide the list of Abbreviations used, while §7 reports the list of the references cited along the document. Annexes are also provided at the end of the document.

TREASURE

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1. Introduction

D2.1 is the deliverable associated with task T2.1 dealing with the definition of an integrated framework for the LCS&CA in the TREASURE context, where LCSA is defined by the UNEP/SETAC as the "evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle" (Valdivia, Ugaya, et al., 2013).

Sustainability statements and reports are becoming a standard request especially from most conscious customers, forcing an increasing number of companies in including sustainability-related objectives in their strategies (Johnson & Srivastava, 2008). Recently, also Circular Economy claims have been merged with the triple bottom line with the goal to combine increased environmental performances with savings in resource consumption and waste production. The measurement of the sustainability and circularity performances of products and companies has been largely recognized as a focal pre-requisite for the actual translation of sustainability and circularity approaches into operations, towards the implementation of the triple bottom line concept in everyday industrial practices (Bettoni, Corti, et al., 2013). Specifically concerning the TREASURE objectives, the exploitation of indexes is recognized to be an effective support to decision-making (Confalonieri, Barni, et al., 2015; Singh, Murty, et al., 2009), allowing designers, managers and decision makers in general to check the current sustainability performances, fix benchmarks and thus promote product, processes, company and supply chain sustainability enhancement, and understand where to act in order to obtain more effective improvements.

Despite the academic and the industrial contexts are permeated by a huge amount of sustainability and circularity assessment methodologies and indicators, only a handful are able to provide an integrated approach that jointly takes into consideration environmental, economic and social aspects, in a quantitative way, and addressing the whole life cycle of firms, goods or services. Amongst them, the ones based on Life Cycle Thinking (LCT) such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) have been acknowledged as holistic and reliable assessment methodologies even though their actual exploitation for the sustainability and circularity improvement of products meets several barriers due to their high level of complexity, the demand of high-quality/quantity data, considerable monetary and human resources to perform the assessment. Complexity and required workload are even higher when integrating Circular Economy recommendations and possible trade-offs have to be managed. The interpretation of assessment results and their exploitation for decision-making is not straightforward since also within the same area, indicators are covering different area of concern and often the information provided by indicators are conflicting each other. Similar considerations can also be made from the perspective of LCS&CA when several sustainability areas must be assessed simultaneously. LCS&CA is often (practically always) providing a scattered vision on S&C, where the four areas are assessed as single entities since an universally recognised method for performing an integrated LCS&CA does not exist.

In this articulated context, D2.1 is meant to propose a step forward in the identification of the mostly acknowledged and tested assessment methodologies, indicators and aggregation/integration methods available in the LC&CA domain, specifically addressing the decision-making needs to be carried out within the TREASURE project. In this regard, a special attention is also given to the conditions where it makes sense to aggregate or it is recommended to keep the data disaggregated.

1.1. Relation with other activities within the project

D2.1 lays the foundations of the Sustainability and Circularity (S&C) performance assessment within the TREASURE ecosystem.

First of all, a direct linkage between D2.1 and the activities carried out in T2.2 concerning the development of the sustainability and circularity advisory framework could be established. The D2.1 assessment framework provides the basis to allow a quantified evaluation of the sustainability and circularity performances of the components, product and processes analysed in the TREASURE project. The sustainability and circularity indicators identified in T2.1 could be exploited in the evaluation of the different decisions to be taken into the three TREASURE pilots via selected and customized sets of KPIs that could specifically address the advisory needs of the eco-design, disassembly and recycling use cases. In addition to the indexes and the related calculation methodologies, the aggregation and integration approaches presented in D2.1 are also evaluated so that a more effective and easier-to-use advisory is developed, addressing the different needs of the decision makers via various possible aggregation levels of the indicators belonging the single S&C areas or in a transversal way embracing an overall integrated vision of S&C.

An additional primary link of the environmental, economic, social and circularity indicators, the related calculation methodologies and the aggregation and integration approaches identified and presented in D2.1 is with the development of the WP4. Specifically, D2.1 results represent the methodological framework for the development of the Sustainability and Circularity assessment tool to be developed by SUPSI within T4.4 "Design of the eco-design, dismantling and recycling modules" where the LCA/LCC tools developed by SUPSI in previous EU and national funded projects are adapted for the project needs integrating the social and circularity areas and offering the possibility for the indicators aggregation. Since the strong linkage with T2.2 already presented, the D2.1 assessment framework is naturally linked also to T4.5 "Circular (AI-based) advisory tool", where the T2.2 advisory framework is translated into algorithms and a software service. Moreover, the S&C framework puts the basis for the T4.2 "TREASURE data lake development" providing insights on the primary data, from use cases, and secondary data, from environmental and social databases, needed to perform the assessments and then exploited by the AI-based advisory.

Having a strong linkage to the S&C integrated assessment/advisory and the related services, T2.1 results are also indirectly linked to the reconfiguration, testing and optimization tasks of WP5 (T5.2, T5.4 and T5.6) and with the validation activities performed in WP6, with a special focus on those described in T6.4 "Validating circularity performance of pilot plants".

Eventually, D2.1 is also related to Task 8.4 "Standardization activities", providing and retrieving insights on the state of the art about S&C assessment available standards and contributing to the standardization roadmap indicating the need of future standardization activities at European level.

2. TREASURE Sustainability Assessment Methodology

This chapter is meant to describe the activities carried out in T2.1 to define the sustainability and circularity impact assessment methodologies to be adopted as the framework for the evaluation of the performance of TREASURE project's activities under the triple bottom line perspective. Starting from the investigation of the consortium expertise in the study and application of assessment methodologies gained through the partners' past and current research activities (see §2.1), the foundations have been laid down for an agreed vision of the T2.1 activity's development. Indeed, the identification of a set of shared open points/questions to be deepened has guided the analysis of the current state of the art on the most accepted, credible, and suitable methodologies nowadays adopted by experts (see §2.2.1.1, §2.2.2.1, §2.2.3.1). Based on the results of the literature review, the characterization of TREASURE assessment methodologies has been proposed for each area of the sustainability (see §2.2.1.2, §2.2.2.2, §2.2.3.4), with a separate but complementary discussion on circularity aspects (see §2.3).

2.1. Consortium expertise on sustainability assessment

In TREASURE project, sustainability of processes and circularity of materials are the drivers towards the development of a set of successful stories covering three key stages of the automotive value chain. The methodological framework beyond this set cannot help leveraging the commitment and competences of the actors involved in its realization. In turn, as first step in the methodology development path, the expertise on sustainability assessment methods of the various project partners has been explored. The sustainability assessment methodologies that are familiar to UNIZAR, MARAS, POLIMI and SUPSI and are meant to be exploited in TREASURE have been summarised as follows:

- UNIZAR deals with identifying the most critical components of vehicles by performing a thermodynamic rarity analysis. The analysis measures the scarcity of metals used in the components according to the difficulty of extraction and difficulty of refining measured through an indicator called thermodynamic rarity. This indicator catches the criticality of those materials that are currently lost in the recycling processes due to their low percentage in mass, by considering the exergy cost (in GJ) needed for producing those critical material from rock to market as a complementary valuable information (Ortego, Valero, et al., 2018). This assessment is not only useful to identify the most critical components, but also to identify recommendations of eco-design.
- MARAS analyses and processes the chemical composition, the chemistry of the components and subcomponents of car parts, calculates recycling and recovery rates from product level till elementary level, optimizes recycling processing flowsheet architectures related to an improved disassembly strategy, simulates and evaluates 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).
- POLIMI has developed the Circular Economy Performance Assessment (CEPA) methodology (Rocca, Sassanelli, et al., 2021). This method provides a set of KPIs that measures the resources circularity levels and the quantification of their environmental and economic benefits. The circularity level of a product is indeed calculated by considering three different sub-methodologies: the Product Circularity Assessment (CPA), Environmental Circularity Assessment (CEA) and Cost Circularity Assessment (CCA).

- SUPSI expertise in the areas of sustainability concerns the research and application in real industrial use cases of assessment methodologies, such as the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approaches. The evaluation of sustainability performances are performed both at company level, for accounting and reporting purposes through the use of inventory level indicators according to Global Reporting Initiative (GRI) and Organisation Environmental Footprint (OEF) initiatives, and at the product level, for decision-making support purpose through the use of impact indicators retrieved from Product Environmental Footprint (PEF) and Environmental Product Declarations (EPD) (Product Category Rules (PCR)). The application of such methodologies and the related calculation tools that has been developed covers a range of application fields that goes from fashion to furniture up to manufacturing equipment and energy efficiency of production processes in the context of European H2020-founded projects, national funded projects and consultancy activities especially carried out in the Ticino and north Italy regions. The development of circularity assessment frameworks complements the investigation activity on assessment methodologies, providing approaches to practically deal with the transition to circular economy strategies in manufacturing. Concerning the social area of sustainability, a very first investigation of the SLCA approach proposed by UNEP and the PSIA methodology manual has been carried out.

To develop a common, shared, and non-conflicting view and understanding of the assessment approach for TREASURE, a brainstorming session has been held during the task's kick-off meeting to discuss partners' previous experience in sustainability evaluation. Following the discussion, a questionnaire has been circulated among the same partners. Both the recap of the discussion carried out during the kick-off meeting and a version of the questionnaire containing all the answers integrated into a unified consortium view can be found in ANNEX 1. The premise of the discussion, fully supported by the consortium's experts, is that whatever the calculation methods and indicators used in the assessment, a **Life Cycle Approach** should be adopted. Indeed, this approach allows to analyse the sustainability performance of a system (a product, a production process, a supply chain…) considering its entire life cycle and all the potential impacts, enabling the identification of hotspots and possible trade-offs, providing an effective limitation of burden shifts between different stages of the life cycle or impact categories and allowing the comparison of the sustainability performance of two or more systems (Sala, Amadei, et al., 2021).

In order to define TREASURE approach and its boundary, the following discussion topics have been identified, touching the main open issues related both to the assessments of the three areas of sustainability and of circularity separately and to the holistic interpretation of the overall sustainability and circularity assessments:

- *How to allocate impacts along closed-loop lifecycles?* The allocation of the impacts generated/avoided by the End-of-Life operations (e.g., recycling, refurbish, reuse etc. processes) from the first life to the successive ones, concerning the entire product, its components, assemblies and its constituting materials can be performed following a closed-loop or an open-loop approach (Frischknecht, 2010). Which is the best one to be exploited in the TREASURE context?
- *How to perform a life cycle assessment in a circular economy context?* LCA, as well as LCC, has been largely adopted in linear economy cases, but it is not so much sensible on materials savings, recyclability and reusability, material rarity and other aspects related to the availability of natural resources. Are LCA and LCC the best methodology to be

applied in a circular economy context? Are there any alternative methodologies that can complement LCA?

- *How to deal with the third area of sustainability triple bottom line, the social area?* During the workshop the presence on social assessment has been investigated and, in compliance with the other sustainability areas, the SLCA approach has been identified as the more suitable one. However, no one of the partners has previously applied such method to study social impacts and no one knows methodologies, initiatives or example for social assessment already applied in automotive. Also, knowledge on how social indicators can really capture variations at the product level (i.e., are they sensitive to variations in the production processes?) is not available in the consortium.
- *How to manage possible conflicting results of sustainability assessments to support decision-making?* Given the assessments for each field of sustainability and for circularity, a further step will be to generate a holistic interpretation of sustainability and circularity impacts and benefits to feed product-related decision-making throughout their lifecycle in order to address the T2.2 needs. This means to define the most suitable integration method to be adopted so that the assessment results interpretation is comprehensible, engaging and exhaustive.

The above questions have been addressed throughout the activities of T2.1 via a survey and then discussed in a workshop. The main findings are reworked and reported in this deliverable, in §2.2 and §2.3 for the first three issues and Section 4 for the last one.

2.2. The sustainability assessment in the TREASURE context

This section is meant to describe the sustainability evaluation methodologies to be exploited in the TREASURE context. First, an analysis of the state of the art on the main environmental, economic, and social assessment methodologies has been carried out. Then, the assessment approach adopted in TREASURE for each area of the triple bottom line has been delineated, addressing the project objectives as selection and modelling criteria.

2.2.1. Environmental sustainability

2.2.1.1. State of the art on main assessment approaches

According to the proposal, the environmental impacts assessment methodology to be investigated for the adoption in TREASURE is the LCA approach with the Product Environmental Footprint (PEF) initiative developed by the European Commission.

The LCA is an analytical and systematic methodology that assesses the environmental impacts of a product or service, throughout its entire life cycle, and is internationally regulated by the ISO 14040 (ISO, 2006a) series of standards that provides a basic framework for the steps necessary to carry out the assessment.

In the same way, the PEF is a methodology for calculating the overall environmental footprint of products. Its purpose is to provide reliable and comparable product information, and thus to promote a single market in the EU for green goods (JRC, 2012). Indeed, PEF presents the objective of providing detailed technical guidelines on how to conduct a product-specific environmental impact assessment study, ensuring the possibility of objective comparison with other products performing the same function. Compared to other LCA-based standards, in fact, its purpose is to improve the comparability, reproducibility, consistency, relevance, focus and efficiency of PEF studies, in order to enable the establishment of a certified statement of environmental impacts.

Life Cycle Assessment – LCA

LCA is an internationally standardized methodology to assess the potential environmental impacts of product systems, according to ISO 14040/44 (ISO, 2006a) (ISO, 2006b). LCA quantifies potential environmental impacts associated with emissions, waste generation and resource consumption of products along the entire life cycle, i.e. from the extraction of raw materials through production and use to final disposal, including recycling, reuse, and energy recovery (European Commission, 2013). Companies, business associations and policy makers exploit this methodology as a decision-supporting tool to quantify environmental pressures and to find trade-offs and areas for achieving improvement considering the whole life cycle of a product or processes (Guinee, 2002).

According to the ISO 14040 standard, LCA consists of four phases:

- **Goal & Scope definition**: the Goal sets the context, the receivers and the communication strategy for the analysis; the Scope addresses the depth and boundary of the analysis, outlining the Product System, the Functional Unit, the Reference Flow, the System Boundary, the allocation methodologies, the Impact Assessment methodology;
- **Inventory analysis**: Life Cycle Inventory (LCI) analysis is the process of identification and quantification of the flows crossing the system in analysis from and to nature (namely the ecosphere), that is the environmental input and output flows associated with a product or a process. In other words, LCI concerns the creation of an inventory of raw materials, energy requirements, resource uses from the input side and atmospheric emissions, land emissions, water emissions, and other releases from the output side over the lifecycle of a product or process (i.e., the system in analysis). The output of an LCI is indeed a compiled inventory of elementary flows from all the processes in the studied product system.
- **Impact Assessment**: Life Cycle Impact Assessment (LCIA) is the evaluation of the potential environmental and human health impacts resulting from the elementary flows determined in the LCI. According to the ISO 14040 and 14044 standards, a completed LCIA accounts for the following mandatory steps:
  - *Selection of impact categories, category indicators, and characterization models*, namely the selection of the list of environmental issues of concern to which LCI results could be assigned (e.g., Climate Change). In order to provide a quantified evaluation of the impacts, the indicators referring to each impact category that allow measuring the environmental impacts (e.g., Global Warming Potential indicator) are also identified. Eventually, the assessment models describing the relationship between the LCI data and the impacts and effects are established;
  - *Classification of inventory results*. LCI data are assigned to the chosen impact categories considering their known environmental effects. For instance, greenhouse gasses are classified on the impact category Climate Change, while the emission of cadmium into the environment is assigned to the Human Toxicity one;
  - *Characterization*, which quantitatively transforms the LCI results for each elementary flow classified in an impact category into an Impact category indicator, via a Characterization Factors (specific for the elementary flow classified in the impact category). The Characterization Factor is a numerical factor that is scientifically determined and is meant to translate the LCI results into impacts,

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representing the environmental mechanism associated to an elementary flow that have effects and impacts on the impact category.

According to ISO 14040/44, additional optional steps inside the LCIA phase could be triggered depending on the goal and scope of the LCA. These include:

- *Normalization*, which is the calculation of the magnitude of category indicator results relative to reference information;
- *Grouping*, which is the sorting and/or the ranking of the impact categories based on value-choices;
- *Weighting*, which is the conversion and possibly the aggregation of indicator results across impact categories using numerical factors based on value-choices. LCIA data prior to weighting should remain available;
- *Data quality analysis*, which is the application of specific techniques, including gravity, uncertainty and sensitivity analysis, to better understanding the significance and reliability of the LCIA results, and triggering possible revisions envisaged by the iterative nature of LCA.

The above optional LCIA elements, if activated, must follow a fully transparent application, evidenced by a documentation reporting performed methods and calculations, and shall be consistent with the goal and scope of the LCA. If any additional information coming from outside the LCIA framework is exploited (e.g., weights based on value-choices of different stakeholders), the use of such information should be explained and reported. The procedure to obtain aggregated environmental, and more in general sustainable, performance results are deepened in Section 4.

- **Interpretation**: this phase is related to the preparation of the results and their analysis results in order to reach conclusions and recommendations. The aims of interpretation are: checking if conclusions are well supported by data and adopted procedures and if they meet the defined goal and scope; perform a series of verification on data exploited for the calculation, of the assumption and on the results (e.g. sensitivity analysis); promoting eventual reiteration for quality improvement of the results; extracting all the possible information that could be exploited for product improvement (i.e. significant issue analysis); preparing a report for the communication of the results.

EU Product Environmental Footprint – PEF

The European Commission launched in 2013 the Product Environmental Footprint (PEF) method as the recommended assessment method to quantify the environmental impacts of products (goods or services) based on LCA (European Commission, 2013). Precisely in comparison with a traditional LCA, a PEF analysis allows to set the elements of the LCA analysis that rely on the subjectivity of the LCA analyst, ranging from the setting of system boundaries to the selection of suitable indicators, based on the system under analysis. For instance, a PEF analysis requires to set system boundaries in order to evaluate the impacts of the entire life cycle of products from "cradle-to-grave" (European Commission, 2018), or "cradle-to-cradle" in case of circular economy contexts as the one addressed in TREASURE. The aim of the PEF method is indeed to enable the effective reduction of the evaluated environmental impacts taking into account the value chain activities related to the whole lifecycle of the product under analysis. Fundamental step for the achievement of this objective is the modelling of the environmental impacts of the flows of material and energy, and the emissions and waste streams associated with a product throughout the life cycle. A PEF Guide (JRC, 2012) has been developed by the European Commission to provide detailed requirements for the modelling and a rigorous guidance on how to perform and calculate a PEF. Additionally, the PEF initiative is meant to provide a common basis to develop environmental declarations that can be compared, stimulating the rise of a green market, free of greenwashing activities.

According to the Guide, a PEF study consists of five phases that mirror the ISO 14040-44 ones, considering as minor differences the separation of goal and scope into two distinct phases and some changes in the nomenclature:

- **Define the goals of PEF study**, the breadth and depth of the study, addressing in detail the following: the intended application(s), the reason(s) for carrying out the study, the target audience(s), the disclosure or not of a comparative study to the public, the commissioner, the review procedure and requirements (if applicable);
- **Define the scope of PEF study**, the system to be evaluated and the associated analytical specifications, addressing in detail the following: the unit of the analysis (the equivalent of the Functional Unit for LCA), reference flow(s) and system boundaries ("cradle-to-grave" as default approach), the selection of the Environmental Footprint Impact Categories (Hauschild M., 2011) recommended ones as default), the selection of additional environmental information (if needed), all considered assumptions and/or limitations;
- **Create the Resource Use and Emissions Profile**, including the compilation and quantification of the inputs and outputs for a given product system throughout its life cycle. Analogously to LCI, an inventory profile of all material and energy resources, both in inputs and outputs, and emissions into air, water and soil for the product value chain shall be compiled;
- **Conduct the Environmental Footprint Impact Assessment**, to calculate the environmental performance of the product. As well as a traditional LCA study, this phase includes classification and characterization as mandatory steps, and normalization and weighting as optional ones (they are mandatory in the context of PEFCR (European Commission, 2018), as described hereafter);
- **Environmental Footprint Interpretation and Reporting**, ensuring that the performance of the PEF model corresponds to the defined goals and quality requirements; and deriving robust conclusions and recommendations from the analysis. PEF aims to be a transparent, rigorous and robust tool to enable the comparison of environmental impacts with the aim of reducing product's footprint.

The PEF Guide provides instruction also on how to develop product category-specific methodological requirements to be used in Product Environmental Footprint Category Rules (PEFCRs). Indeed, PEFCRs complement the PEF Guide providing more detailed guidelines for making a PEF study for pre-defined product categories that fulfil the same function. PEFCRs are meant to regulate several aspects that are usually left to the LCA practitioner's choice (e.g., the indicators list, the system boundaries…), but that hinder the comparison between studies that are addressing product belonging to a specific product category. During the Environmental Footprint pilot phase in the period 2013-2018, instructions on how to develop a PEFCR have been provided, together with the definition and realization of a set of product-specific rules [available at (European Commission, n.d.)], and communication vehicles (such as labels, environmental product declarations, green claims, websites, infographics, etc.) for spreading information on life cycle environmental performance to different stakeholders have been tested. According to PEFCR Guide, the procedure to create a PEFCR is structured as follows ((European Commission, 2018)):

- **Definition of PEF product category,** outlining the description of the product(s), the function of the product(s), and a description of its technical performance, the use and the EoL stage of the product(s) if known, and the scope of the PEFCRs;
- **Definition of the product "model" based on representative product,** at least one product "model" for each PEFCR as it forms the basis for the modelling of the next phase of PEF screening, outlining bill of materials, system boundary, assumptions on transportation systems, use scenario (if relevant) and EoL scenario;
- **PEF screening,** which is a preliminary identification of the most relevant lifecycle phases, processes, elementary flows, and environmental impact categories for the product, and of the required quality for the data in order to provide a preliminary definition of a benchmark for the product category;
- **Draft PEFCR,** constituting the guiding document to carry out the next step of PEFCR supporting studies**;**
- **PEFCR supporting studies**, which are (at least three) PEF studies conducted on the basis of the draft PEFCR and used to test the pertinence and to check for draft PEFCR implementability before the final PEFCR is released;
- **Confirmation of benchmark(s) and determination of performance classes**, the analysis of the PEF prepared allows to verify selected benchmark and to set environmental performance classes developed on the identified reference**;**
- **Final PEFCR,** the rules are validated and made available to the public**.**

The purpose of the PEFCRs is twofold: PEFCRs aims at converging all the initiatives addressing the increasing demand of methods and tools to rule the development of declarations for products (such as the Product Category Rules (PCRs) based on the ISO 14025 standard (ISO, 2006c)) into a unique set of requirements to simplify the methodological landscape. Moreover, PEFCRs are thought to increase the reproducibility, consistency and relevance of PEF studies (European Commission, 2013), shifting the focus towards those aspects and parameters that matter the most to enable a better comparison of the information on the most relevant environmental impacts for the categories of products that perform the same function. Indeed, for a given product, comparability is only possible if the results are based on the same PEFCRs. A PEF study can be conducted for products for which there is currently no PEFCR but cannot be used to make comparative assertions that are intended to be disclosed to the public. If the intention of the study is to make public claims of superior environmental performance compared to similar products, the rules defined in a PEFCR document should be used.

2.2.1.2. TREASURE environmental assessment methodology

In light of the above and referring to TREASURE project and its ambitions, the following considerations may be addressed. As a first aspect to be considered, TREASURE's purpose is to provide new strategies to assess and improve the circularity of critical materials contained in the electric and electronic components embedded in cars, specifically addressing a set of pre-defined components from SEAT vehicles (see D3.1 "Criticality analysis of selected vehicles" and D3.2 "Disassemblability analysis"). The focus of the activities and, consequently, of the assessment is on the End-of-Life phases (EoL) of disassembly and recycling and on the Begin-of-Life phase (BoL) of design of the lifecycle of those components oriented to their higher circularity performances, while the Middle-of-Life phase has not a primary role in the project and its performances are rather not investigated. Secondly, considering the product category subject of the research, no PEFCR has been developed in the Environmental Footprint pilot phase that specifically sets rules to evaluate the environmental impacts of electric and electronic components. Thus, the approach that will be adopted in the environmental assessment is the traditional LCA methodology with:

- A "cradle-to-cradle" perspective in setting system boundaries, which takes into account the circularity dimension of the analysis and matches the scope of connecting the EoL activities with the BoL ones;
- A focus on BoL and EoL phases as they are considered as the most relevant lifecycle stages for the purpose of the analysis. Especially, the EoL phase will be addressed furtherly by complementing the LCA study with additional methodologies, such as the Exergy analysis and the Recyclability analysis (see §432.3.1), to enhance the relevance of the circularity aspects in TREASURE context. The Bol phase will be addressed by delineating its strong interdependence with the EoL phase, with the aim of highlighting and quantifying the differential impacts created by BoL decisions on the EoL performances;
- A LCI phase that will address all the flows of the products systems with a detail going down to the characterization of the elements, which nowadays is not provided by the LCA studies and supporting tools;
- A LCIA phase whose step of selection of impact categories and related indicators is addressed in §3.1;
- An interpretation of the results that will converge in the realization of a methodological foundation for the Advisory feedbacks (furtherly discussed in D2.2).

Considering the importance of the EoL phase in the TREASURE context, and that LCA has been developed mainly to address linear cases, an additional analysis is provided in the following in order to investigate how circularity aspects, mainly related to recycle could be managed via LCA.

The allocation problem

An additional consideration arises concerning the allocation of the impacts generated and the possible "credits" (i.e., impacts avoided) created by an EoL strategy along multiple life cycles of a product system. There are several ways to consider how the burdens of the materials and the recycling process itself are divided. It is worth noticing that there is no physical division between the two lives so there is no 'right' answer to the question. Different allocations offer different ways of looking at the same system and will provide different insights. Different approaches could be applied depending on the implemented EoL strategy: in the case of the recycling strategy, according to ISO 14040/44, the closed-loop and the open-loop approaches have been identified (ETH, 2015):

- In open loop approach, the recycled materials are used in other products, and the allocation occurs based on either the physical properties (e.g., mass), the economic value (market value of scrap compared to price of primary material), or the number of subsequent uses of the recycled material;
- In the closed-loop approach, the recycled materials are used in identical products or open-loop but without any change in the inherent properties of the materials. The first use of virgin material in applicable open-loop product systems may be treated according to open-loop recycling procedure. The allocation is avoided since recycled materials substitute primary materials. Obviously, this represents the ideal approach, since the metal mixology of products and the state of the art of recycling technologies make it quite complicate to fully put into practice closed-loop recycling.

The current ISO standards ISO 14040/44 do not provide specific guidance on the allocation issue in general and its application on reuse and recycling in particular, apart from distinguishing explicitly the situation in which material undergoes changes in inherent properties (quality loss) and the situation in which it does not.

Especially in the LCA application for plastic and metal recycling however, two ISO-compliant approaches for assessing the benefits of recycling are commonly used:

- The **Recycled Content approach**, or *cut-off method*, implying that the recycling environmental burdens are attributed to the product that sends the material to recycling, no matter which kind of material is constituting it. The impacts are allocated as follows:
    - The virgin material production is allocated to the product using the virgin material;
    - The environmental impacts of extraction, beneficiation and refining of primary material are attributed to the first use of that material product;
    - The environmental impacts of collection, beneficiation and refining of scrap are attributed to the second use of the material.

  This method gives incentives to use recycled material, as long as the recycling has less environmental impact than the virgin materials production. In the recycled content approach, no credits are granted. Figure 1 shows a representation of the EoL allocation Recycled Content approach.

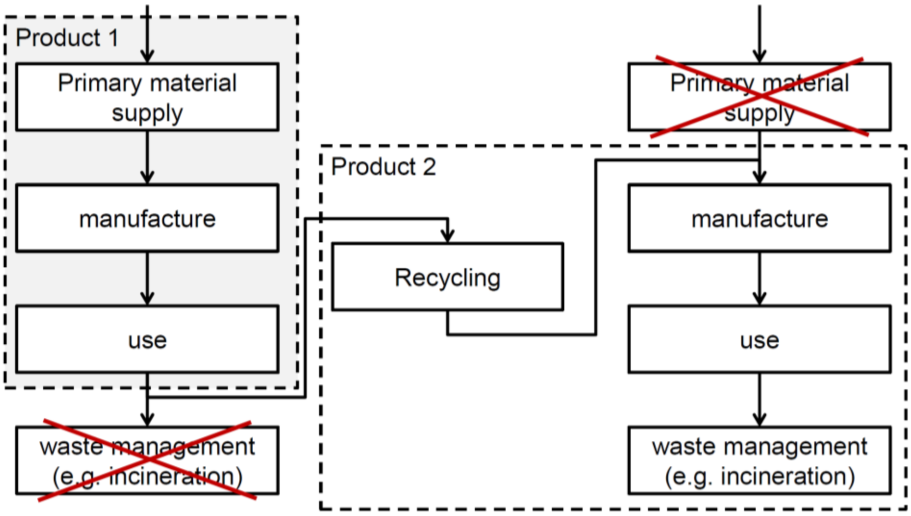

Figure 1. EoL allocation – Recycled Content approach

- The **End-of-Life Recycling approach**, or *avoided burden approach*, implying that the environmental credits generated by recycling are assigned to the product that use the recycled material. The impacts and credits are allocated as follows:
    - The environmental impacts of the avoided primary material production are credited to the product that sends the material to recycling;
    - The material input to the product under analysis always bears the environmental impacts of primary material production; irrespective of the specific origin of input material (whether primary or recycled).

The avoided burden approach encourages recycling at EoL but does little to encourage the reuse of recycled products or materials. The End-of-Life Recycling approach claims to be ISO-compliant because ISO 14044 prefers system expansion to allocation. The clauses on allocation procedures for reuse and recycling, however, do not mention system expansion explicitly. Figure 2 shows a representation of the EoL allocation Recycled approach, and Figure 3 shows a representation of the allocation of burdens and credits in End-of-Life Recycling approach.

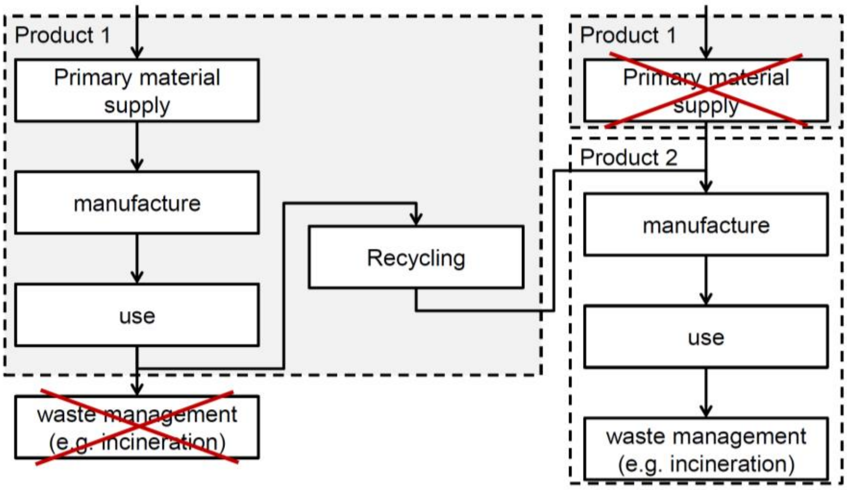

Figure 2. EoL allocation – End-of-Life Recycling approach

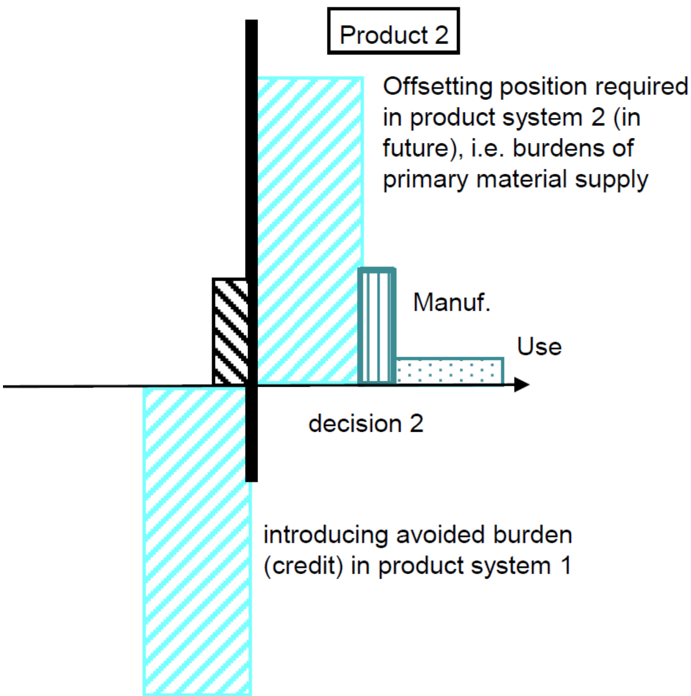

Figure 3. Allocation of burdens and credits in End-of-Life Recycling approach

Other two approaches for recycling allocation are the one proposed by the European Commission in the context of PEF recommendation and the one proposed in the Environmental Product Declaration Standard EN15804:

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- The **Circular Footprint Formula (CFF)** is recommended by the European Union (Zampori, L., & Pant, 2019a) for dealing with materials and end-of-life allocation problems in LCA, in the context of the PEF initiative. CFF makes it possible to account for the benefits and burdens of recycling processes, energy recovery, and the use of secondary materials, considering the boundaries between the first and second production systems. The CFF is described in detail in §2.3.1 as an approach to assess the level of circularity of a product system.
- The **EN 15804 EPD approach** accounts for allocation based on net output flows of secondary materials. Referring to Figure 4 representing two life cycles of the product system, the net output flow of secondary material is given by the input flow R1 minus the output flow R2. The loads are given by the net output flow multiplied by the environmental impacts of the recycling process, (R2 - R1) * $E_{recyclingEoL}$, and the benefits are given by the net output flow multiplied by the environmental impacts of the extraction, refinement and production of the virgin material, with negative sign, - (R2 - R1) * E_V. The load and benefits however are accounted beyond the system boundary. Thus, the allocation is not mandatory to be declared and if the allocation is performed it has to be reported separately.

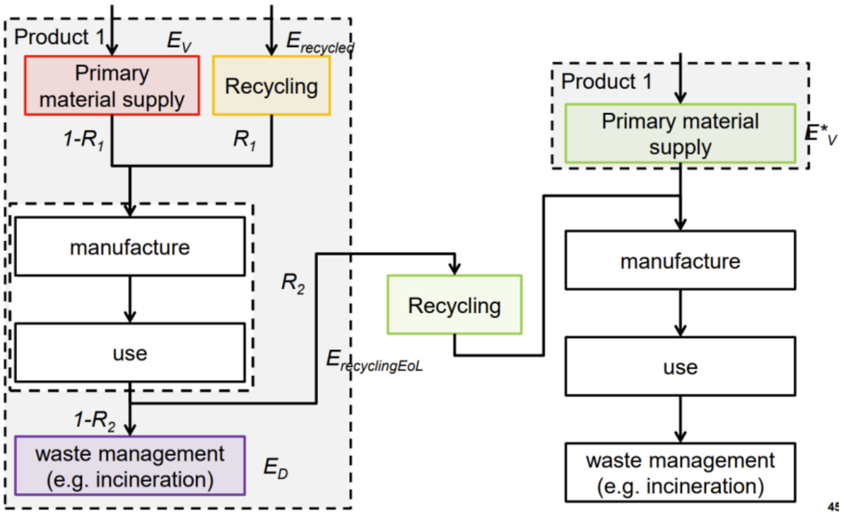

Figure 4. EoL allocation – EN 15804 EPD approach

The approach selection is related to which kind of EoL scenario must be promoted. For instance, metal industry opts for the closed-loop approach since it is meant to promote that the producer is responsible of the product EoL rather than being focalized on purchasing recycled material (currently a quite standard situation concerning metals). In TREASURE, the selected approach for the allocation problem is End-of-life Recycling approach since the focus of the TREASURE activities is on the recyclability of materials at the EoL phase instead of on the use of recycled content in BoL phase. However, the allocation of impacts is a minor issue in the initial phases of the project: indeed, the first point to deal with is to understand the quality of the recycled content and verify in which way this content can be reused as raw material input for a new electronic component in a car.

Environmental sustainability assessment conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section *'Methodologies and indicators selected for the environmental assessment'*.

2.2.2. Economic sustainability

According to the proposal, the economic impacts assessment methodology to be adopted in TREASURE is the Life Cycle Costing (LCC) approach based on the ISO 15686-5 2017 "Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing" (ISO, 2017), which is a norm specifically developed for building sector applications. Indeed, although LCC is the oldest form of evaluation among the sustainability ones, there is no standard ruling univocally the approach regardless the field of application, and several methods have been established (Wulf, Werker, et al., 2019). As a result, no standard definition has been provided in literature. The one adopted in this deliverable is the definition by (Rebitzer & Hunkeler, 2003) that best fits the TREASURE context according to authors*: "an assessment of all costs associated with **the life cycle** of a product that are directly covered by any one or more of **the actors** in the product life cycle, e.g., supplier, producer, user/consumer, EOL-actor, with complimentary inclusion of **the externalities** that are anticipated to be internalized in the decision-relevant future*". Actors and externalities are the main concepts around which the analysis of the state of the art is conducted and discussed in this section.

In addition to the LCC perspective suggested by the project DoA, an investigation on the economic evaluation from the financial point of view has been also carried out so that the economic evaluation is not only focused on the cost aspects. The adoption of financial indicators may be justified for the evaluation of KETs as enablers of the transition to a sustainable and circular approach in the processes of the automotive value chain. In this regard, the assessment of initial investments can be supported by indicators that not only consider the cost dimension, but also the financial sustainability of the case under consideration. Financial indicators could extend the concept of economic sustainability beyond the LCC, compensating for its limitations and criticalities. Since financial indicators are not embedded in a fully-fledged assessment methodology, the list of these indexes is directly reported in §3.2 where the economic indicators are described with no further in-depth analysis in this chapter.

2.2.2.1. State of the art on main Life Cycle Costing (LCC) approaches

The life cycle oriented nature of the LCC methodology has driven its selection both to fit the initial statement of this deliverable, i.e., to adopt a life cycle approach, and both to leverage on the major works from the Society of Environmental Toxicology and Chemistry (SETAC) Europe Working Group on LCC, resulting in (Hunkeler, Lichtenvort, et al., 2008) (Swarr, Hunkeler, et al., 2011) and targeting to an international consensus for a standard that parallels the ISO 14040 standard for LCA. As presented in (Hunkeler, Lichtenvort, et al., 2008), the LCC approach can be adopted according to three different sub-types, conventional LCC (cLCC), environmental LCC (eLCC), and societal LCC (sLCC). Going from cLCC to sLCC, the three sub-types are enlarging their boundaries of analysis, including the sub-type before. Hereafter, the cLCC, eLCC, and sLCC are presented outlining their main differences in terms of costs to be assessed and boundaries of the analysis, perspectives of the stakeholder, and management of externalities:

- **Conventional LCC (cLCC) –** assessment of the costs associated with the life cycle of a products that are directly covered by one actor, typically the manufacturer or eventually the user of the product (Rebitzer & Hunkeler, 2003). The considered costs are only the internal costs covered throughout the life of the product without including the EoL phase if it is not borne by the main actor. Standards from various government bodies, organization, and industry sectors have been developed, including the above-mentioned ISO 15686-5 (ISO, 2017)and the ISO 15663 (ISO, 2021), which address, respectively, the buildings and constructed assets and the sectors of petroleum,

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petrochemical and natural gas industries, the IEC 60300-3-3:2017 “Dependability management - Part 3-3: Application guide - Life cycle costing”, the AS/NZS 4536:1999 “Life cycle costing — An application guide”. However, up to now, there is not a standardized general procedure to conduct cLCC as for LCA. The effort put in this sense by SETAC has resulted into the following sub-types of LCC.

- **Environmental LCC (eLCC) –** assessment of all the costs associated with the life cycle of a product that are directly covered by one or more actors, e.g., suppliers, manufacturers, users or consumers, and/or end-of-life actors, thus enlarging the analysis to multiple stakeholders with respect to cLCC. Again, in comparison to cLCC, the system boundaries are extended to the whole life cycle of the product, assessing also the EoL phase costs. Moreover, the considered costs are the internal costs plus external costs expected to be internalized in the decision relevant future, e.g., costs for CO_2 emissions due to known environmental policies. The term “environmental” LCC underlines the intent of aligning with the environmental LCA. Indeed, the structure of the eLCC follows the structure in phases defined by the ISO 14040-series for LCA. More about the eLCC is addressed in the section below.
- **Societal LCC (sLCC) –** assessment of all costs associated with the life cycle of a product that are covered by the society overall (locally, as well as nationally and internationally), also including governments, whether today or in the long-term future. The sLCC therefore extends the eLCC including a broader range of stakeholders’ perspective and including moreover all external costs, monetarizing all the social and environmental externalities, whether soon to be internalized or not (Hunkeler, Lichtenvort, et al., 2008).

Among the above sub-types of LCC, the eLCC is deepened hereafter hence it constitutes yet a less mature assessment, but a more complete one with respect to cLCC, addressing the whole life cycle of a product, a multiple stakeholder perspective, and a cost structure also involving the environmental externalities. Moreover, the eLCC is consistent with the LCA, which is the environmental assessment methodology adopted in TREASURE, as stated on §2.2.1.2. The sLCC could be even a step ahead cost assessment, but it is not considered as it is not consistent with the LCA and thus not recommended to be used in combination due to risk of double counting the same impacts and of inconsistencies.

Environmental Life Cycle Costing – eLCC

The effort of SETAC, converged in (Hunkeler, Lichtenvort, et al., 2008) (Swarr, Hunkeler, et al., 2011) targeted to the ultimate goal of building consensus for an international LCC standard that parallels the ISO 14040 standard for LCA (Swarr, Hunkeler, et al., 2011). Indeed, their code of practice describes how to adopt the LCC methodology considering the need of having a methodology working alongside with the LCA in the evaluation of impacts on the economic side. This translates into a methodology structure that traces the four phases of LCA one to provide a common ground of analysis and into a costs structure that takes into account the association of costs with the technical stages characterizing the product’s life rather than associated to the time of owning a product, as for example in the Total Cost of Ownership (TCO) methodology, which is ruled by the IEC 60300-3-3: 2017 (IEC, 2017). The methodology structure for eLCC is hereafter described, with the aim of pointing out similarities and differences with the LCA counterpart (see §2.2.1.1):

- **eLCC goal and scope:** due to the comparative nature of eLCC studies and its tied link with LCA, the formulation of goal and scope and functional unit becomes critical in its consistency. Indeed, similarly to LCA, it is crucial to establish a consistent definition of the product system and cut-off criteria that do not conflict with the intended goal and scope of the study. However, it must be taken into account that, considering the costs incurred throughout a life cycle, different actors bear the costs and can have very different perspectives and potentially conflicting goals.
- **eLCC inventory:** the same issues of the LCA counterpart must be faced in developing a consistent data set, which at the same time is not business sensitive, e.g., customized cost models and terminology may have to be reconciled; cost data can be more volatile than physical units; data will need to be restated in a common currency at present value using appropriate exchange and discount rates; allocation issues.
- **eLCC impact assessment:** since the economic inventory data are expressed in the same unit, there is no need for characterization or weighting. However, the aggregation of cost data is not so straightforward, as deepened in §4.4.
- **eLCC interpretation:** the procedures for interpretation, communication, and review are analogous to those for an LCA.

Considering the eLCC goal and scope and the issue of bearing different stakeholder perspectives, it is clear that the outcome of LCC depends strongly on the actor's perspective. Most mature economic approaches (e.g., cLCC, TCO) mainly focus on one specific group of stakeholders, generally the manufacturer or the product user. The multi-stakeholder perspective means facing the challenge of avoiding double-counting issues and of identifying economic metrics that do not overlap with metrics assessing the other sustainability spheres, especially in the integration of the sustainability and circularity framework. Indeed, while LCSA single scores can facilitate a decision-making process to prioritise choices, they come with some limitations in terms of transparency and interpretation by experts, thus creating the necessity to adopt both single and disaggregated indications as complementary information tools. These aspects are discussed for TREASURE case in Section 4.

Considering the inventory phase, the cost structure of an eLCC includes mainly the following cost items, in common with cLCC and called **"internal" costs**: costs related to the research and development activities; cost of materials; cost of energy; cost of labour; cost of waste management; cost of logistic and transport; cost of maintenance and repair, cost of EoL activities. Most of these costs items have to be taken into account during different life cycle phases (e.g., the cost of energy is accounted both in manufacturing and in the use phase). The cost modelling relying on these cost items is described in detail in §3.2. The term "internal" stands for internal with respect to defined system boundaries: indeed, this set of costs is borne directly by the involved stakeholder that is paying for the activities directly related to his business. To this set, the costs classified as "external" ones, following the same reasoning, are added with respect to a cLCC cost structure. The **"external" costs** are the costs that are not accounted for in the system and are not directly borne by a stakeholder, but are related to the externalities, namely to the events that, even if their origin in the production process is not generated in the same context, are effects of the anthropic activities in the ecosystem, thus on the natural (i.e., environment) system out of the analysed system boundaries (Carlos & Mattos, 2022). Those costs come from the monetarization of the environmental externalities and constitute one of the enlarged-scope features of eLCC with respect to cLCC. The external costs include costs such as: future waste management cost, emission controls cost or environmental taxes and/or subsidies. Concerning this latter type of costs, the following sub-chapter describes the challenges related the introduction of the monetized externalities in the assessment framework methodology development.

The externalities' monetarization problem

The monetarization of environmental externalities is a process embraced by experts, but at the same time difficult to be realized (Wulf, Werker, et al., 2019). In eLCC for instance, the externalities that are expected to be internalized in the decision-relevant future comprise real money flows, as well as internal costs, and thus they are included through their monetarization. However, the integration of the monetised environmental externalities projected to be internalized in the cost assessment leads to additional methodological complexity. Indeed, when the externalities are internalized for decision support, they introduce several degrees of uncertainty in the analysis, starting from the extension of the externalities to be considered, coming to their economic quantification. As a first aspect to be considered, the economic assessment should clarify the expression "decision-relevant future", in order to understand which of the environmental externalities must be internalized in monetary terms for decision-making purposes. Second aspect to be consider, eLCC takes into account that most of the costs and environmental impacts are being fixed during the design phase and are used to support decision in a planning (or ex ante) approach (Hunkeler, Lichtenvort, et al., 2008). This results in some case in the unavailability of the information needed to monetize the externalities; for instance, when there is no environmental regulation or measures for existing environmental targets to be achieved (extending the reasoning from company and global scale), there is not a generally approved monetary value to assign to related externalities. There are several approaches and tools for the quantification of externalities for products, such as Ecovalue12, Stepwise2006, LIME3, Ecotax, EVR, EPS, the Environmental Prices Handbook, Trucost and the MMG-Method (Arendt, Bachmann, et al., 2020). According to (Arendt, Bachmann, et al., 2020), the tools are classified following the criteria of: cost perspective (as in (Bachmann, 2019)); included Area of Protection (AoP); use of equity weighting; geographical scope; used discount rate; marginality or non-marginality of the impacts; handling of the uncertainty. From the qualitative and quantitative comparison of the tools, authors claimed that (Arendt, Bachmann, et al., 2020):

- The most influential criterion is the geographical scope: LIME3, Stepwise2006, EPS and Trucost are the only methods whose monetarization factors can be used globally, while the other are European, or even national-specific;
- The equity weighting and the discount rate turn out to be less important. Concerning discounting, the eLCC aims to be compatible with a steady state analysis like the LCA one, and the environmental impacts to be monetized are usually not discounted. As proof, the use of discount rate and of equity weighting turns out to be the least relevant criterion in terms of impact on monetarization results.
- Most methods use the damage costs as cost perspective, whereas the EVR uses abatement costs and Ecotax uses societies' Willing-To-Pay. Exception is made for the impact category of Global Warming, for which most methods use abatement costs;
- Most methods use marginal costs, in line with the usual assessment in LCA, while there is no uniformity with the approaches to handle uncertainty in the different methods.
- The AoPs covered by the study were the resources, human health and ecosystems ones. While for the human health AoP valuing is more developed and different monetarization methods converge to more or less the same results, for the ecosystem is practically the

opposite. Current monetization methods use a wide variety of monetary valuation approaches, leading to a variety of monetary damage values. The goal of the eLCC should be to adopt a coherent method especially concerning the reference region of the method with respect to the region of the case study.

Given that, it has been possible to select the set of the “soon-to-be internalized” externalities (the externalities that generate monetary flows in a time-horizon relevant for decision-making) and to give them a consistent monetary quantification, another main issue is related to the problem of double counting. If from one side, double counting must be avoided in an overall sustainability and circularity assessment framework, from the other one, in each specific analysis the possibility of trade-offs between economic and environmental assessments’ results must be addressed, in order to understand whether it is worth keeping a multiple perspective (i.e., both environmental and economic) on a specific externality, since its relevance in both the sustainability areas justify its twofold inclusion (Horn & Zamagni, 2020).

2.2.2.2. TREASURE economic assessment methodology

In light of what discussed above and referring to TREASURE project and its ambitions, the following considerations may be addressed regarding the economic assessment. The first aspect to be considered actually refers to the final goal of the analysis carried out in T2.1, that is, to delineate a global and coherent sustainability and circularity methodological framework for the assessment of the project activities and for the development of the sustainability and circularity Advisory Tool. To this aim, the consistency and the possibility to have connection points among the assessments of each of the three sustainability areas plus the circularity one are crucial aspects to be taken into account for the selection of an evaluation methodology. Thus, the assessment of the economic sphere is addressed through the eLCC, trying to account not only for the costs generated by the technological processes under analysis, but also for the externalities through the monetarization of the environmental impacts generated by the same technological processes. As confirmed by (Hoogmartens, Van Passel, et al., 2014), eLCC, LCA and sLCA, described in §2.2.3, can act in complementary way to assess the whole sustainability level, without incurring in double counting issue. However, the monetarization process needs to be deepened when coming in practice to the integrated sustainability and circularity assessment view.

The second consideration supports the selection of eLCC and is driven by the application of the eLCC to TREASURE context. In TREASURE applied research activities, the focus is set on the analysis and improvement of technical processes at the BoL (i.e., eco-design methodologies) and EoL (i.e., disassembly and recycling optimized best routes) phases of electric and electronic car components’ life cycle. Hence, the economic assessment must account for multiple stakeholders’ perspectives coincident with the different actors involved in the design, disassembly, and recycling processes and taking a decision-making role in the related life cycle phases. Thus, the economic indicators quantifying the costs incurred on each assessed life cycle phase by each related stakeholder, even if this implies a challenge in the selection of suitable metrics that have to be necessarily customized on the stakeholder, or even on the decision that the stakeholder needs to take leveraging on those metrics. Moreover, considering decisions involving the whole life cycle of a product, an additional challenge is constituted by the interpretation of conflicting results, since the economic impacts could be beneficial for one actor and unfavourable for another one in the value chain. These aspects will be deepened in D2.2.

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Third aspect to be addressed concerns the nature of the economic indicators to be selected. For sure, a cost assessment against the disassemblability rate has to be performed, and cost-driven reasoning has to be made to achieve a trade-off between an optimal recycling route in terms of criticality recovered and in terms of incurred costs, in order to find the best recycling route for each disassembly level. In order to carry out an analysis that allows to take into account the net economic impacts of the investigated activities, the costs must be deducted with the revenues deriving from the recovery of critical materials, and reasoning on financial assessment, eventually on the long term, must be considered. This aspect is discussed in §3.2.

The final consideration is linked to the need to find metrics to evaluate the circularity improvement that TREASURE research aims to provide to automotive sector. The impacts of the EoL phase processes are crucial to be assessed to establish if closing the loop on materials leads actually not only to a circular but also to a sustainable improvement. Being the CE a new economic framework, its interaction with LCC methodology needs to be addressed. In this sense, circularity aspects can be taken into account in the economic assessment in two different ways: either in a separate manner (1) or by focusing specifically on the application of LCC methodology (2). In case (1), circularity aspects are mainly accounted for by different amounts of materials and/or energy consumption depending on the type of the process, but without requiring any change on the LCC approach. Instead, case (2) deals with the application of innovative LCC models that consider the multiple functionalities and extended uses of a product. In literature, a possible alternative approach to LCC, more appropriately fitting the economic evaluation in the circular economy context, is identified in the LCC method for the Circular Economy (CE-LCC) by (Wouterszoon Jansen, van Stijn, et al., 2020), which builds on and extends the Total Life Cycle Costing Model (TLCCM) by (Bradley, Jawahir, et al., 2018). This methodology is hereafter presented.

CE-oriented LCC (CE-LCC)

The CE-oriented LCC (CE-LCC) has been developed by (Wouterszoon Jansen, van Stijn, et al., 2020) based on existing LCC methodologies, adapted to meet the requirements of CE products. Indeed, the CE-LCC leverages on the eLCC methodology as eLCC has been structured and designed to facilitate its use in conjunction with LCA in a multi-criteria assessment and incorporates costs' perspectives of multiple stakeholders. With respect to other models addressing the economic measurements of products facing multiple life cycles, as for instance the TLCCM, the CE-LCC claims to be applicable to complex products on multiple scale levels rather than to products as a singular unit. In fact, the CE-LCC adapts the eLCC methodology with the aim of: i. addressing products as a composite of components and parts with different and multiple use cycles; ii. including processes that take place after the end of use; iii. providing practical and usable information to all stakeholders involved; iv facilitating the alignment of the functional unit and system boundaries with LCA for multi-criteria assessments (Wouterszoon Jansen, van Stijn, et al., 2020).

The model proposes the following. The total cost of a product for each life cycle is structured in layers: it is the sum of the total costs per component, which in turn is given by the sum of the total cost per part. This in order to deal with the possibility to have use cycles with different duration going to one part to another one in the same product.

The total cost is divided in domains according to the stakeholder involved, specifically it is given by the sum of total incurred costs from the manufacturer, from the customer and from the EoL actors. For each stakeholder the costs per parts are calculated including different cost items. For instance, the manufacturer covers the costs related to raw material, material processing, manufacturing, transport and installation. The most relevant feature of this cost model is that it takes into account not only the cost but also the value generated by re-circulating or extending the useful life of the products components/materials.

However, as evidenced in the above section dedicated to eLCC, even if specific stakeholder discount rates are exploited to deal with the differences in goals and perspectives, the sum of costs incurred by different stakeholders is not so straightforward, and the risk is to not correctly address the stakeholders' needs and to consider all stakeholders as their cost-footprint equally increases/decreases.

The other drawback of the CE-LCC method is that it leads to an increment in terms of complexity of the circular product modelling, requiring more data and modelling assumptions. In TREASURE this drawback can be dealt with as the project aims at dealing with high granular data. However, the granularity could be very challenging when it comes to company implementation.

In light of the above, TREASURE project position for the economic frame is to develop the economic assessment in increasing level of complexity, starting from the cLCC cost breakdown structure, which is equivalent to the TCO, trying to enlarge the costs by including the monetarization of the externalities, if the calculation is feasible and the implementation is consistent with the integrative view of sustainability and circularity assessment framework, and allocating costs in a circular economy perspective, considering multiple stages of the life cycles and multiple stakeholders perspectives.

Economic sustainability assessment conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section '*Methodologies and indicators selected for the economic assessment*'.

2.2.3. Social sustainability

This chapter examines one of the three spheres of sustainability, specifically social sustainability.

Social sustainability can be defined as a measure of human well-being, which is not only related to a concern about simple existence, but also to the possibility of having a better lifestyle.

To this end, it is necessary for any entity, especially organizations/businesses (encompassing the entire supply chain) that can differentially influence to achieve the goal of human well-being, to act on socio-cultural issues. Among these, it is important to mention intergenerational equity, which is closely related to environmental sustainability, i.e., using only the natural resources we need at the present time and leaving some for future generations. In addition to the socio-cultural issue mentioned, others arise such as: rising living standards of people who lack shelter, clean water and adequate food to survive, population growth, human health, cultural needs, etc (Abdel-Mohsen O. Mohamed, Evan K. Paleologos, 2021).

But how can organizations/companies understand where to intervene to improve their level of social sustainability? The answer is: by calculating their social impacts in the different social categories (e.g. local employment). They, following a methodological process, can perform a social impacts assessment and derive which are the socio-cultural issues where improvement actions need to be implemented.

In accordance with the objective of Task 2.1 of the TREASURE project, namely the definition of an integrated framework including the social aspect of sustainability, it is necessary to perform an analysis of social impacts assessment methodologies.

In the following, through a state-of-the-art analysis, the main methodologies adopted for the assessment of social impacts and the main supporting databases are presented. Methodologies and databases were examined and then evaluated according to various criteria in order to define which methodology and database is the most suitable in relation to the TREASURE context.

2.2.3.1. State of the art on SLCA

In this section is reported the analysis of the state of the art of the existing methodologies to perform a social life cycle assessment, which are: The United Nations Environmental Programme (UNEP) Social LCA Guidelines (United Nations Environment Programme, 2020), The Handbook on Product Social Impact Assessment (PSIA) (Goedkoop, M. J. ., 2020), Social Footprint (SF) (Bo P. Weidema, 2018) and Life Cycle SDG Assessment (LCSDGA) (Weidema, B., Goedkoop, M., Meijer, E., & Harmens, 2020).

These methodologies, with different approaches, provide insight into the degree of social sustainability achieved in any organization/company, enabling it to understand what strengths it has and what areas need improvement.

In addition, a description of existing databases that support social impact calculations for different stakeholders is provided. The databases that appear most often in the examples in the literature are the Social Hotspots Database (SHDB) (C. B. Norris, Aulisio, et al., 2012), and the Product Social Impact Life Cycle Assessment (PSILCA) (Maister, K., Di Noi, C., Ciroth, A., & Srocka, 2020), which, according to (Ramos Huarachi, Piekarski, et al., 2020), address the SLCA with more effort and can be integrated with SimaPro[2] (for SHDB) and OpenLCA[3] (for both, SHDB and PSILCA). They provide high quality and transparent generic data facilitating the calculation of the indicators present in the methodologies.

The topic of social database is especially important within the TREASURE context where automated calculation of sustainability impacts is required to timely support the decision-making process.

The following is a brief description of all the methodologies and databases just mentioned, in order to understand their structure and characteristics.

Social assessment methodologies

The United Nations Environmental Programme (UNEP) Social LCA Guidelines

The Guidelines for Social Life Cycle Assessment (SLCA) of Products (United Nations Environment Programme, 2020) produced by the Life Cycle Initiative[4] (hosted by UNEP[5]) and the Social LC Alliance[6] provide a roadmap and a flashlight for stakeholders engaging in the assessment of social and socio-economic impacts of products' life cycle, encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling;

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[2] https://simapro.com

[3] https://www.openlca.org

[4] https://www.lifecycleinitiative.org

[5] https://www.unep.org

[6] https://www.social-lca.org

and final disposal. It is developed as an addition to Life Cycle Assessment, in order to include the social aspect of sustainability in the LCA methodology.

Investigating the SLCA approach, the development steps described in the UNEP Guidelines are derived from the ISO 14044[7] framework as: Goal and Scope definition, Life cycle inventory analysis, Life cycle impact assessment, and Interpretation. During the development of these methodological steps, stakeholders play a key role because organizations, directly or indirectly, influence what happens to them, making proactive management of the social impacts on the stakeholders crucial. For this reason, the identification and management of social impacts, both positive and negative, is carried out on stakeholder categories which are: Workers, Local Communities, Value Chain Actors (e.g. suppliers), Consumers, Children and Society.

Linked to the stakeholder categories, the impact subcategories, such us Human Rights, Working Conditions, Cultural Heritage, and Socio-economic repercussions, etc., comprise socially significant themes or attributes. These subcategories are assessed using impact indicators, which are calculated using data from the product life cycle inventory.

Focusing on the impact assessment, two are the main families of possible impact assessment approaches that can be selected considering the aim of the study. The two approaches are:

- Reference Scale Assessment (formerly Type I or RS SLCIA), where impact indicators can be benchmarked to provide social hotspots or social performance results, and
- Impact Pathway Assessment (formerly Type II or IP SLCIA), where consequential social impacts are assessed through characterizing the cause-effect chain.

Once the data has been collected and the impacts have been assessed, the interpretation phase, which is the final phase, is performed where the results of the SLCA are checked and discussed, forming a basis for conclusions, recommendations, and decision-making in accordance with the Goal and Scope definition.

The Handbook on Product Social Impact Assessment (PSIA)
The Handbook for Product Social Impact Assessment (PSIA) (Goedkoop, M. J. ., 2020) developed by the Roundtable Members (Social sustainability decision-making body of the Social Value Initiative, composed of figures such as: Global competence leader life-cycle assessment, Director Sustainability Methods, Senior Manager Sustainability and Environmental, social, and governance (ESG) Fuji Europe Africa, etc.) describes a consensus-based methodology to assess positive and negative social impacts of products and services on four stakeholder groups: Workers, Local Communities, Small-scale Entrepreneurs and Users. The PSIA methodology focuses on assessing social impacts of individual products and services rather than the impact of a company as a whole and has strong links with the environmental Life-Cycle Assessment (LCA) methodology.

Exploring the PSIA methodology, all the steps are structured around the ISO 14040 standard (ISO, 2006a) for environmental LCA, with the aim of reaching the level of completeness and reliability.

After a preparation phase where the context is defined, the Goal and Scope phase and an additional, non-compulsory phase concerning the Circular Economy follow. At this point, it is

[7] https://www.iso.org/standard/38498.html

essential to understand which stakeholder has the most significant negative or positive impacts through a hotspot identification phase.

Once the hotspots have been identified, an evaluation phase is performed, assessing performance through indicators and positioning the stakeholder according to a scale of reference, and a final phase of interpreting the results.

Social Footprint (SF)

The quantitative social valuation approach proposed by (Bo P. Weidema, 2018), namely the Social Footprint, aims to monetize social impacts through a common monetary unit for each social impact. In this way, social impacts can be aggregated.

The method aims to assess the social footprints of products by collecting input and output data on processes with high value-added or high labour hours. By focusing only on macro-processes, this method is non-production-specific, and does not require a huge amount of data or detailed descriptions of impact pathways. Since it does not go into the details of the company's production processes, the impacts considered using this approach are primarily related to income redistribution and productivity impacts of missing governance. The results are expressed in QALYs (Quality Adjusted Life Years), so it is possible to measure the change on a given population group. The two principles behind this method are:

- Non-production-specific impacts, represent most social and economic impacts and any intervention that changes the amount of QALY for a population group will always give a greater change in welfare than an intervention of the same monetary value that only affects the level of consumption of the same population group.
- The current difference in productivity per hour of work between countries, given by the sum of externalities that reduce productivity. This sum can be used to monetize the results expressed in QALY.

This approach is a key component of the Life Cycle Sustainable Development Goals (SDG) Assessment, but it’s not necessarily compliant with UNEP.

Life Cycle Sustainable Development Goals (SDG) Assessment (LCSDGA)

In 2015, UN member states drafted the 17 Sustainable Development Goals (SDGs) (Weidema, B., Goedkoop, M., Meijer, E., & Harmens, 2020), related to 169 targets[8] and more than 200 indicators to guide governments towards sustainable development in 2030. However, SDGs represent an important reference not only for governments but also for companies which can use LCA to assess environmental and social impact at the product level, using LCA-based metrics for the SDGs. Through the LCSDGA methodology, companies can link the SDGs to environmental and social LCA, bringing out two situations:

1. Companies that want to understand which products and impact categories contribute to which SDGs by cleaning up their current LCA procedures and results.
2. Companies that want to move beyond the current LCA indicators and towards a more complete integration of SDG indicators.

In order to meet the two different needs, two different methodologies have been developed: Life Cycle SDG screening (LCSS), which is useful in the first case because it can link companies LCA results to SDG targets in a qualitative way, and Life Cycle SDG assessment (LCSA), which is

[8] https://sdgs.un.org

useful in the second case because it allows SDG indicators to be integrated in a qualitative and comprehensive way.

The steps of the SDG screening and assessment are similar to those of a regular LCA study (according to the ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b)) as follows: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation.

Social assessment databases

Product Social Impact Life Cycle Assessment database (PSILCA)

The Product Social Impact Life Cycle Assessment database (Maister, K., Di Noi, C., Ciroth, A., & Srocka, 2020), is an innovative database for social LCA developed by GreenDelta[9]. It includes comprehensive generic inventory information for almost 15,000 industries and commodities and is used to calculate and assess the social impact of a product throughout its life cycle and to identify social hotspots.

Based on the Eora multi-regional input/output database[10], PSILCA covers 14,838 sectors for almost 190 countries. For most countries, the industry sectors are specific, i.e., different from one country to another, maximising the available information. Therefore, the total number of sectors per country varies therefore between 26 and 1044, including very detailed sectors as "barber shops" for example.

For roughly one third of the countries, data are provided for about 26 economic sectors (called harmonized sectors, found in all countries) typically for countries for which not much information is available. For the remainder, the number of economic sectors increases.

In order to make the database broadly applicable, PSILCA contains indicators for all stakeholders discussed in literature: workers, local communities, society and value chain actors. The current version of the database covers 69 risk-assessed quantitative and qualitative social indicators relating to 25 social and socio-economic subcategories.

Social Hotspots Database (SHDB)

Social Hotspots Database (SHDB) (C. B. Norris, Aulisio, et al., 2012) is a life cycle inventory database for performing “Social Life Cycle Assessment” (SLCA). It provides access to a renowned Global Input-Output model, transparent and high-quality data as well as state-of-the-art impact assessment methods.

It uses the Global Trade Analysis Project's[11] 140-region and 57-sector Input/output model to enable geographic-specific supply chain modelling. Payment of wages provided by the Global IO model combined with estimates of sector- and country-specific wage rates allows to estimate labour intensity and report results using Life Cycle Attribute Assessment (scope of a product system at risk of or audited for different social risks/issues).The modelling system, used together with social risk level characterizations, allows to express social risks and opportunities relative to each of over 155 different indicators by sector and country.

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[9] https://www.greendelta.com
[10] https://worldmrio.com
[11] https://www.gtap.agecon.purdue.edu/databases/v9/default.asp

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

Thus, the database allows to: model global product and organization supply chains, calculate a product or organization social risks footprint and identify product and organization social hotspots.

2.2.3.2. Methodology selection

Following the state-of-the-art research phase of the methodologies able to calculate the social impact and the supporting databases, it is necessary to determine which of the mentioned methodologies, i.e., UNEP methodology, PSIA, Social Footprint and Life Cycle SDG Assessment, are the most performing and suitable for the TREASURE context.

To this end, four selection criteria have been identified and described below. Those criteria have been developed within the TREASURE context and then compared and validated with those exploited into the ORIENTING project[12] (Horn & Zamagni, 2020), finding an optimal correspondence between the two sets.

- **Completeness.** During the analysis of existing methodologies, it became evident that each of them had a different number of indicators and impact allocation categories (e.g., different number of stakeholders on which the impact is allocated). For this reason, they were evaluated according to the number of indicators provided and the number of impact allocation categories, rewarding those with a greater number. In addition, structural and descriptive completeness of the methodological steps is also considered in the completeness criterion.
- **Presence of supporting material.** Another fundamental point is the number and quality of material provided by the methodologies, which is essential to help the stakeholder understand the methodology clearly. In fact, some methodologies have several explanatory files and various use cases that can clarify doubts and provide calculation examples.
- **If quantitative.** In a TREASURE perspective, an aspect that should not be ignored is the importance of obtaining impact assessment data that are purely quantitative, excluding qualitative factors. The relevance of this evaluation criterion is linked to the nature of the TREASURE platform, which will leverage artificial intelligence to support the choice of product/process alternatives. Therefore, a methodology must include a number of quantitative indicators in order to automate the assessment process.
- **Compatibility with database structure.** The last but not least important criteria is compatibility with the database structure. This aspect, closely linked to the concept of automating the calculation of impacts, is very important since the available databases must be structurally compatible with the methodologies.

Once the selection criteria were defined, each methodology was scored from 0 to 3 following the scale reported in Table 1 below.

Table 1. Methodology selection criteria rating scale

Score	Description
0	The methodology does not meet the criteria
1	The methodology slightly satisfies the criteria
2	The methodology moderately satisfies the criteria
3	The methodology fully satisfies the criteria

[12] https://orienting.eu

At this point, having defined the criteria and the scale of score, the four methodologies reported in §2.2.3.1 have been reanalyzed in order to evaluate them and define the most performing one.

Below, Figure 5 shows a Radar chart representing the score obtained by each methodology for each criterion. Analyzing it, it is possible to see that the methodology with the largest area is the one developed by UNEP, which meets the criteria with the highest scores.

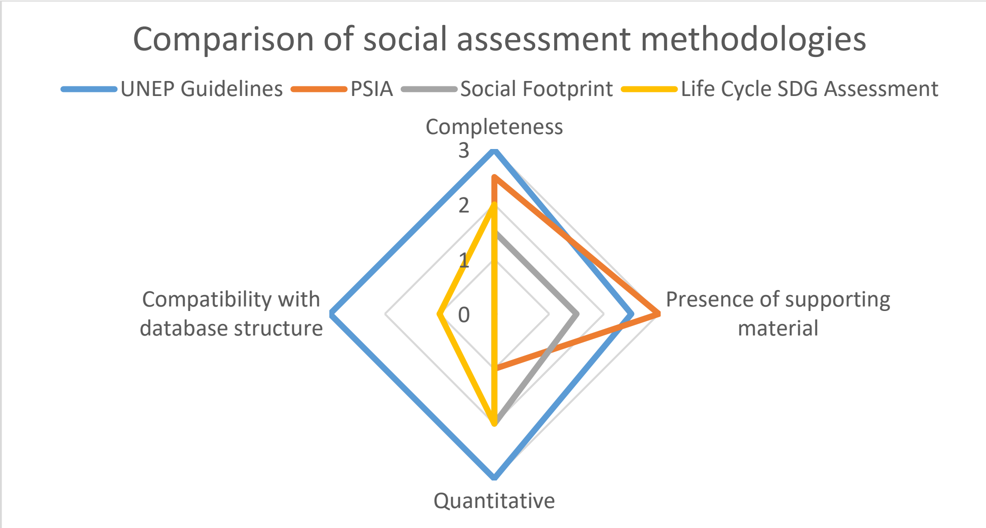

Figure 5. Comparison of social assessment methodologies

By analyzing the scores obtained by the various methodologies from the chart shown here, it is possible to see why the UNEP methodology performs the best.

Starting from the criterion of "Completeness", the UNEP methodology obtained the highest score. In fact, in accordance with the criterion, the UNEP methodology compared to the PSIA methodology has more impact allocation categories (UNEP has six impact allocation categories, while PSIA four) and shows more indicators. Similarly, compared to the Life Cycle SDG Assessment methodology, the number of impact allocation categories correspond but UNEP presents a greater number of indicators, equally compared to the Social Footprint methodology. Moreover, the UNEP methodology is structurally more comprehensive and robust.

Regarding the criterion of "Presence of Supporting Material", the UNEP methodology presents a comprehensive and understandable user guide and a document where it shows all classified social indicators with references to standards, data collection guidelines, and limitations and policy relevance of the topic in question. In addition, several helpful examples of the methodology's application are available in the literature. In fact, it scores higher because the PSIA methodology presents much supporting but qualitatively less material, while the other two methodologies present less supporting and less structured material.

The third criterion, fundamental to the TREASURE project, results in "If quantitative". The UNEP methodology in this case performs the best as it provides quantitative indicators and especially quantitative results aggregation methodologies.

The last criterion, which is also particularly relevant in relation to the project, is the "Compatibility with database structure." In relation to this criterion two methodologies, namely the Life Cycle SDG Assessment methodology and the Social Footprint methodology, receive a score of 0 because they are not compatible with the structures of the two databases explained in §2.2.3.1. As for the PSIA methodology, it has a lower level of compatibility than UNEP.

During the development of the baseline task, a key element emerged to validate the choice to develop the analysis of the methodology developed by UNEP. In particular, a project funded by the European Union, the ORIENTING project (Horn & Zamagni, 2020), has found, which aims to develop a methodology for a comprehensive assessment of the life cycle sustainability of products and services to consider all variables (economic, environmental and social).

Focusing on the social sphere, in the deliverable related to Task 1.3 from WP1 of ORIENTING project (Harmens & Goedkoop, 2021), all social assessment methodologies and related databases derived from the state of the art are analyzed and compared. This analysis has shown that the UNEP methodology meets more than other methodologies, criteria such as: stakeholder acceptance, applicability, transparency, scientific robustness, completeness, and compatibility with life-cycle approach. Therefore, the social assessment methodology chosen is the UNEP methodology detailed in §2.2.3.1.

2.2.3.3. Database selection

Once the methodology to be developed has been selected, it is necessary to carry out a comparison between the databases.

To this end, similarly to what has been done for the selection of methodologies, comparison parameters have been defined as follows:

- **Completeness.** As these are databases, each one presents a different number of indicators, countries, and economic sectors.
- **Presence of supporting material.** During the analysis, the presence of explanatory support material was found to be fundamental. In fact, in order to understand the structure and use of each database, the presence of an informative manual, attached examples and related webinars is a determining criterion.

To carry out the comparison, unlike the case of methodology selection, the two criteria were analyzed quantitatively, mapping the number of indicators, countries present, sectors and related documentation.

Below is shown the table (Table 2) used to compare the two databases.

Table 2. Description of databases according to the comparison parameters

	Completeness			Supporting material	Compatibility with UNEP methodology	Reference year
	Number of indicators	Number of countries	Number of economic sectors			
PSILCA database	69	190	15’000	Web site, database documentation, free webinar, use cases	Same stakeholders as UNEP	Currently 2017
SHDB	155	140	57	Web site	There is not a stakeholder’s approach	Reference year and temporal coverage are not clear

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

Mapping these characteristics, it is possible to observe that the PSILCA database presents a smaller number of indicators, but they are correlated to a greater number of countries and economic sectors.

It is essential to pay particular attention to the number of economic sectors, because if a company that wants to calculate its social impact using a database does not find its economic sector, then it will be excluded from the possibility of calculation.

In addition, with regard to the availability of documentation, PSILCA is much more provided than SHDB, allowing prospective buyers to explore the database, helping them to understand if it is what they were looking for, before investing in its purchase.

Another determining factor, is the compatibility with the methodologies. In fact, having determined as the chosen methodology the UNEP methodology, it results as the PSILCA database presents structural compatibility with it. In fact, both allocate impacts on stakeholders, which is not done by the SHDB database.

Finally, it should be mentioned that with PSILCA it is possible to trace the reference year used for assessments, currently 2017. On the other hand, with SHDB it is not clear which reference year it uses, if any.

Therefore, as a result of these analyses, the most performing database is the PSILCA database.

Following the selection of the best performing methodology and database, social indicators are analyzed in §3.3.

2.2.3.4. Implementation of UNEP methodology in TREASURE

The macro-phases of the UNEP methodology consist of the identification of a Goal & Scope, preparation of an inventory, impact assessment and interpretation of the results. An attempt has been made to explore these steps through the lens of TREASURE, expanding on sub-steps for each of them:

- *Goal & Scope* – in this phase, the goal and scope of the analysis are defined. The Guidelines for SLCA of Products (United Nations Environment Programme, 2020), produced by the Life Cycle Initiative (hosted by UNEP) and the Social LC Alliance, provide the following goal and scope examples:
    - To support sustainable design of products.
    - To support Human Rights Due Diligence of organizations.
    - To identify main social Hotspots of a product and/or organizations.
    - To quantify and qualify the potential social performance of products and/or related impacts, to support sustainable consumption.
    - To examine potential social improvement options along the life cycle.
    - To assess the most relevant stages in the social value chain in terms of social impacts/hotspots (materiality, transparency).
    - To assess and compare, when possible, potential social performance and/or social impacts of product-system.
    - To communicate the potential social performance and/or social impacts of the product to the public.
    - To understand if the product value chain contributes to the social development of its stakeholders.

In TREASURE, the goal and scope will be defined with the project partners through surveys that will be structured in D2.2 and will be circulated among the partners in advance of the development of the advisory tool. These surveys will allow the social dimension of the project to be defined, thus identifying not only the Goal and Scope, but also the stakeholders to be safeguarded associated with it and prioritizing the impact categories to be monitored associated with the stakeholders. Participants in the surveys will be guided by guiding questions such as: What should be the social Goal and Scope to be assessed in TREASURE considering the European context? Who do you want to protect taking into account the Goal and Scope that has just emerged? At what stages of the life cycle are they involved? What are the impact categories associated to be monitored?

- *Inventory* – this phase concerns the creation of the inventory of indicators to be considered, whether from external sources or measured on site. §3.3 deals with describing this phase. The selection of indicators usually follows the results emerging from the Goal and Scope, however it was preferred to identify and classify all of them, as they can be used by the advisory tool and the PSILCA database in the assessment phase according to the need emerging at the time and considering that the Goal and Scope has not yet been defined;
- *Impact assessments* – the assessment phase involves the use of the PSILCA database, with which it will be possible to calculate the social impacts associated with the stakeholders to be protected. Then, according to the project's goal and scope, it will be possible to compare these results with those obtained from the assessment of primary data using the same calculation engine as PSILCA, modifying the parameters by entering real data. More information available in §3.3 and §4.5;
- *Interpretation of the results* - the results will be interpreted in relation to the goal and scope, and who is consulting them. For example, it may be necessary to aggregate the results into a few quantitative indicators or a single qualitative indicator depending on who is to make the decision. More information available in §4.5.

Social sustainability assessment conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section '*Methodologies and indicators selected for the social assessment*'.

2.3. The circularity assessment in the TREASURE context

This section is meant to describe the circularity evaluation methodology to be exploited in the TREASURE context. The Circular Economy (CE) is a key aspect of the project, as the declared fundamental intent of TREASURE is to test innovative methods and technologies to make the automotive sector more circular and go beyond some of the historical limitations characterizing this industry. In order to better understand how CE is addressed by TREASURE, it is possible to start from the definition of CE provided by (Measuring Circularity, 2019). It states that CE is a systems solution framework that addresses global challenges like climate change, biodiversity loss, waste, and pollution, relying on three principles:

1) Elimination of waste and pollution;
2) Circulation of products and materials (at their highest value);
3) Regeneration of nature.

The focus of TREASURE project is mainly set on the second CE principle, which tackle the challenge of keeping products and materials in use as longer as possible, retaining their intrinsic value at the high-quality level. This has also positive effects on the first principle since the recycling of materials contained in automotive electronic components leads to the elimination of wastes that often can also be classified as harmful. There are a number of ways through which products and materials can be kept in circulation, but two fundamental cycles have been identified – the technical cycle and the biological cycle. In the technical cycle, products are reused, repaired, remanufactured, and recycled, while in the biological cycle, biodegradable materials are returned to the earth through processes like composting and anaerobic digestion. TREASURE deals with the technical cycle, and in particular with the recycling process as mean to retain materials in use as long as possible. To verify the improvement in circularity that TREASURE aims to introduce in the automotive sector for the specific processes of disassembly and recycling of electrical and electronic components and considering how the design phase can positively affect the EoL ones, measures of circularity need to be addressed, and a general framework for the circularity analysis must be investigated. Thus, in this chapter an analysis of the state of the art on the main circularity assessment methodologies has been carried out. Then, the assessment approach adopted in TREASURE has been delineated, addressing the project objectives as selection and modelling criteria.

2.3.1. State of the art on main assessment approaches

According to the proposal, the circularity level assessment methodologies to be investigated for the adoption in TREASURE are the Circular Footprint Formula (CFF) approach proposed by the EC in the framework of the PEF projects and the Circular Economy Performance Assessment (CEPA) method proposed by POLIMI in the FENIX project[13]. From the methodological point of view, CFF and CEPA results to be more structured approaches, dealing with different aspects of circularity evaluation, encompassing material, resources and energy issues on a lifecycle perspective.

As can be deduced from the introduction to this section and the analysis and definition of CE taken from Ellen MacArthur Foundation, CE has the aim to find a sustainable way to keep materials and their intrinsic value as long as possible on stage. This has to be done addressing the whole life cycle of a product. In order to find out which features products need to own to be truly circular, it is worth to evaluate the EoL stages of a product or a component and test the

[13] https://www.fenix-project.eu

actual performances (for business, people and the environment) of the technical processes that products and materials need to undergo to retain their functionality. This is performed also considering the expertise already available in this field in TREASURE consortium. In contrast to what have emerged for the other areas of sustainability, literature review shows that only few well acknowledged methodologies structured on a holistic vision of circularity issues and on a lifecycle perspective are indeed available. Most of the time the CE evaluation is performed via single indexes that are evaluating single aspect of the circularity performances.

Considering therefore the recycling phase, two approaches have been investigated as possible measurement frames for its circularity performance. The first approach has been developed in the EF initiative context, where recycling and energy recovery, as well as using secondary materials and energy, have been analysed to understand how to account for their benefits and burdens. With the final aim of providing a guidance able to assure reproducibility and fairness of the environmental analysis, the topic of the EoL allocation (for which an overview is provided in §2.2.2.2) has to be addressed to answer the following:

- Where is the boundary between the first and the second product systems' lives?
- How should benefits and burdens of generating and of using recycled material be shared between the first and the second product systems?
- Since generated secondary materials and energy carriers avoid primary materials and energy carriers being produced: how to select the specific primary material and/or energy that is avoided?
- How to handle down-cycling, i.e., differences in quality between secondary materials or energy and the primary materials or energy?
- How to avoid double counting or gaps of benefits and burdens?

In order to address these issues, the EF, specifically in the context of PEF initiative, presents a method for the allocation called Circular Footprint Formula (CFF).

The second approach has been developed in the context of FENIX H2020 project, which lays down the foundation, methodological and technical, to TREASURE project. In that context, the Circular Economy Performance Assessment (CEPA) has been thought to provide in a single indicator the level of circularity reached by a specific product. The two approaches are described in the following.

Besides the CFF and CEPA methodologies, the thermodynamic criticality analysis (performed by UNIZAR and SEAT) and the recyclability assessment (performed by MARAS, Van Schaik and Reuter (2016)) are also presented as components of the methodological framework since they are related to the consortium expertise on this topic and they are especially addressing the project objectives on circularity assessment.

In addition to those approaches, that indeed include also the description of the related indicators, §3.4 presents a series of supplementary CE indicators that are addressing more specific areas of circularity.

Circular Footprint Formula – CFF

The CFF has been proposed in the context of PEF initiative by the European Commission (Union, 2016). According to the PEFCR guidance (European Commission, 2018), the EoL is a life cycle phase that in general includes the waste of the product in analysis. The current PEF Guide (Recommendation 2013/179/EU) require the use of a formula to model product waste, commonly known as End-of-Life (EoL) formula, but actually after the feedbacks received by some pilots participating to the EF pilot phase and the further experience gathered meanwhile, the Commission re-considered the EoL formula and, together with interested stakeholders, came up with the alternative proposal of "Circular Footprint Formula" (CFF). The CFF allows dealing with materials and end-of-life allocation problems and accounting for the benefits and burdens of recycling processes, energy recovery, and the use of secondary materials, considering the boundaries between the first and second production systems.

The CFF presents a modular formulation composed by three macro-terms, accounting respectively for the material, the energy and the disposal at EoL stage (Wolf, Partl, et al., 2020):

$$CFF = Material + Energy + Disposal \quad \text{(Eq. 2.1)}$$

The three terms of CFF are detailed in the following. The material contribution term is given by:

$$Material = (1 - R_1)E_V + R_1 * \left(AE_{recycled} + (a - A)E_V * \frac{Q_{Sin}}{Q_p}\right) + (1 - A)R_2 * \left(E_{recycling} - E_V^* * \frac{Q_{Sout}}{Q_P}\right) \quad \text{(Eq. 2.2)}$$

Looking inside Eq. 2.2, the material contribution accounts for:

- The LCI data associated to virgin material, $(1 - R_1)E_V$, aiming at quantifying the production burdens, where:
  - R_1 is the proportion of material in the input to the production that has been recycled from a previous system;
  - E_V is the specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.
- The LCI data associated to recycled material, $R_1 * \left(AE_{recycled} + (1 - A)E_V * \frac{Q_{Sin}}{Q_p}\right)$, aiming at quantifying the benefits and burdens related to the recycled material in input, where:
  - A is the allocation factor of burdens and benefits between supplier and user of recycled materials (i.e., between first and second product system or product life);
  - $E_{recycled}$ are the specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled material, including collection, sorting and transportation processes;
  - $\frac{Q_{Sin}}{Q_p}$ is the ratio of quality of the ingoing recycled material over the quality of the primary material;
- The LCI data associated to the material recycling process minus the credit for avoided the production of virgin material, $(1 - A)R_2 * \left(E_{recycling} - E_V^* * \frac{Q_{Sout}}{Q_P}\right)$, aiming at quantifying the benefits and burdens of related to the secondary material in output, where:
  - R_2 is the proportion of the material in the product that will be recycled in a subsequent system, measured at the output of the recycling plant to take into account the inefficiencies in the collection and recycling processes;
  - E_V^* is the specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials;

- $\frac{Q_{Sout}}{Q_P}$ is the ratio of quality of the outgoing recycled material over the quality of the primary material.

The energy contribution term is given by:

$$Energy = (1 - B)R_3 * (E_{ER} - LHV * X_{ER,heat} * E_{SE,heat} - LHV * X_{ER,elec} * E_{SE,elec})$$
(Eq. 2.3)

Looking inside Eq. 2.3, the energy contribution accounts for:

- The LCI data associated to the energy recovery process minus the credit for avoided exploitation of primary energy, where:
  - B is the allocation factor of energy recovery processes. It applies both to burdens and benefits;
  - R_3 is the proportion of the material in the product that is used for energy recovery at EoL;
  - $(E_{ER} - LHV * X_{ER,heat} * E_{SE,heat} - LHV * X_{ER,elec} * E_{SE,elec})$ accounts for the environmental impact of incineration and credits for recovered energy. It is available as combined EF secondary data set, per material, so there is no need to manually calculate, usually.

The disposal term contribution is given by:

$$Disposal = (1 - R_2 - R_3) * E_D \qquad \text{(Eq. 2.4)}$$

Looking inside Eq. 2.4, the disposal contribution accounts for:

- The LCI data associated to the disposal of remaining waste, where:
  - R_3 is the proportion of the material in the product that is used for energy recovery at EoL;
  - E_D is the specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery or other usable product output.

A graphical representation of the material term contribution is provided in Figure 6. In TREASURE this is the most interesting term since energy recovery and disposal have to be minimized.

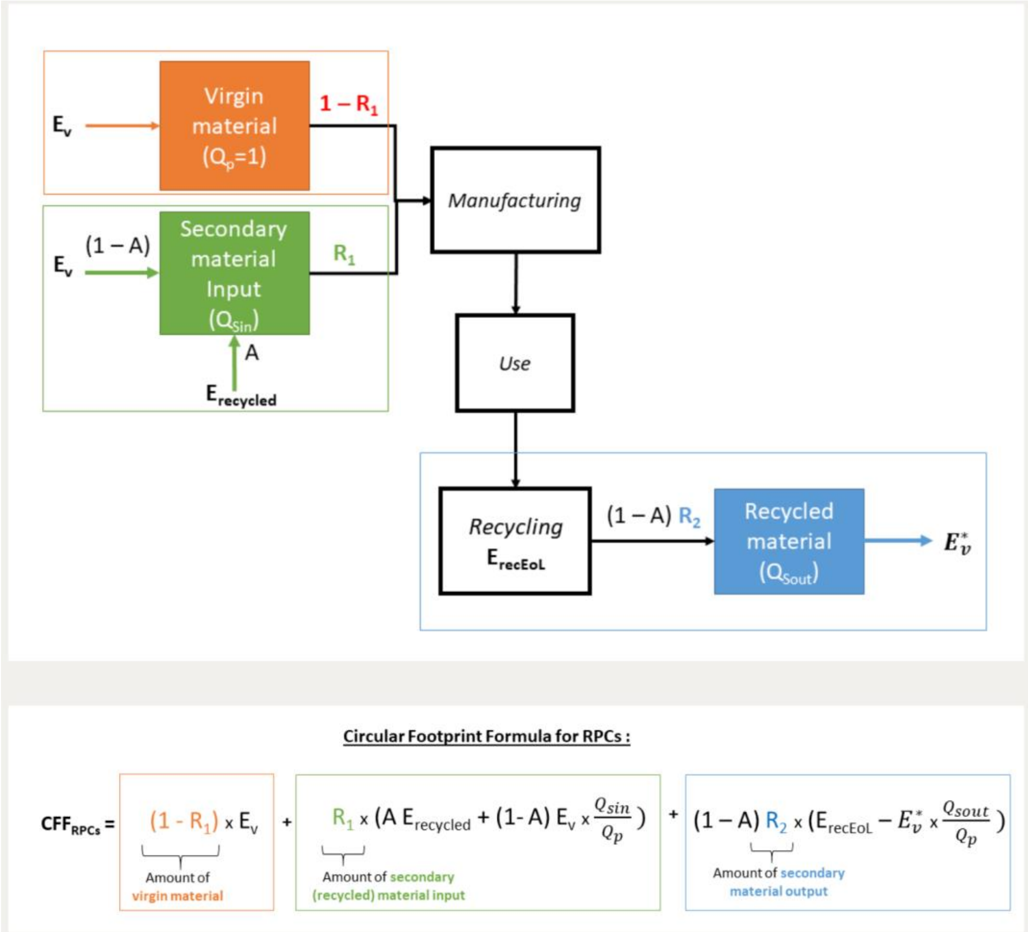

Figure 6. CFF graphical representation of material contribution's term (source https://areco.org.es/en/the-circular-footprint-formula/)

Circular Economy Performance Assessment – CEPA

CEPA method has been developed by POLIMI in the context of FENIX project. This method provides a set of KPIs that measures the resources circularity levels of a product within its life cycle and the quantification of the environmental and economic benefits related with circular economy (Rocca, Sassanelli, et al., 2021). The circularity level of a product is indeed calculated by considering three different sub-methodologies: the Product Circularity Assessment (CPA), the Environmental Circularity Assessment (CEA) and the Cost Circularity Assessment (CCA).

Going more in detail on the three sub-methodologies, the focus of this paragraph is on the CPA, which allows the calculation of the circular share of resource flows used during a product life cycle and, thus, deals with the circularity level of a product in a narrow sense. The CPA is the first layer upon which applying the CEA and CCA, sub-methodologies that respectively account for economic and environmental impacts associated to the degree of circularity of the analyzed product. Indeed, the CCA allows the calculation of the cost savings generated by both the triggering of materials and other resources circularity and related to energy circularity; while the CEA relies on the LCA methodology and allows the quantification of the emissions and other forms of pollution avoided by triggering the resources flows circularity present throughout the entire life cycle.

The CPA is structured in four phases (Rocca, Sassanelli, et al., 2021):

- **Objectives definition and settings** – similarly to the Goal & Scope definition phase of LCA, this first phase identifies the context and the boundaries of the analysis by defining product system, functional unit and reference flow, data characteristics (e.g. precision, completeness, representativeness, etc.), allocation procedures, hypothesis and limitations.
- **Inventory analysis and resource flow decomposition** – this phase includes the compilation and quantification of the inputs and outputs for each life cycle phase of a product, considering every process unit included in the system boundaries. First, the product's life cycle phases are described. Then, the inventory of the resource is created considering energy flows (i.e., electricity and thermal energy); material flows (i.e., raw materials constituting the product); and complementary resource flows (e.g., water, cooling fluids, chemical additives, consumables, etc.). The circularity level of the resources is quantified as the ratio between saved resources and those used in case of a new production. The following conditions/routes involving the above inventory flows enabling the circularity of resources are analysed: energy flows from renewable energy sources; thermal energy flows from thermal recovery; energy flows from recovery of discarded materials and resources; material flows in input either from other systems or from the same system; material flows intended for re-use in the same system or in other systems; resource flows saved as a result of maintenance and repair activities.
- **Weights and Indexes calculation** – this phase includes the analysis of the resources present in the life cycle with the aim to calculate their potential reuse, based on their characteristics, such as the "physical" weight of materials and other resources, the weight of each phase in terms of resources used, the recyclability characteristics of the materials.
- **Circularity Indicators calculation** – this phase is composed of three sub-phases: i. the creation of the Circularity Product Indicator (CPI), ii. the circularity yield vector creation, and iii. the calculation of the final Circularity Function.

The CPI is given by the following formula:

$$CPI = \sqrt{\frac{ECI^2 + MCI^2 + RCI^2}{3}} * 100 \qquad \text{(Eq. 2.5)}$$

Where the *ECI* is the Energy circularity Indicator, the *MCI* is the Material (absorbed) Circularity Indicator, and the *RCI* is the Resource (absorbed) Circularity Indicator of the product in the life cycle. The details for each above term are available directly in (Rocca, Sassanelli, et al., 2021).

The Circularity yield vector, η_c, is the quantification of the generated circularity (i.e., resources made available for the same system or for other systems) compared to those absorbed (i.e., received in input from the same system or from other systems).

$$\Phi = \pi * CPI^2 * (1 + \eta_c) \qquad \text{(Eq. 2.6)}$$

where the Circularity yield vector, η_c, is the quantification of the generated circularity (i.e., resources made available for the same system or for other systems) compared to those absorbed (i.e., received in input from the same system or from other systems). The Circularity Function thus considers the circularity quantity in input (CPI) and the capacity of generating circularity in output (yield vector).

Thermodynamic criticality analysis

The exergy analysis (through thermodynamic rarity indicator) is proposed as a unifying indicator to incorporate the quality of the materials used and the dissipation effect in the recycling processes. In the context of WP3 activities and deliverables, the thermodynamic criticality analysis (performed by UNIZAR and SEAT) allowed the calculation of the criticality of materials in exergetic terms for the five components identified from SEAT's vehicles, namely combi instrument, infotainment, sensors, exterior mirrors, and additional brake lighting. The thermodynamic rarity indicator allows to rank the materials to be recover on the basis of their criticality and no more in terms of mass content with respect to the whole material content processed. The exergy assessment can be performed also at the EoL stage. The thermodynamic rarity indicator has to be added to the Circularity indicators described in §3.4. More details on the methodology can be found in in the dedicated deliverable from WP3 (Ortego, Valero, et al., 2018).

The recyclability assessment by MARAS

The recyclability assessment performed by MARAS provides in turn the Recyclability Index (RI). RI, developed by (M. A. Reuter & van Schaik, 2016), is based on simulation models that have their origins in minerals and metallurgical processing. It is related to the previous work by the authors that conceptualize and transmit the recycling result of a product as well as of the individual materials in a direct, simple and clear manner. It helps to allow the consumer to make informed purchasing decisions and to communicate greener design. It is comparable to the EU Energy Labels. The Recycling Index includes two indicators: Recycling Index (RI) and Material Recycling Index (Material-RI). Material-RI shows the recovering rate of singular elements or components of the product, in particular: the higher the recycling rate per material or element, the more closely the Recycling Index develops into a Circular definition of the CE. The weighted average of the different recycling indicators is the base for the overall recycling rate as illustrated by the RI. More information can be found in the dedicated deliverable from WP3.

2.3.2. TREASURE circularity assessment methodology

In light of the methodologies analysed and referring to TREASURE ambitions, the following considerations can be stated. Notwithstanding the evaluation of the circularity performances is at its early stage, the CFF and the CEPA methodologies provide a methodologic approach to the assessment of the materials (and energy) circularity level that could be adopted to evaluate the TREASURE performances. CEPA methodology is more focused on closing the loop on materials, while CFF methodology takes into account also the issue of retaining the quality of secondary material in the loop. Moreover, the CFF has been proposed in the EF context and developed in the same framework of the PEF methodology, which is actually the common thread of the environmental TREASURE assessment. For this reason, the CFF methodology is the chosen one to be applied in the project context. Being presented here, the related indicator is no more listed in §3.4, while it is already discussed in the section dedicated to the circularity aggregation framework (see §4.2) since it results as a single indicator assessing the material, energy, and disposal contribution to circularity of a material flow along multiple life cycles. Therefore, CFF appears to be one of the major candidates to the role of aggregation's method for the circularity pillar.

In addition to the CFF methodology, the expertise of two partners of the consortium will be exploited to assess the capacity of EoL practices to keep the quality of recycled material and avoiding downcycling. The exergy analysis (through thermodynamic rarity indicator) is proposed as a unifying indicator to incorporate the quality of the materials used and the dissipation effect in the recycling processes. Moreover, the exergy assessment can be combined with the recyclability assessment from MARAS and the related Recyclability Index (RI). These indicators and its graphical representation are also reported in §3.4 together with the list of most used circular indicators adopted at material and product level emerged from a literature research.

Circularity assessment conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section '*Methodologies and indicators selected for the circularity assessment*'.

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3. TREASURE sustainability & circularity indicators

Starting from the assessment methodologies analysed in Section 2, this chapter presents the identification and the preliminary selection of indicators for environmental, economic, and social area of sustainability, together with those related to circularity. The described methodologies often propose a large set of indicators to investigate the sustainability and circularity performances of a system, covering a wide set of environmental, economic, social and circularity areas of interest, sometimes proposing also different calculation approaches for the same impact area. Given this articulated context, the following sections are meant to identify the most suitable indexes to be exploited in the TREASURE context, showcasing the criteria and the reasoning behind the identification and the selection performed. Further developments of the selection activity will be examined and presented in D2.2, together with the tools adopted for the refinement.

3.1. Environmental indicators

As reported in §2.2.1, one of the first steps needed to prepare an LCIA is the selection of the impact categories to be addressed together with the related category indicators and characterization methodologies. To this end, a potential list of environmental indicators can be retrieved, in order of relevance, from:

- PEFCR, if already developed for the specific product category;
- PCR, if already developed for the specific product type;
- PEF's default impact categories, if no PEFCRs or PCR are available;
- Literature works on LCA performed on the same product category.

Considering TREASURE case, no PEFCR has been developed yet for electric and electronic components, thus other initiatives, such as the Environmental Product Declarations (EPDs) relying on the ISO14025[14] certification schemes, can be investigated to find given Product Category Rule (PCR) providing a standardized LCA recipe. Among the existing PCRs, which are retrievable from the libraries contained in the database of the Program Operator managing the specific labelling scheme (e.g., the International EPD® System)[15], no one already available meets the object of TREASURE analysis. It is therefore possible to consider as preliminary list of environmental indicators the default one proposed by the PEF Guide[16], and reported in Table 3. This list of general environmental indicators is based on the default set of 14 midpoint impact categories and the default set of midpoint LCIA methods recommended in the ILCD Handbook.

Table 3. PEF's default environmental indicators

Impact category	Category indicator	Recommended default LCIA methodology
Climate change	Radiative forcing as Global Warming Potential (GWP100) [kg $CO_{2\ eq}$]	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Acidification	Accumulated Exceedance (AE) [mol $H+_{eq}$]	Accumulated Exceedance model (Seppälä, Posch, et al., 2006), (Posch, Seppälä, et al., 2008)

[14] ISO, "ISO 14025:2006 Environmental labels and declarations — Type III environmental declarations — Principles and procedures," 2006.
[15] Environdec, "PCR Library," 2021
[16] https://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

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Eutrophication – terrestrial	Accumulate Exceedance (AE) [mol N $_{eq}$]	Accumulated Exceedance model (Seppälä, Posch, et al., 2006), (Posch, Seppälä, et al., 2008)
Eutrophication – aquatic, fresh water	Fraction of nutrients reaching freshwater end compartment (P) [kg P $_{eq}$]	EUTREND model as implemented in ReCiPe (Struijs, J., Beusen, A., 2009)
Eutrophication – aquatic, marine	Fraction of nutrients reaching marine end compartment (N) [kg N $_{eq}$]	EUTREND model as implemented in ReCiPe (Struijs, J., Beusen, A., 2009)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase [kg NMVOC $_{eq}$]	LOTOS – EUROS model as implemented in ReCiPe 2008 (van Zelm, Huijbregts, et al., 2008)
Ozone depletion	Ozone Depletion Potential (ODP) [kg CFC-11 $_{eq}$]	EDIP model ((WMO), 1999)
Resource use – fossils	Abiotic resource depletion – fossil fuels (ADP-fossil) [MJ]	CML 2002 (Van Oers L., 2002)
Water use	User deprivation potential (deprivation-weighted water consumption) [m^3 world $_{eq}$]	Available WAter Remaining (AWARE) as recommended by (Boulay A.M., 2018)
Resource use – minerals and metals	Abiotic resource depletion (ADP ultimate reserves) [kg Sb $_{eq}$]	CML 2002 (Van Oers L., 2002)
Land use	• Soil quality index [dimensionless (pt)] • Biotic production [kg biotic production] • Erosion resistance [kg soil] • Mechanical filtration [m^3 water] • Groundwater replenishment [m^3 groundwater]	Soil quality index based on LANCA (Bos, U., Horn, R., 2016) (Beck, Tabea, 2010)
Eco-toxicity – aquatic, fresh water	Comparative Toxic Unit for ecosystems (CTU_e) [CTU_e]	USEtox model (Rosenbaum, Bachmann, et al., 2008)
Human toxicity – non cancer	Comparative Toxic Unit for humans (CTU_h) [CTU_h]	USEtox model (Rosenbaum, Bachmann, et al., 2008)
Human toxicity – cancer	Comparative Toxic Unit for humans (CTU_h) [CTU_h]	USEtox model (Rosenbaum, Bachmann, et al., 2008)

The list of potential environmental indicators could be refined considering the literature on the topic. According to (Gehring, Prenzel, et al., 2021), other impacts assessment methodologies exploited in previous LCA studies on e-wastes management are midpoint ones such as CML 2002

(Ozkan, Elginoz, et al., 2018) and IMPACT 2002+ (Compagno, Ingrao, et al., 2014) and ReCiPe 2016 (Nunes, Kohlbeck, et al., 2021), (Ismail & Hanafiah, 2021).

Environmental indicators conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section ' *Methodologies and indicators selected for the environmental assessment*'.

3.2. Economic indicators

According to §2.2.2.2, the economic indicators included in TREASURE are the costs indicators foreseen by eLCC methodology. The cost structure comes from cLCC methodology, upon which ISO standards related to other sectors are built on ((ISO, 2017), (ISO, 2021)), considering the costs of internalized environmental externalities. The cost's structure includes the following type of costs:

- costs related to the research and development activities;
- cost of labour;
- operating costs, such as cost of materials; energy; cost of fuel; cost of ancillary materials use (e.g., cost of water); costs of spare parts;
- EoL-associated costs, such as cost of waste management; cost of collection and of disposal;
- cost of logistics and transport;
- Costs imputed to environmental externalities linked to the product during its life cycle; these costs may include the cost of greenhouse gas emissions, other climate change mitigation costs, and expanding the concept, the costs associated with the main environmental impact categories. The condition is that the monetary value can be determined and verified.

According to the eLCC approach, the total cost indicator will be given by the sum of the costs arisen along the life cycle phases of the product in analysis and incurred by the stakeholders involved. Since in TREASURE three life cycle phases are analyzed (i.e., BoL design, EoL disassembly and recycling phases), and the three main stakeholders involved correspond to the BoL actors (i.e., car and parts manufacturers) and to the EoL ones (i.e., disassemblers and recyclers), the cost structure has been rearranged as shown in Table 4:

- The cost items considered are grouped as: labour, supplies, energy, logistics, service, disposal, and externalities cost.
- Each row represents one of the above types of cost, following the same order.
- Each column represents a life cycle phase, corresponding to the involved stakeholder (designer and manufacturer, disassembler, and recycler).
- The cost items are interpreted with the perspective of the stakeholder involved, and a calculation formula is provided, according to (Rossi, Leone, et al., 2022).

In D2.2, surveys will be developed and then circulated to the pilots to verify the existence, quality and availability of the various data to perform sustainability assessments. The survey dedicated to economic data will have the additional purpose of verifying that all cost items have been identified and catalogued, and no major contribution to overall cost as been omitted.

Table 4. Cost indicators

Life cycle phase	BoL (design / manufacturing)	EoL (disassembly)	EoL (recycling)
Cost items	$Personnel\ Cost = personnel\ cost\ rate \left[\frac{€}{h}\right] * work\ load\ [h]$	$Labor\ Cost = labor\ cost\ rate \left[\frac{€}{h}\right] * time\ to\ disassembly\ [h]$	$Labor\ Cost = labor\ cost\ rate \left[\frac{€}{h}\right] * work\ load\ [h]$
	$Raw\ Material^{17}\ Cost = aw\ material\ cost\ rate \left[\frac{€}{kg}\right] * material\ weight\ [kg]$ $Ancillary\ Material\ Cost = \left(water\ cost \left[\frac{€}{l}\right] * water\ consumption \left[\frac{l}{h}\right] + oil\ cost \left[\frac{€}{l}\right] * oil\ consumption \left[\frac{l}{h}\right] + \ldots\right) * time\ to\ recycle\ [h]$	$Hardware\ \&\ Spare\ Components\ Cost\ [€]$	$Ancillary\ Material\ Cost = \left(water\ cost \left[\frac{€}{l}\right] * water\ consumption \left[\frac{l}{h}\right] + oil\ cost \left[\frac{€}{l}\right] * oil\ consumption \left[\frac{l}{h}\right] + \ldots\right) * time\ to\ recycle\ [h]$
	$Energy\ Cost = power\ absorbed\ [kW] * energy\ cost \left[\frac{€}{kWh}\right] * time\ to\ produce\ [h]$	$Energy\ Cost = power\ absorbed\ [kW] * energy\ cost \left[\frac{€}{kWh}\right] * time\ to\ disassembly\ [h]$	$Energy\ Cost = fuel\ cost \left[\frac{€}{l}\right] * fuel\ needed\ [l] + power\ absorbed\ [kW] * energy\ cost \left[\frac{€}{kWh}\right] * time\ to\ recycle\ [h]$
	$Purchasing\ Cost = trasportation\ cost \left[\frac{€}{km * t}\right] * trasportation\ distance\ [km] * material\ weigth\ [kg]$	$Collection\ Cost = trasportation\ cost \left[\frac{€}{km * t}\right] * trasportation\ distance\ [km] * material\ weigth\ [kg]$	$\text{Collection cost} = trasportation\ cost \left[\frac{€}{km * t}\right] * trasportation\ distance\ [km] * material\ weigth[kg]$

[17] Either virgin or recycled material

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	$Service\ Cost\ (C_{services}) = C_{lights} + C_{telephone} + C_{adv} + C_{non-invasive\ maint.actions} + \ldots$	$Service\ Cost\ (C_{services}) = C_{lights} + C_{non-invasive\ maint.actions} + \ldots$	$Service\ Cost\ (C_{services}) = C_{lights} + C_{non-invasive\ maint.actions} + \ldots$
	Environmental externalities, such as the cost of greenhouse gas emissions, other climate change mitigation costs, and expanding the concept: the costs associated with the main environmental impact categories		

Considering the environmental externalities, the Eco-costs approach[18] is proposed for their internalization. The monetary valuation of environmental impacts and related environmental aspects is performed combining the LCA indicators midpoint with the monetary valuation factors proposed by the Eco-costs and then aggregated into an end point-like single indicator. Eco-costs are a measure to express the amount of environmental burden of a product on the basis of prevention of that burden. They are the costs which should be incurred to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth. The "Eco-costs" represents a single indicator, whose calculation is bases on classification and characterization tables as well as for LCA, but the normalization and weighting steps are different from the ones of LCA. Normalisation is done by calculating the marginal prevention costs for a region (i.e., the European Union), while the weighting step is avoided since the total result is the sum of the eco-costs of all midpoints. The model of Eco-costs is shown in Figure 7. Environmental mid-point indicators are translated into monetary end-point indicators via the monetary characterization factors, then the single monetary end-point indicators addressing the single areas of protection (i.e., human health, ecosystems, given carbon footprint, resource scarcity) are summed to obtain the single Eco-costs indicator.

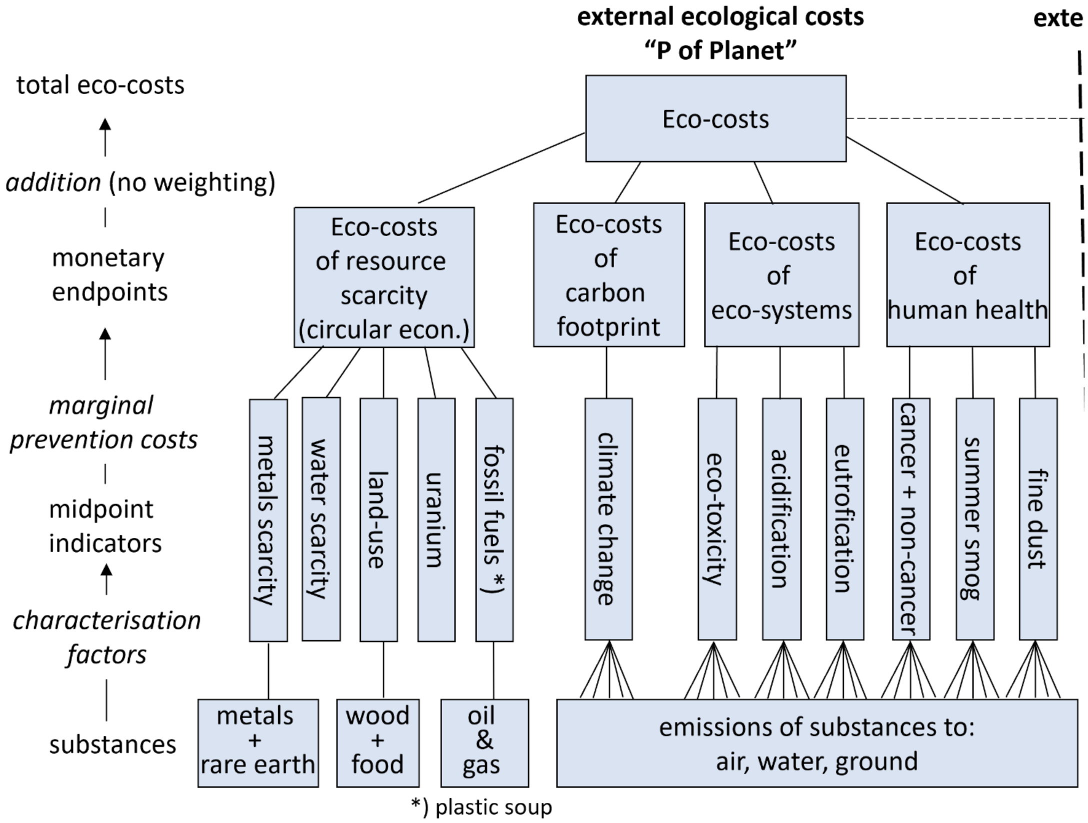

Figure 7. Eco-costs model (source https://www.ecocostsvalue.com/eco-costs/)

Table 5 from (Metrics, 2022) reports the multiplying factors for each addressed midpoint indicator concerning the emission of substances, while the eco-cost of resource scarcity are described in §3.4.3 since it can be considered as a circular economy indicator.

[18] https://www.ecocostsvalue.com/eco-costs/

Table 5. Eco-costs model - midpoint characterization table and related multipliers for emissions

Category	Multiplier (Marginal Prevention Costs)	Midpoint Table
Eco-costs of global warming	0.116 €/kg CO_2 equivalent	Potential 100 years, IPCC 2013, including climate-carbon feedbacks (EF version)
Eco-costs of acidification	8.75 € / kg SO_2 equivalent (= 6.68 € / mol H^+ eq)	EF table (including EU country factors)
Eco-costs of eutrophication	4.70 € / kg PO_4 equivalent (= 14.40 € / kg P eq)	EF table (including EU country factors)
Photochemical oxidant formation ('summer smog')	5.35 € / kg NOx equivalent (NMVOS equivalent) = 9.08 euro/kg C_2H_4 eq)	LOTOS-EUROS model
Eco-costs of fine dust	35.0 €/kg fine dust PM2.5 equivalent	UNEP/CETAC plus EF table
Eco-costs of ecotoxicity	340.0 €/kg Cu equivalent	UseTox 2 (recommended plus interim), freshwater ecotoxicity (EF version)
Eco-costs of human toxicity cancer	3754 €/kg Benzo(a)pyrene equivalent	UseTox 2 (recommended plus interim), cancer (EF version)
Eco-costs of human toxicity non-cancer	25500 €/kg Mercury. equivalent	UseTox 2 (recommended plus interim), non-cancer (EF version)

The listed marginal prevention costs at midpoint level can be combined to monetary endpoints in three groups, plus global warming as a separate group, as shown in Figure 7:

- Eco-cost of human health, given by the sum of carcinogens, summer smog, fine dust;
- Eco-cost of ecosystems, given by the sum of acidification, eutrophication, ecotoxicity;
- Eco cost of carbon footprint, given by the climate change;
- Eco cost of resource scarcity, given by the sum of abiotic depletion (scarcity of metals, REE, and energy carriers), land-use, water, and land-fill.

The total eco-costs indicator is given by the sum of human health, ecosystems, resource scarcity and carbon footprint. The total eco-cost for each life cycle phase considered in TREASURE is given by the sum of human health, ecosystems, resource scarcity and carbon footprint evaluated from the LCIA data of each single phase.

Beside the cost assessment, explicitly required also in the project DoA, also financial indicators are addressed in TREASURE so that the economic evaluation is not only focused on the cost issue, but also linked to possible reasoning concerning the margins, profits, payback time… related to the TREASURE innovations introduced. In Table 6 below, a list of financial indicators are listed, selecting the ones proposed in literature and in previous research works on the topic (Rossi, Leone, et al., 2022). For each indicator it is provided a possible application to the project, mainly considering its scope, that is, the recovery of critical and precious raw materials.

Table 6. Financial indicators

Indicator	Description	Formula
Net Profit Margin (NPM) as in (Dočekalová & Kocmanová, 2016)	NPM, or simply Net Margin, measures how much net income or profit is generated as a percentage of revenue. It is the ratio of net profits to revenues for a specific product. In TREASURE, it could be declined to materials level by considering as revenue the actual market price of the material and as costs the costs associated to its recovery (inverse logistic, disassembly and recycling costs).	$NPM = \frac{R - COGS - E - I - T}{R} * 100$ Where R is the revenue; COGS is the cost of goods sold; E is the operating cost and other expenses; I is the interest; T are the taxes; R - COGS - E - I – T is the net income
Return On Sale (ROS) as in (IBM, 2018)	ROS is a ratio used to evaluate a company's operational efficiency. This measure provides insight into how much profit is being produced per dollar of sales. An increasing ROS indicates that a company is improving efficiency, while a decreasing ROS could signal impending financial troubles. In TREASURE, this indicator can be adapted to material level by considering only the operating profit and net sales related to the specific material.	$ROS = \frac{Operating\ Profit}{Net\ Sales}$ Where Operating Profit are the earnings before interest or the earnings before interest and taxes (EBIT), and the Net Sales is the sum of a company's gross sales minus its returns, allowances, and discounts.
Resale value (RV)	This economic indicator, considering the TREASURE context, refers to the market value at day x of a given recycled material (e.g. the market value per kg of recycled Ag at day x).	$RV_{tot}\,(t) = \sum_{i=1}^{n} RV_i(t) \times m_i$ The total Resale Value RV_{tot} is obtained by the sum of all $RV_i \left[\frac{€}{Kg}\right]$, given *n* materials *i*, at a given time t multiplied by the respective mass m_i obtained after recycling.
Return On Investment (ROI) as in (Team, 2022)	ROI is a performance measure used to evaluate the efficiency or profitability of an investment or to compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost.	$ROI = \frac{Current\ Value\ of\ Investment - Cost\ of\ Investment}{Cost\ of\ Investment}$ Where Current Value of Investment refers to the proceeds obtained from the sale of the investment of interest.

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Net Present Value (NPV) as in (Rocca, Sassanelli, et al., 2021)	NPV represent the difference between today's value of the expected cash flows and today's value of invested cash.	$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$ where C_t is the net cash inflows-outflows in a single period t; r is the discount rate or return that could be earned in different investments; n is the total number of time periods
Amortization as in (Rossi, Leone, et al., 2022)	Amortization refers to the depreciation of multi-year assets, such as software, machinery, equipment, etc.	$$C_{amm} = \frac{C_{multi-year\ assets}}{t_{amm}}$$ where C_{amm} is the amortization rate per year (€/y); $C_{multi-year\ assets}$ is the total cost of the multi-year assets in (€); and t_{am} is the amortization horizon in (y)
Payback time (PBT) as in (Rocca, Sassanelli, et al., 2021)	PBT helps to determine how long it takes to recover the initial costs associated with an investment.	$$PBT = \frac{cost\ of\ investments}{average\ annual\ cash\ flow}$$

While the application of cost indicators for TREASURE's economic assessments is quite straightforward to be implemented, the financial indicators' applicability needs further reasoning. The nature of some of the selected financial indicators justify their application to the evaluation of investments in new equipment, infrastructure modification, and more in general to do some reasoning about the economic return and evaluate the financial sustainability of a given decision for the assessment at the product, component, or material level, thus requiring an extra explanation on the reasoning of their selection. In TREASURE, the sustainability and circularity assessment address the EoL technical processes for electronic waste in automotive, at the level of products and materials, focusing on the recycling of critical materials recovered from the disassembly of the PCBs embedded in car parts. The adoption of financial indicators may be not justified for what concerns the initial assessment phase, in which costs is the only driver to decide the best disassembly and recycling routes, but for next steps in the project, as for the evaluation of KETs as enablers of the transition to a sustainable and circular approach in the processes of the automotive value chain. In this regard, the assessment of initial investments can be supported by indicators that not only consider the cost dimension, but also the financial sustainability of the case under consideration (be it an investment, process change, material change, product change, and so on). Financial indicators could extend the concept of economic sustainability beyond the LCC, compensating for its limitations and criticalities. For instance, financial indicators, such as NPV and ROI, can support the decision-makers for the economic pillar when come to decide: for the adoption of new disassembly stations to help disassemblers, i.e., robotic cell with cobot and machine vision systems; for the industrial implementation of the new prototype of recovery processes; and for the diffusion at the industrialization level and not more at the prototypal one, of the in-moulding structural electronic process. Thus, the financial indicators listed in the above Table 6 are kept in consideration for the final aim of establishing economic KPIs driving decision-making, and are revised in D2.2, where the decisions to be supported in analysed each life cycle stage are depicted.

Economic indicators conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section '*Methodologies and indicators selected for the economic assessment*'.

3.3. Social indicators

As a result of the analysis of the state of the art and selection of the methodology for assessing social impacts (see §2.2.3), it arises that the one most performing and suitable for the TREASURE context was the methodology developed by UNEP: The United Nations Environmental Program (UNEP) Social LCA Guidelines (United Nations Environment Programme, 2020).

The methodology, consisting of a series of development stages such as: Goal and Scope definition, Social Life Cycle Inventory, Social Life Cycle Impact Assessment and Interpretation, allows, through the provision of a methodological sheet, the detailed exploration of the Social Life Cycle Impact phase, to guide the application of SLCA. In particular, it provides guidance for the data collection phase, which is the most labour-intensive activity when conducting a social LCA.

To do this, the UNEP methodological sheet, provides a number of different indicators depending on the availability of data and the objective and scope of the study. The indicators reported follow the structure of the methodology, so they are related to the 6 stakeholders: Worker, Local community, Value chain actors (not including consumers), Consumer, Society and Children.

For each stakeholder category, there are subcategories of impact, to which a set of indicators are related. A diagram depicting the stakeholders and related impact categories is shown in Figure 8 below.

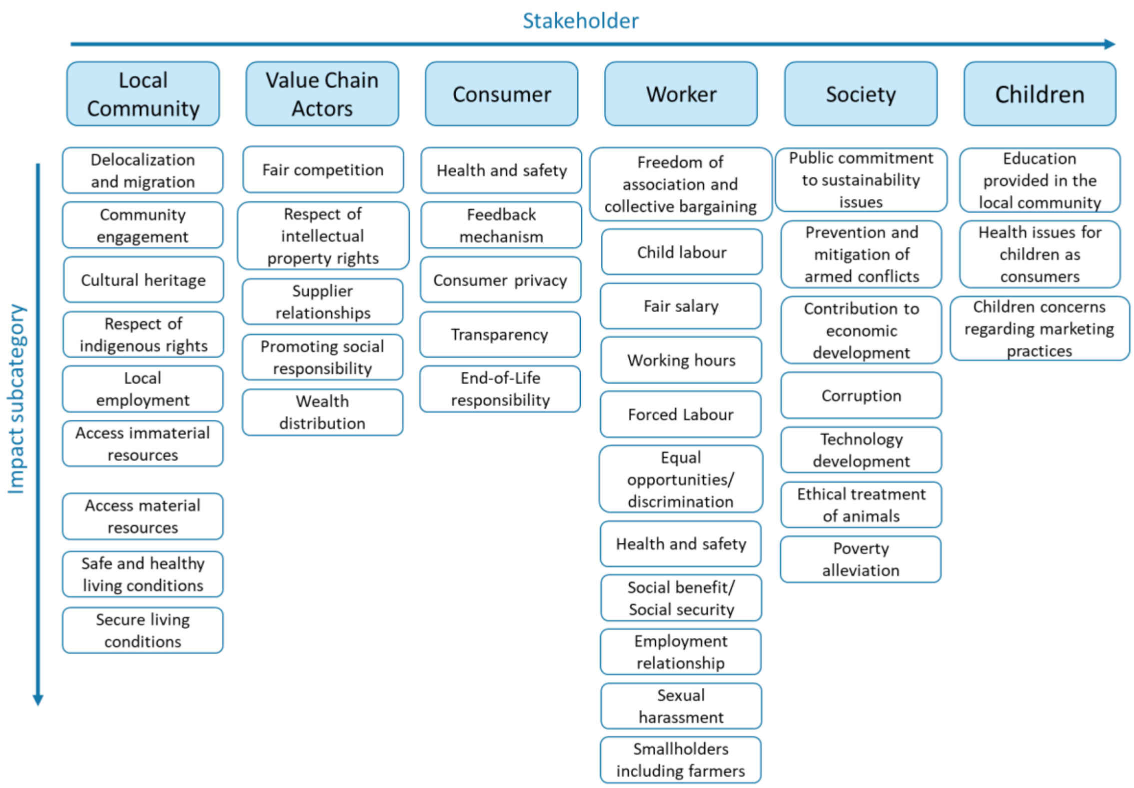

Figure 8. UNEP Social LCA methodology – stakeholders and impact categories

In general, the ultimate objectives of the methodological sheet are to:

- Avoid misunderstandings related to impact subcategories during the assessment process and clarify their relationship to stakeholders;
- Provide metrics for each subcategory, including inventory indicators, units of measure, and potential data sources for hotspot assessment;
- Improve simplicity and consistency of application across case studies;
- Provides comprehensive open-source resources for SLCA.

3.3.1. Structure of the indicators

Following an initial overview of the organization of indicators, it is necessary to investigate in detail how indicators are reported and described by the UNEP methodology, given in the document called "Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021" (United Nations Environment Programme, 2021).

To facilitate the analysis and promote consistency, UNEP describes the impact categories using the information classes listed in the following:

- **Definition**. A detailed description of the impact category under consideration is provided. In addition, the specific objective pursued by the evaluation of this impact category is described, along with a brief explanation of how the evaluation is conducted.
- **Policy relevance**. This class explains the relevance of the impact category in sustainable development. A description of the importance of evaluating this category is thus given, particularly explaining the ways in which the subcategory could enhance or deter sustainable development. In addition, a list of "international instruments," i.e., conventions and agreements that pertain to the subcategory, is provided.
- **Assessment of data**. This section provides examples of data sources for the category indicator.
- **Generic analysis**. This field describes which kind of generic data sources can be exploited for the impact category in analysis, and in some cases, links to actual country-level data are given. The generic analysis is performed using secondary data coming from databases and statistical collections.
- **Specific analysis**. Concerning the impact category in analysis, this class suggests some specific indicators and specific data sources to perform social LCA at the organization level. Specific data sources are those constituted by primary data directly collected in the companies.
- **Limitations of the subcategory**. This field indicates which limitations may occur during data collection and what therefore must be taken care of during the assessment.
- **References**. Relevant documents and websites are listed as references and suggestions for further information.

Having analyzed the information described, in order to determine the social indicators, firstly the description to understand the meaning of the impact category and secondly the information on generic and specific analysis were relevant. The remaining information was left out as not relevant to the objective of the task.

Going into detail, the assessment for each impact category can be performed through two different types of analysis: generic analysis and specific analysis. Through generic analysis, a high-level assessment can be performed, so it allows estimating the impacts of the examined organization based on secondary data. Since this data is collected from various entities, it estimates the impacts generated based on the geographic location or economic sector of the object under analysis, thus representing only an approximation of the real impact generated. In this case, unlike the specific analysis where the UNEP methodology provides indicators, generic data sources are provided to carry out the generic analysis. So, only the instruments from which to extrapolate generic indicators of interest are provided; all possible computable generic indicators are not mapped directly from the UNEP methodology.

Regarding the specific analysis, indicators are given for each category where primary data, i.e., specially collected data, are needed to perform the calculation. In order to simplify the collection of primary data, possible data sources, such as interviews, report reviews, etc., are also indicated for each specific indicator.

It is important to specify how the two analyses are not mutually exclusive. In fact, some indicators can be analyzed both at generic analysis and specific level (e.g., child labor), obtaining however different results since in one case the analysis is based on a secondary data source (e.g. the child labor level of a geographic area) while in the other case on a primary one (e.g. the number of child employed in a specific production site could be zero even though in the country the firm belong to the average is higher than zero); other indicators are on the contrary purely specific. Thus, both types of analysis can be used to carry out social assessment depending on the data available, so for certain indicators primary or secondary data source can be used, and for others purely primary.

In accordance with the objective of T2.1 and the overall TREASURE project, all indicators derived from the generic analysis and the specific analysis were mapped, analyzed and then selected.

3.3.2. Indicators selection methodology

After a study of the structure of the social indicators, both generic and specific, were mapped into ANNEX 2 and analyzed individually. This is done in order to determine criteria for selecting indicators in compliance with the TREASURE context and the project goals and to reduce the total number of considered indicators. In fact, the UNEP methodology proposes indicators that, if on the one hand result to be a wide set of indexes able to offer a complete vision on the social themes, on the other hand are not so much manageable in the decision-making process.

The determining factor in performing the selection of suitable indicators was a fundamental requirement of the project: the automation of the process of calculating impacts. Since the TREASURE platform is at the center of all the activities carried out in TREASURE project, it is essential that all assessment processes be as automated as possible, allowing anyone who wants to carry out a comparison of impacts or to obtain decision making support to speed up and simplify the process. In accordance with this aspect, generic analysis has been identified as the preferable one in the TREASURE context, since specific analysis is exploiting primary data that requires time and efforts to be collected and elaborated. Despite this, specific analysis cannot be excluded from the Social Assessment since it provides a more focus and precise view at the social level of the company/organization.

Moreover, specific indicators have been also investigated considering the future possibility to build appropriate tools and databases for the collection and elaboration of primary data concerning the TREASURE pilots. In addition to the generic and specific indicators categorization, further selection criteria are investigated in the following paragraphs, in an attempt to simplify indexes selection.

Generic analysis

Concerning the generic analysis, as previously mentioned, an assessment can be performed by mapping indicators derived from the suggested data sources for each impact category associated with each stakeholder.

Going into detail, the UNEP methodology suggests for each impact category a number of data sources on which the person performing the analysis can extrapolate more indicators, so more data, from each. Over time, the UNEP methodology has undergone several modifications. In fact, the previous version developed in 2013 of the "S-LCA methodological sheet" (United Nations Environment Programme, 2013) document indicated the specific indicators to be calculated for each impact category with related possible data sources from which to extrapolate. In the most recent version, the detail of the specific indicator has been removed and the compiler must employ an effort to search for the desired indicators.

In total, the UNEP methodology suggests about 60 sources (e.g., The World Bank Group[19], World Trade Organization[20], International Labor Organization[21], United Nations[22], etc.) that can provide data related to multiple impact categories. It became clear that there is a substantial number of data sources so that the management, the analysis, extrapolation of indicators of interest, and the calculation of impacts requires high effort and would not allow the compliance with the criterion mentioned earlier: automation of calculation processes. To meet this need, the best performing solution is not to use the generic data sources provided by the UNEP methodology but to use the PSILCA database to conduct the generic assessment.

A key element that confirms the choice of the PSILCA database is the correspondence between the database data sources and UNEP suggested data source. In fact, PSILCA relies its data on statistical agencies such as the World Bank (World Bank, 2015), the International Labor Organization (2019, 1999), the World Health Organization (Compact, 2017a), and the United Nations (Compact, 2017b), etc., cited in UNEP. In addition, private or government databases are also taken into account, such as the Database on Institutional Characteristics of Trade Unions, Wage Setting, State Intervention and Social Pacts (ICTWSS 2013 from the Amsterdam Institute for Advanced Labor Studies (AIAS)), public records on Environmental Health and Safety (EHS) violations, by company or sector ((USDOL), 2014) (EHSToday, 2015) etc.

Another criterion that confirms the choice of using the PSILCA database as a tool to conduct the generic analysis is that all the indicators are quantitative. In fact, to make the assessment more precise, it is necessary to have quantitative indicators so as not to conduct approximate analysis.

Given the generic indicators, it is necessary to apply an additional selection criterion: the consistency with the European context. The decision to apply this selection criterion stems from the geographical location of all pilots involved in the TREASURE project, which are located on European territory. It is important to specify that in case the assessment is extended to the supply chain, there is the possibility that there are actors outside the European territory.

[19] https://www.worldbank.org/en/home
[20] https://www.wto.org
[21] https://www.ilo.org/global/lang--en/index.htm
[22] https://www.un.org/en/

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In this case a complete list of indicators is reserved unfiltered with the criterion of "European context suitability".

Many indicators contained in the PSILCA database appear to be unsuitable for the project context because they deal with criteria that are necessarily met as they are mandated by law. They were therefore excluded and a final list of generic indicators has been prepared.

Specific analysis

The specific analysis, unlike the generic one, has a much higher number of indicators. In fact, 162 specific social indicators emerged as a result of the mapping.

They are categorized by impact category, and for each one of them, in order to facilitate the collection of data needed to calculate them, are presented the data sources, such as: site visit or site-specific audit, interviews with employees, management, review of organization-specific reports, such as GRI reports or audits etc.

Despite the suggested data sources, it is necessary to make a selection of indicators following ad hoc criteria for the TREASURE context.

First, in order to perform a specific assessment that is accurate, it is necessary to make it as quantitative as possible by basing it on numerical or Boolean data and cleaning it of indicators of a qualitative nature. So, to meet this criterion, a screening of all indicators was performed, eliminating those that required qualitative answers (such as "Strength of organizational risk assessment with regard to potential for material resource conflict").

In some cases, it was possible to reformulate some qualitative indicators by turning them into quantitative ones, going to redefine it and associate it with a unit of measurement. For example, the original indicator was stated as: "Presence of documented initiatives and activities geared toward supporting and promoting cultural heritage (e.g., funding of cultural activities and events)" and has been modified as follows: "Indicate the economic extent of investment [€] in place to protect and/or support cultural heritage."

Another selection factor is whether the indicator is suitable for the European context. During the analysis of the indicators, it became apparent that some of them are not suitable for the European context because they are requirements imposed by law that must necessarily be met, such as the percentage of working children under the legal age.

Thus, quantitative indicators consistent with the European context were considered as suitable.

3.3.2.1 Identified indicators

As stated in the previous sections, UNEP methodology includes generic and specific analysis. Both are explored in this chapter, specifying their use in the TREASURE project.

Regarding the generic analysis, the use of the PSILCA database is recommended, which allows the calculation of social indicators for all the stakeholders and the related impact categories. Appropriately filtered to be consistent with the European context, they allow the assessment of social impacts at a high level.

Increasing the level of detail, social indicators belonging to the specific analysis are also analyzed. Since these are 162 indicators, they were skimmed by selecting only quantitative indicators consistent with the European context. Despite the effort required to calculate them, it is recommended, where possible, to perform specific analysis as it is more precise.

Generic indicators

As a result of the logical process described above, it was decided not to use the approach suggested by the UNEP methodology, i.e., extrapolation of indicators from the data sources provided by the methodology, but to use the PSILCA database, which provides a set of indicators, to carry out the generic analysis. PSILCA database relies on the same or similar data sources cited by UNEP and also allows for the calculation of actual indicators derived from them.

The PSILCA indicators, initially numbering 74 indicators, were selected by applying a single criterion: consistency with the European context.

As a result of the analysis and application of the selection criterion, which if consistent with the European context, 53 generic social indicators derived from the PSILCA database were found.

The selected indicators that the database allows to calculate, broken down by stakeholder are reported in Table 7. The stakeholders considered by the database are: Workers, Value chain actors, Society, Consumer and Local community. Apart from these, an additional stakeholder considered in the UNEP methodology is missing: Children. The absence of the stakeholder within the database is due to the update of the UNEP methodology (2021) which is after the latest version of the PSILCA database (2020). So, in the generic analysis phase the Children stakeholder is excluded but a comprehensive analysis of the other stakeholders can still be performed.

Table 7. List of indicators contained in PSILCA database

Stakeholder	Category	Indicator	Unit of Measurement
Worker	Fair salary	Living wage, per month	USD
		Minimum wage, per month	USD
		Sector average wage, per month	USD
	Working hours	Hours of work per employee, per week	h
	Equal opportunities/ discrimination	Women in the labour force (total)	% of economically active population
		Women in the sectoral labour force	ratio
		Gender wage gap	%
	Health and Safety	Accident rate at workplace	Cases per 100,000 employees and year
		Fatal accidents at workplace	Cases per 100,000 employees and year
		DALYs due to indoor and outdoor air and water pollution	DALYs per 1,000 inhabitants in the country
		Presence of sufficient safety measures	OSHA cases per 100,000 employees in the sector
		Workers affected by natural disasters	%
	Social benefits, legal issues	Social security expenditures	% of GDP
		Evidence of violations of laws and employment regulations	Violation cases
	Freedom of Association and Collective Bargaining	Trade union density	% of employees organised in trade unions
		Right of Association	score of ordinal 0-3 scale

		Right of Collective bargaining	score of ordinal 0-3 scale
		Right to strike	score of ordinal 0-3 scale
Value chain actors	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Cases per 10,000 employees in the sector
	Corruption	Public sector corruption	Score (Corruption Perceptions Index score of the country)
		Active involvement of enterprises in corruption and bribery	%
	Promoting social responsibility	Membership in an initiative that promotes social responsibility along the supply chain	Number of companies
Society	Contribution to economic development	Public expenditure on education	% of GDP
	Health and Safety	Health expenditure, total	% of GDP
		Health expenditure, public	% of total health expenditure
		Health expenditure, out-of-pocket	% of total health expenditure
		Health expenditure, external resources	% of total health expenditure
		Domestic and External Health Expenditure	% of total health expenditure
		Domestic General Government Health Expenditure	% of total health expenditure
		Life expectancy at birth	Years
Consumer	Health and Safety	Violations of mandatory health and safety standards	Cases of Violation
		Presence of commissions or institutions to detect violations of standards and protect consumers from health and safety risks	Y/N
		Presence of management measures to assess consumer health and safety	Y/N or #
Local community	Access to material resources	Level of industrial water use (related to total withdrawal)	% of total water withdrawal
		Level of industrial water use (Related to renewable water resources)	% of renewable water resources
		Extraction of biomass (related to area)	t/km^2
		Extraction of biomass (related to population)	t/cap
		Extraction of fossil fuels	t/cap
		Extraction of industrial and construction minerals	t/cap
		Extraction of ores	t/cap
		Certified environmental management systems (CMEs)	# CEMs (ISO 14001) in sector per 10,000 employees

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	Safe and healthy living conditions	Pollution level of the country	Index
		Drinking water coverage	% of the population
		Sanitation coverage	% of the population
	Local employment	Unemployment rate in the country	% of the population
	Delocalization and migration	International migrant workers in the sector	% (of total workers in the sector)
		International Migrant Stock	% (of total population)
		Net migration rate	‰ (= per 1,000 persons)
		Asylum Seekers Rate	% (Asylum Seekers/Total Population)
		Emigration rate	% (of total population)
		Immigration rate	% (of total population)
		Human rights issues faced by migrants	yes/no
	Labor Footprints	Embodied value-added total	$/$

As mentioned before, the indicators reported here are specially filtered for the European context. With a view to extending the assessment of social impacts along the entire supply chain, the possibility arises that there are actors operating outside of Europe. For this in ANNEX 2, it is possible to find the complete list of indicators provided by the PSILCA database in order to enable the execution of a comprehensive assessment.

Specific indicators

The specific indicators proposed by the UNEP methodology, present a high numerousness in fact 162 specific indicators were mapped, divided among the 6 stakeholders.

Despite this, in the first stage of indicator analysis emerged from state-of-the-art analysis of social indicators (Barni, Capuzzimati, et al., 2022) (United Nations Environment Programme, 2021), how some indicators were not mentioned by UNEP. For this reason, a number of social indicators has been added in various impact categories.

In an attempt to meet the criterion of automating the calculation of social impacts and to simplify the collection, management and calculation, the specific indicators were filtered by applying a first criterion, i.e., if quantitative. From this first selection, it was evident that most of the specific indicators suggested by the UNEP methodology were either qualitative or not convertible to quantitative, thus not suitable. The second criterion, i.e., consistency with the European context, made it possible to bring the indicators closer to the project context, excluding unsuitable indicators because their fulfillment is required by law.

Applying these filters resulted in 79 specific indicators that allow for a quantitative assessment and in line with the European context.

The analysis and selection processes were performed on an Excel format sheet. In this file, for each indicator the following areas are indicated:

- Stakeholder of reference and impact category;
- Unit of measurement of the indicator;

- Data source;
- If quantitative;
- If consistent with the European context.

In addition, in order to simplify data collection, for each indicator that is quantitative and consistent with the European context, it is indicated whether it is related to the product, thus whether a change in the product affects the indicator, and the business departments where those performing the analysis might find the data are indicated. The company department reported represents an indication since it can vary according to the organization of the considered context. Table 8 reports an extract of the document with the indicators organized as just described.

A complete list of social indicators, including specific ones, can be found in ANNEX 2.

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Table 8. Extract of the list of specific social indicators derived by applying the selection criteria

Stakeholder	Category	Indicator	Type	Unit of Measurement	Data Sources / Methodology	Quantitative indicators?	Suitable for the European context (company pc	Product related?	In which department of the company/or
Local Community	Community Engagement	Number of meetings with community stakeholders (residents, community groups, developers , government workers (and the agencies they represent), etc.)	Specific	# of meetings	Site visit or site-specific audit Interviews with community members, employees, management and NGOs Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Management
Local Community	Community Engagement	Indicate the percentage [%] of employees that participate in social initiatives	Specific - added	Percentage [%]	Site visit or site-specific audit Interviews with community members, employees, management and NGOs Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	HR
Local Community	Community Engagement	Indicate the extent [€. If hours, please convert them in €] of organisation's support for community initiatives	Specific	Euro [€]	Site visit or site-specific audit Interviews with management and NGOs Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Accounting
Local Community	Cultural Heritage	Are there policies/management plans in place to protect and/or support cultural heritage? [Yes/No]	Specific	Y/N	Site visit or site-specific audit Interviews with community members, management and NGOs Review of organization-specific reports, such as GRI reports and Social Impact Assessments	Yes	Yes	No	Management
Local Community	Cultural Heritage	Indicate the economic size of investments [€] in place to protect and/or support cultural heritage	Specific	Euro [€]	Site visit or site-specific audit Interviews with community members, management and NGOs Consultation of documents/reports	Yes	Yes	No	Accounting
Local Community	Local Employment	Indicate the percentage [%] of workforce hired locally	Specific	Percentage [%]	Site visit or site-specific audit Interviews with management	Yes	Yes	No	HR
Local Community	Local Employment	Indicate the percentage [%] of local suppliers (within a radius of 150 km)	Specific	Percentage [%]	Site visit or site-specific audit Interviews with management Review of organization-specific reports, such as GRI or COP reports	Yes	Yes	No	Purchase

3.3.3. Social indicators selected for TREASURE

The analysis process performed on the social assessment methodology developed by UNEP and the PSILCA database resulted in two different approaches: generic approach and specific approach.

The generic approach, which allows for social assessment based on secondary data, relies entirely on the PSILCA database with indicators that have been selected within the TREASURE context. This approach, as formulated in this deliverable, fully satisfies the need to obtain a social-level automated result because the PSILCA database can be used with open-source software "Open LCA" developed by GreenDelta or the assessment tools developed by SUPSI in previous EU projects. It is important to point out that a generic type of analysis allows for an approximation of social impacts because the indicators refer to a certain geographic location and economic sector. So, the use of secondary data represents an estimate of impacts that may be far from the real social impacts generated. Another relevant aspect is related to the extent to which impacts are calculated along the supply chain. In fact, since the indicators are filtered on consistency with the European context, they are not suitable to carry out the assessment of actors operating outside Europe. In this case, it is necessary to perform the assessment by taking advantage of all indicators, without the application of the "European context suitability" criterion. Knowing this, despite diverging from the automation of impact calculations, the specific analysis performs better to obtain a more accurate assessment. Through the specific analysis, a social assessment can be performed using primary data, then directly collected by the reference company and considering both its inner activities and the ones performed by its suppliers. Several are the specific indicators suggested by UNEP, which is a relevant factor since a consistent effort is needed to collect the necessary data. Therefore, they were filtered by considering only quantitative indicators and those consistent with the European context, obtaining 79 specific social indicators.

Detailed the two types of studies, we recommend the use of the generic analysis in the TREASURE context, which over time, as more pilots iterate with the TREASURE platform, may be replaced by the specific analysis due to increasing data availability.

Once the social assessment methodology and related indicators have been identified and the supporting database determined, the next step, which will be covered in D2.2, is the adaptation of the indicators to the TREASURE use cases. This will be done through the support of a survey that will allow the various pilots to perform a selection of indicators based on their relevance in relation to their work. As a result, they will be further filtered, allowing for an assessment consistent with the TREASURE context.

In addition, having defined the indicators, it is necessary to create a methodology for aggregating the results, provided in §4.5, to obtain an assessment of the social impacts assigned to each stakeholder considered.

Social indicators conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section '*Methodologies and indicators selected for the social assessment*'.

3.4. Circular indicators

Beside the methodology framework described in §2.3, the circularity dimension has been investigated in its measurability aspects through an extensive literature review on existing circular indicators. In the following sub-sections, the steps performed to delineate the set of most shared circularity indicators are described.

3.4.1. State of the art on circularity indicators

The literature review was aimed at defining the set of circularity indicators suitable to support quantitatively the research activities of TREASURE project. The keywords driving the state-of-the-art research were the following: "circular economy", "circularity", "indicators", "literature review", "metrics", "assessment", "evaluation", "measuring". From six literature review works, it has been possible to get access to papers, reviews of papers, works from institutional organizations and from consulting agencies dealing with the measurement of circular economy level, addressing the assessment at the level of material, product, company and nation. The very first criterion for the selection of the indicators was indeed driven by the TREASURE's level of the analysis: being the circularity addressed at the material and product level, the relevant indicators to be collected are the ones that are classified as "nano" and "micro" indicators using the specific terminology adopted to describe the CE implementation level of analysis. Considering no double counting of indicators reported by more than one of the six literature reviews, 106 indicators were retrieved, including online, excel spreadsheet and analytical tools, which are classified according to the taxonomy defined and presented in the following sections.

3.4.2. Taxonomy definition and indicators' classification

Starting from the taxonomy provided in (Saidani, Yannou, et al., 2019), the taxonomy adopted in this deliverable to classify the indicators has been defined and reported in Table 9 below.

Table 9. Taxonomy definition

Taxonomy field	What it defines?
Description	Definition of the indicator and its working principles
CE implementation level	Level of the CE evaluation analysis addressed by the indicator (i.e., nano, micro, meso or macro level). Actually, only nano and micro level were addressed.
Evaluation method	Type of assessment approach provided by the indicator (i.e., qualitative or quantitative approach)
Dimensionality	Number of outputs provided by the indicator (i.e., single indicator or set of indicators)
Data required	Overview of required data to calculate the indicators
Evaluation format	Type of formulation of the indicator (i.e., excel spreadsheet tool, web-based tool, analytical formula(s), multi-criteria decision tool)
Involved life cycle phase(s)	Life cycle phases addressed by the indicator (i.e., production, use, EoL)
Purpose	Final usage for which the indicator was developed (i.e., information purpose, helping to understand the situation, e.g., tracking progress, benchmarking, hotspot identification; decision-making purpose, helping to take action for managerial activities, strategies formulation, policy choice; communication purpose, internally on the achievements to the stakeholders, or externally to the public; and learning purpose, e.g., education of workforce, awareness among consumers)
Transversality	Applicable generically or to a specific industrial application field

According the defined taxonomy, the set of 106 indicators were analysed and all the information required to fill in the fields were collected in an excel spreadsheet. The following considerations come out from filling the excel spreadsheet:

- There is a significant presence of set of indicators (multiple indicators);
- The majority of the indicators' field of application is not specified, since they are applicable to different sectors;
- The most involved life cycle phase is the EoL;
- The most frequent purposes for which the indicators were developed are the information tracking and the decision-making purposes. The second one is the most interesting purpose in TREASURE context.

3.4.3. Selection criteria and resulting indicators' set

Given the list of 106 indicators classified accordingly to the taxonomy showed in the above section, two screening processes have been performed. The screenings were based on the taxonomy presented in the above section and on the applicability of the indicators to the TREASURE context and scopes.

The first screening of the indicators list has been carried out considering only the indicators with taxonomy fields "Evaluation method" and "Evaluation format" classified, respectively, as "quantitative" and "analytical formula(s)", namely only the indicators providing a measurable output were taken into consideration. The screening results in the selection of 62 indicators out of the initial set of 106.

Among this sub-set of 62 indicators, the second screening was carried out considering as selection criteria the taxonomy fields of "Data required" and "Involved life cycle phases". Considering the fitting to TREASURE context and the possibility to integrate the indicators as assessment instruments in an advisory logic scheme, only the indicators involving the evaluation of EoL performance, either of disassembly or recycling phases, were considered. The data required for the calculation of those indicators are analysed in terms of availability. The resulting indicators are 15 and are listed and described in the following sub-sections.

Recycling Index from Recyclability Benefit Rate (RBR_{RI})

The Recycling Index from Recyclability Benefit Rate (RBR_{RI}) is defined as the ratio of the potential environmental savings that can be achieved from recycling the product over the environmental burdens of virgin production followed by disposal (Favi, Germani, et al., 2017). It is given by:

$$I_{EOL,RC} = \frac{V_{RC}-C_{RL}-C_{dd}-C_C}{V_{RC}} \qquad \text{(Eq. 3.1)}$$

Where:

- $V_{Rc} = m * R_f * C_{Rc}$ is the value of recycled material, given by the multiplication of the mass of the component, m, in [kg], the recycling factor, R_f, [%], and the recycled material cost, C_{Rc}, in [€/kg];
- C_{RL} is the reverse supply chain cost [€];
- C_{dd} is the destructive disassembly operations cost [€];
- C_C is the cleaning operations cost [€].

Recycling Index (RI)

The Material-RI expresses the recycling rate of individual elements for the processing flow sheet of a specific product or redesign. The RIs were presented as a tool to visualise the quantified calculation of the recycling performance of a product or recycling route.

The following are the Material Recycling Flower and Recycling Index (see Figure 9) coming from recycling simulation (M. Reuter & Schaik, 2015).

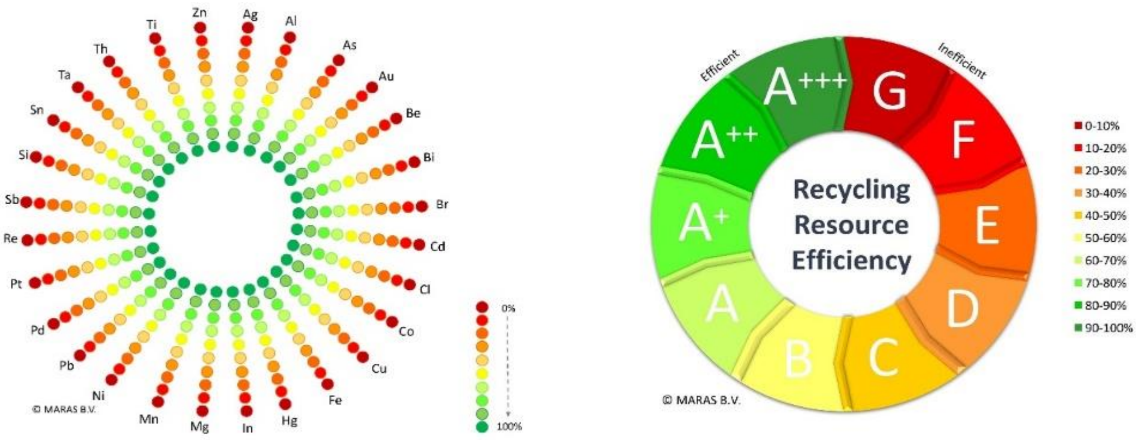

Figure 9. Material Recycling Flower (left) and Recycling Index (right)

Material Circularity Indicator (MCI)

The MCI measures the level of circularity of a product assessing how linear or restorative the flow of the materials is for the product and how long and intensely the product is used compared to similar industry average products.
MCI assigns a score between 0 and 1, describing the circularity of products that, in practice, will sit somewhere between these two extremes. Indeed, MCI ranges from a fully 'linear' product, which is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase (MCI=0), to a fully 'circular' product, which contains no virgin feedstock, is completely collected for recycling or component reuse, and where the recycling efficiency is 100% (MCI = 1). The MCI is given by:

$$MCI_p = \max\left(0, MCI'_p\right) \qquad \text{(Eq. 3.2)}$$

$$MCI'_p = 1 - LFI * F(X) \qquad \text{(Eq. 3.3)}$$

where:

- LFI is the Linear Flow Index, calculated as follows:

$$LFI = \frac{V+W}{2M+\frac{W_F-W_C}{2}} \qquad \text{(Eq. 3.4)}$$

It measures the proportion of material flowing in a linear fashion, with respect to the sum of the material flowing in a linear and a restorative fashion. Namely, it is the ratio of material sourced from virgin materials, V, and ending up as unrecoverable waste, W, over the total mass flow, $2M + \frac{W_F-W_C}{2}$, where M is the mass of the product, W_C is the mass of unrecoverable waste generated in the process of recycling parts of the product, and W_F is the mass of unrecoverable waste generated when producing recycled feedstock for the product);

- $F(X)$ is the Utility Factor, calculated as follows:

$$F(X) = \frac{0.9}{X}$$

- It is built as a function of the utility X of a product, accounting both for the length of the product's use phase with respect to industrial average lifetime (L/L_{avg}) and for the intensity of use with respect to an industrial-average product, in terms of functional units (U/U_{avg}) (Measuring Circularity, 2019).

Product Circularity Indicator (PCI)

The PCI is a further development of the Material Circularity Index from Ellen MacArthur Foundation, aiming at overcoming the main limitations identified in the MCI. It differs from the MCI since the recycled content is defined at the material level and not at the product level, considers and assigns more benefits to the reuse of components than to direct recycling, material recovery and material recycling are fully part of the product system, and flow exchanges of material with the external boundaries of the system are not treated as completely circular in the PCI calculation method (Bracquené, Dewulf, et al., 2020). The PCI is given by:

$$PCI = 1 - \frac{LFI}{X} \qquad \text{(Eq. 3.5)}$$

Where:

- $LFI = \frac{V+W+Q_{in}R_{in}-Q_{out}R_{out}}{V_{linear}+W_{linear}}$ (Eq. 3.6)
- $X = \left(\frac{L}{L_d}\right)\left(\frac{I}{I_d}\right) = \frac{Available\ or\ used\ functional\ units}{Expected\ functionale\ units}$ (Eq. 3.7)

The MCI and PCI indicators are deepened in §4.2 since they provide an aggregation vision of CE aspect to be evaluated.

Circular Calculator – Circularity (CC_C)

The CC_C is based on the percentage of circular mass present in the total number of products that are introduced to the market. It considers circular inflows and outflows, understood as the use of recycled resources and the non-generation of waste. The inflow of materials into the system contributes to half of the indicator and the outflow to the remaining 50%. In a fully linear scenario, the circularity is null as only virgin materials are used and at the end of their life, they all end up as waste. In a fully circular scenario, circularity is 100% as no virgin materials are used and no waste is generated (De Pauw, Van Der Grinten, et al., 2021; Dell'ambrogio, Menato, et al., 2022).

$$CC_C = 100\% - \frac{M\%_{virgin}+M\%_{wasted}+M\%_{downcycled}+M\%_{scrap}}{2} \qquad \text{(Eq. 3.8)}$$

Where:

- $M\%_{virgin}$ is the mass percentage of virgin materials (see ANNEX 3);
- $M\%_{wasted}$ is the mass percentage of wasted materials (see ANNEX 3);
- $M\%_{downcycled}$ is the mass percentage of downcycled materials (see ANNEX 3);

- M_{scrap} is the mass percentage of scrap materials (see ANNEX 3).

Old scrap Collection Rate (CR)

The CR is the measurement of how much of the end-of-life material in [kg] is collected and enters the recycling chain (UNEP-IPR, 2011).

The formula is reported below.

$$CR = \frac{EoL\ products\ collected\ for\ recycling}{EoL\ products} \qquad \text{(Eq. 3.9)}$$

Circularity Transition Indicators (CTI)

The CTI is based on material flows through the company. By analyzing these flows, the company determines its ability and ambition to minimize resource extraction and waste material flows (WBCSD, 2022). It entails the assessment of the flows within the company's boundaries (see Figure 10) at three key intervention points:

- Inflow – how circular are the materials the company sources?
- Outflow's recovery potential – how does the company design and process its materials to ensure they can be technically recovered (e.g., by designing for disassembly, design for recyclability, etc.)?
- Outflow's actual recovery – how much of the company's outflow is actually recovered?

In TREASURE, the following indicators can be extrapolated to be adopted at product or material level.

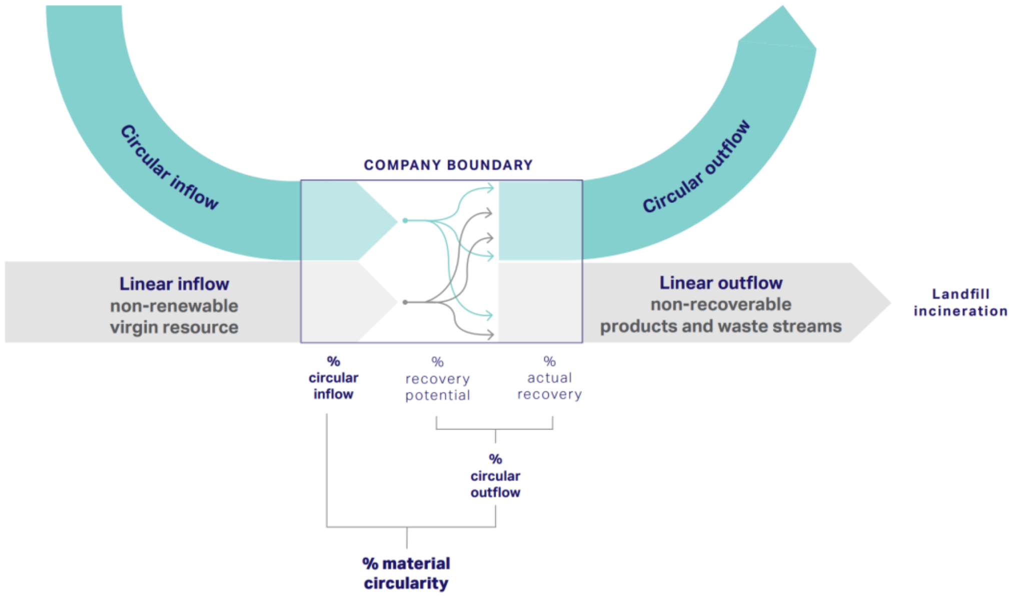

Figure 10. Circular Transition Indicator – material flows across company's boundary (source (WBCSD, 2022)*)*

Close the Loop indicator: % material circularity

$$\%\ material\ circularity = \frac{\%circular\ outflow\ total * total\ mass\ inflow - \%circular\ inflow\ total * total\ mass\ outflow}{total\ mass\ flow\ crossing\ system\ boundaries} \qquad \text{(Eq. 3.10)}$$

Where the $\% \, circular \, inflow$ of each component/product is given by the percentage of renewable or non-virgin content multiplied by the mass of the component/product; the $\% \, circular \, outflow$ of each component/product is given by the percentage expressing the recovery potential multiplied by the percentage expressing the actual recovery.

Optimize the Loop indicator: % critical material

$$\% \, critical \, inflow = \frac{mass \, of \, inflow \, defined \, as \, critical}{total \, mass \, of \, linear \, inflow} * 100\% \qquad \text{(Eq. 3.11)}$$

Value the Loop indicator: circular material productivity and CTI revenue

$$circular \, material \, productivity = \frac{revenue}{total \, mass \, of \, linear \, inflow} \qquad \text{(Eq. 3.12)}$$

CTI revenue is the revenue adjusted for the % material circularity of a product:

$$CTI \, revenue_{product} = \left[\frac{\%circular \, inflow + \% \, circular \, outflow}{2}\right] * revenue \qquad \text{(Eq. 3.13)}$$

Material and Energy Circularity Indicators (MECI)

The MECI is a simplified MCI considering only material and energy (heat and electricity) circularity, adopted for larger scale supply networks with numerous technologies, process and products (Zore, Čuček, et al., 2018).

In this case, energy circularity is not taken into account, as it is not closely related with the TREASURE project.

$$Circularity \;\; of \, raw \, materials \, in \, the \, supply \, chain \, \left(F^{Material}\right) = \frac{\sum_{i \in R} q_{mi}{}^{Circulated \, feedstock}}{\sum_{i \in R} q_{mi}{}^{Total \, feedstock}} * 100\% \qquad \text{(Eq. 3.14)}$$

Where:

- $q_{mi}{}^{Total \, feedstock}$ represents the total amounts of feedstock used in the production system;
- $q_{mi}{}^{Circulated \, feedstock}$ stands for recycled, reused or recovered feedstock (only recycled feedstock is considered in TREASURE case).

Resource Efficiency Assessment of Products (REAPro)

The REAPro method allows to assess the resource efficiency of a selected product considering a set of different criteria. In particular, the method is structured in order to drive the practitioners through the analysis of EoL treatments and to identify potential areas of improvement. The calculation of Reusability/Recyclability/Recoverability (RRR) rate (in mass and in terms of environmental impacts/benefits) and Recycled content rate (in mass and in terms of environmental impacts/benefits) is performed (Ardente & Mathieux, 2014).

Reusability/Recyclability/Recoverability (RRR) rates (in mass):

$$RRR = \frac{\sum_{I=1}^{P} m_i * X_{RRR,i}}{m} * 100 \qquad \text{(Eq. 3.15)}$$

Where:

- RRR = Reusability/Recyclability/Recoverability rates [%] (only Recyclability for TREASURE case);
- m_i = mass of the ith part of the product [kg];
- $X_{RRR,i}$ = rates of the i_{th} part of the product that is potentially reusable/recyclable/recoverable (X_{reuse}; X_{recyc} and X_{recov} respectively) [%] (only recyclable for TREASURE case).

Reusability/Recyclability/Recoverability (RRR) rates (in terms of environmental impacts/benefits):

$$R_{cyc,n} = \frac{\sum_{i=i}^{p}\left(m_{recyc_i} * X_{recyc_i} * D_{n,i}\right) + \sum_{i=i}^{p}\left(m_{recyc_i} * X_{recyc_i} * (k_i * V_{n,i}^* - R_{n,i}))_{n,i}\right)}{V_n + M_n + U_n + D_n} * 100 \qquad \text{(Eq. 3.16)}$$

Where:

- p = number of parts of the product [dimensionless];
- m = total product's mass [kg];
- $R_{cyc,n}$ = "Recyclability benefit" rate (for the "n" impact category) [%];
- m_{recyc_i} = mass of the i_{th} recyclable part of the product [kg];
- V_n, M_n, U_n, D_n = impacts (for the "n_{th}" impact category) due to the production of virgin materials, manufacturing, use and disposal of the product [unit];
- $V_{n,i}^*$ = impact (for the "n_{th}" impact category) due to the production (as virgin) of the material assumed to be substituted by the i_{th} recyclable material of the product [unit/kg];
- $R_{n,i}$ = impact (for the "n_{th}" impact category) due to the recycling of the i_{th} recyclable part [unit/kg].

Recycled content rate (in mass)

$$R_{content} = \frac{\sum_{i=1}^{p} m_{r,i}}{m} * 100 \qquad \text{(Eq. 3.17)}$$

Where:

- $R_{content}$ = recycled content of the product [%];
- $m_{r,i}$ = mass of recycled material in the i_{th} part [kg].

Recycled content rate (in terms of environmental impacts/benefits)

$$RCB_n = \frac{\sum_{i=1}^{K} m_{r,i} * (V_{n,i} - R_{n,i}^*)}{V_n + M_n + U_n + D_n} * 100 \qquad \text{(Eq. 3.18)}$$

Where:

- RCB_n = recycled content benefit rate of the product (for the n_{th} impact category) [%];
- $R_{n,i}^*$ = impact (for the n_{th} impact category) of the recycled material used for the i_{th} product's part [$\frac{unit}{kg}$];
- $m_{r,i}$ = mass of the i_{th} recycled material in the product [kg];
- $V_{n,i}$ = impact (for the n_{th} impact category) due to the production (as virgin) of the material substituted by the i_{th} recyclable material of the product [$\frac{unit}{kg}$].

Potential Recycle Index (PRI) – part of Sustainability Performance indicators (SPI)

The PRI is defined as the measurement of the degree of potential recycling of components within a product. The recycling of components contributes to reducing the primary extraction of raw material; therefore, the material follows a circular path in a new product lifecycle. Nevertheless, the material flow balance is not 100% conservative in the product lifecycle due to the recycling process efficiency, which involves an unrecoverable waste fraction that is generated (Mesa, Esparragoza, et al., 2018).

$$Potential\ Recycle\ Index = \frac{\sum_{i=1}^{n} M_i * F_i * E_i}{M_t} \qquad \text{(Eq. 3.19)}$$

Where:

- M_i is the mass of the i_{th} component;
- F_i is the fraction of recyclable mass of the i_{th} component;
- E_i is the efficiency of the recycling process for the same component;
- M_t is the total mass of the product;
- n is the number of modules or components involved in the product.

Product Recycling Desirability Index (PRDI)

The PRDI is an integration of Material Security Index (MSI) and Recycling Technology Readiness (TRL). This integration enables a generic approach to the global assessment of recycling potential. MSI is the availability to access to the material resources on which economies depend on, as well as the ability to cope with volatility, increasing scarcity and rising prices. TRL is technological maturity assessment approach (Mohamed Sultan, Lou, et al., 2017).

$$D_{Desiderability} = \left(D_{Simplicity} + D_{MSI} + D_{TRL}\right) \qquad \text{(Eq. 3.20)}$$

$D_{Desiderability}$ is the aggregate desirability recycling index for a selected product considering multiple factors of products simplicity, material security index of constituent materials and the maturity of technologies for reclaiming the materials, where each term is defined as follows:

$$D_{MSI} = \sum_{i=1}^{n} \frac{M_i * S_i}{M_T * S_{top}} \qquad \text{(Eq. 3.21)}$$

Where:

- D_{MSI} is the recycling desirability considering the material security index;
- n is the maximum number of a particular discrete material type in the product;
- M_i and M_T are the mass of material in a product or component and total product mass respectively;
- S_i is the material security index of recycling a particular material that is part of a product assembly;
- S_{top} is the top scale for the material security index.

$$D_{TRL} = \sum_{i=1}^{n} \frac{M_i * R_i}{M_T * R_{top}} \qquad \text{(Eq. 3.22)}$$

Where:

- D_{TRL} is the recycling desirability, considering recycling technology maturity;
- n is the maximum number of a particular recycling technology used in the product;

- M_i and M_T are the mass of the discrete material in a product or component and total product mass respectively;
- R_i is the technology readiness level assessment of recycling technology for a particular material that is part of the product assembly;
- R_{top} is the top scale for the TRL scale.

$$D_{Simplicity} = 1 - \left(\frac{H}{H_{top}}\right) \qquad \text{(Eq. 3.23)}$$

Where:

- $D_{Simplicity}$ is the recycling desirability index considering simplicity of separating materials (the inverse of complexity);
- H_{top} is the top scale for the material complexity index
- H is the complexity index:

$$H_m = K * \sum_{i=1}^{M} C_i \, logC_i \qquad \text{(Eq. 3.24)}$$

Where:

- M is the number of component materials in a mixture;
- C_i is the mass fraction of a material in a part that makes a product assembly;
  - K is a constant value of -1 used to change the values into a positive index.

Multidimensional Indicator Set (MIS)

The MIS offers a framework that aims to support decision-making processes on product design, to identify opportunities for the optimization of WEEE EoL scenarios, and to assess the achieved (or expected) results of implemented (or planned) recycling optimization strategies. It involves four indicators: Weight recovery of target material(s), Recovery of scarce materials, Closure of material cycles and Avoided environmental burdens (Nelen, Manshoven, et al., 2014).

$$Recycled\ index\ (RI) = a_1 * I_W + a_2 * I_S + a_3 * I_C + a_4 * I_E \quad \text{(Eq. 3.25)}$$

With weighting factors $(a_i) \sum a_i = 1$;

Where:

$$Recycled\ material\ weight\ (I_W) = \frac{\sum_{i=1}^{m} W'_i}{\sum_{j=1}^{m} W_j} \qquad \text{(Eq. 3.26)}$$

- Numerator represents the total weight of recycled target materials;
- Denominator represents the total weight of the input of the recycling process;
- m is the number of output fractions from the recycling process, destined for material recovery;
- n is the number of materials present in the input of the recycling process;
- W'_i is the weight of target material(s) in output fraction i;
- W_j is the weight of material j present in the input of the recycling process.

The indicator equals 1 in the hypothetical situation that over the complete recycling chain all input materials are completely recovered in output fractions composed of only target materials and desired impurities.

$$Recycled\ material\ criticality\ (I_S) = \frac{\sum_{i=1}^{m} W'_i * EI_i * SR_i}{\sum_{j=1}^{m} W_j * EI_J * SR_J} \qquad \text{(Eq. 3.27)}$$

- Numerator represents the total criticality of recycled target materials;
- Denominator represents the total criticality of materials present in the input of the recycling process;
- m is the number of output fractions from the recycling process, destined for material recovery;
- n is the number of materials present in the input of the recycling process;
- W'_i is the weight of target material in output fraction i;
- W_j is the weight of material i present in the input of the recycling process;
- EI is the economic importance of the material;
- SR is the supply risk of the material.

The indicator equals 1 in the hypothetical situation that all materials present in the input of the recycling process of which the supply is of concern to the EU, are completely recovered as target material(s) and desired impurities in output fractions.

$$Degree\ of\ material\ cycle\ closure\ (I_C) = \frac{\sum_{i=1}^{m} W'_i * V'_i}{\sum_{j=1}^{m} W_j * V_J} \qquad \text{(Eq. 3.28)}$$

- Numerator represents the current market price of the recycled output fractions;
- Denominator represents the current market price of the materials present in the EEE;
- m is the number of output fractions from the recycling process, destined for material recovery;
- n is the number of materials present in the input of the recycling process;
- W'_i is the output fraction that contains material i;
- W_j is the weight of material i present in the input of the recycling process;
- V'_i is the current market price of output fraction i;
- V_i current market price of the material j, present in the EEE.

The indicator equals 1 in the ideal situation that all materials are recovered and the market price that can be obtained for the recycled materials, products or substances equals the current market price of the materials in the original device.

$$Avoided\ environmental\ burdens\ (I_E) = \frac{\sum_{i=1}^{m} W'_i * B'_i}{\sum_{j=1}^{m} W_j * B_J} \qquad \text{(Eq. 3.29)}$$

- Numerator represents the environmental burden that is avoided by the recycling of the materials;
- Denominator represents the total environmental burden generated by the production of the materials in the EE;
- m is the number of output fractions from the recycling process, destined for material recovery;
- n is the number of materials present in the input of the recycling process;
- W'_i is the weight of target material(s) in the output fraction i;
- W_j is the weight of material i present in the input of the recycling process;

- B'_i is the environmental burden associated with the production of the material that is avoided by the recycled output fraction;
- B_i environmental burden associated with the production of the material present in the EEE.

The indicator equals 1 in the ideal situation of closed-loop recycling of all input materials. Its value decreases with reduced material weight recovery or when the output fraction substitutes a resource with a lower production burden than that of the production of the materials that compose the fraction. If desired, specific environmental impact categories can be accounted for (e.g., climate change or eco-toxicity).

Material Reutilization Score (MRS) (part of Assessment of Circular Economy Strategies at the Product Level (APL))

The MRS is the metric used to quantify material reutilization. With regard to the technical cycle, the MRS quantifies the recyclability potential of a product considering two variables: the intrinsic recyclability (IR) of the product, i.e., the % of the product that can be recycled at least once after its initial use stage and the % recycled content (RC). The MRS is given by the weighted average of the two variables, where the first one is given twice the weight of the second one (Niero & Kalbar, 2019).

$$Material\ Reutilization\ Score\ (MRS) = \frac{[(\%\ IR\ of\ the\ product)*2]+[(\%\ RC\ in\ the\ product)*1]}{3*100}$$

(Eq. 3.30)

Where:

- IR is the intrinsic recyclability of the product, namely the % of the product that can be recycled at least once after its initial use stage;
- RC is the % of recycled content.

Circularity of Material Quality (QC)

The QC is based on the energy use of recycled products versus their counterparts produced from primary material inputs only (Steinmann, Huijbregts, et al., 2019).

$$Material\ Quality\ (Q_C) = \frac{\alpha*(E_{prod,s}-E_{r,s})-E_{c,s}-\beta*E_{d,s}}{E_p} \quad \text{(Eq. 3.31)}$$

Where:

- α is the amount in kg of secondary material that can be made from recycling 1 kg of primary material. Note that α is < 1 if there are losses and no extra primary material input is required, while α > 1 if relatively large amounts of primary materials need to be added for dilution (dimensionless);
- β is the ratio of diluting material to primary material to be recycled (dimensionless);
- $E_{prod,s}$ is the cradle-to-gate life cycle energy (in $\frac{MJ}{kg}$) required for producing material with the same quality as the secondary material from primary inputs (i.e., without the use of recycled materials) (in $\frac{MJ}{kg}$);
- $E_{r,s}$ is the direct cradle-to-gate life cycle energy requirement for producing the secondary material from material that is to be recycled (in $\frac{MJ}{kg}$);

- $E_{c,s}$ is the energy required for cleaning (can include pre-processing, pre-treatment and sorting) the material inputs per kg primary material to be recycled (in $\frac{MJ}{kg}$);
- $E_{d,s}$ is the embodied cradle-to-gate life cycle energy in the primary materials required for dilution, necessary to obtain secondary material of sufficient quality (in $\frac{MJ}{kg}$);
- E_p is the cradle-to-gate life cycle energy required for producing 1 kg of primary material (in $\frac{MJ}{kg}$)

Eco-costs of resource scarcity

The "eco-costs" model presented in §3.2 can be considered as an indicator for circularity in the theory of the circular economy for the endpoint indicator of resource scarcity.

The environmental mid-point indicators for resource scarcity are the following: metals scarcity, water scarcity, land-use, uranium, fossil fuels. They are translated into monetary end-point indicator via the monetary characterization factors (Metrics, 2022).

A third and final selection round is expected to be carry out based on a validation survey, whose aims and structure will be described in detail in D2.2. The survey will explore the consortium opinion on the applicability of the selected circular indicators as instrument to catch the circularity level of the core automotive value chain processes, exploiting both the research and industry perspectives.

Circularity indicators conclusions

Conclusions concerning this chapter have been provided in Section 5109 and can be consulted under the sub-section '*Methodologies and indicators selected for the circularity assessment*'.

4. Sustainability aggregation framework

In this chapter, the main findings of a literature revision have been reported investigating the integration of the assessments for the environmental, economic, and social spheres of sustainability plus the one for circularity domain in an overall Life Cycle Sustainability and Circularity Assessment framework (LCS&CA). An analysis of the aggregation approaches, both at the single area level and at the overall LCS&CA level, has been carried out to depict the integration methodology best fitting the TREASURE project's peculiarities and objectives. Responses to a questionnaire circulated among project partners with experience in sustainability have been also considered.

An LCSA and circularity analysis uses the combination of several methodologies, as a single, universally recognised method for performing LCSA does not exist. Methodologies for performing assessments in the individual areas of sustainability and circularity, on the other hand, are more widely recognised and provide quantitative indicators. Interpreting the results and using them for decision-making is not straightforward: within the same area, indicators covering different sub-areas of impact coexist. How, then, is it possible to make decisions when the information provided by the set of indicators may be conflicting? Similar considerations can also be made from the perspective of LCS&CA when several sustainability areas must be assessed simultaneously. The literature review carried out in this chapter was aimed at understanding which aggregation methods existed; which ones were recommended for the individual areas of sustainability and circularity; which ones were recommended for the aggregation of the three areas with that of circularity. It was also examined under which conditions it made sense to aggregate, respectively under which conditions it was recommended to keep the data disaggregated. Life Cycle Sustainability Assessment (LCSA) is defined by the UNEP/SETAC as the "evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle" (Valdivia, Ugaya, et al., 2013).

In the last decade, a number of sustainability assessment approaches, tools and discussion papers have been presented to experts from academia, policy bodies, agencies for development, addressing nation, regional or sectoral concerns. However, no systematic quantitative tool for the holistic evaluation of sustainability impacts is available yet, but a recommendation of principles to be used (World Bank, 2010). As already presented in §2, the evaluation of the single areas of sustainability and of circularity in a lifecycle perspective is almost acknowledged both in academic and industrial contexts, even though some limitations have been highlighted and here summarized. Environmental life cycle assessment (LCA) and life cycle costing (LCC), the economic component of the approach, are quite developed and are well on their way into mainstream business practices. LCA is the most mature and standardized methodology within LCSA. Besides the widely used classical approach to assess a specific process chain of a product or service, LCAs based on economic input–output tables are also conducted, concentrating on one side on the process chain, on the other side on the supply chains of a technology or sector. The limitations for LCA as a part of LCSA are mainly the non-transparent representation of methodological aspects, e.g., applied LCIA method, and the documentation of the inventory. From a literature review, most SLCA studies focus on the workers and refer to ISO 14044 (ISO, 2006b) as standard approach to be transferred to SLCA in the framework of LCSA. Main limitations are: (1) the selection of the indicators to quantitatively measure social impact, though being able to capture social complexities, cost-effectiveness, and time constraints; (2) the transferability of case-specific indicators to other cases and at meso-macro level. Choosing purely social indicators is often challenging. Consequently, some studies combine the social and the economic dimension and use socioeconomic indicators for their analysis. To address the economic sustainability of a product or technology (LCC), its total costs are evaluated from the perspective of all actors directly involved with the product or technology (Swarr, Hunkeler, et al., 2011). LCC can differently considered by the different actors involved along the life cycle: manufacturers can benefit from the comparison of a product's competitiveness with alternatives in addition to highlighting the key drivers of costs and areas in which improvements could be made; for government procurement, a major motivation for conducting life cycle costing was the recognition that there had been insufficient focus on the costs incurred during the operating life of a product, whereas the investment or acquisition costs were viewed to be over-estimated; for consumers, to include in the analysis assurances and other costs related to maintenance and use phase. Limitations of this method are mainly related to the evolution in time of the economic conditions, the difficult conversion of externalities into monetary values.

Once sustainable indicators concerning the single areas are calculated, the normalization, weighting, and aggregation, together methods for Multi-Criteria Decision Analysis (MCDA), considered as alternative methods to normalisation and therefore explained in a dedicated chapter (see §4.1.1.1) (Pizzol, Laurent, et al., 2017) (Prado, Cinelli, et al., 2020) (Wulf, Werker, et al., 2019; Wulf, Zapp, et al., 2017), of different impact categories can be performed. Nevertheless, UNEP/SETAC guidelines advises the presentation of plain results without weighting and aggregation. Thus, ranking approaches are then necessary to include qualitative results from the SLCA. The use of MCDA for decision making based on LCSA is a value-based process (De Luca, Iofrida, et al., 2017). MCDA do not have a well-defined (deterministic) solution, but a set of Pareto-optimal solutions. These solutions represent the optimal trade-offs between objectives and may be subject to large variations due to the uncertainties of the input data. It is necessary to define which objectives are the most important, which ranges of given parameters are acceptable, etc, to identify satisfactory solutions. This formulation of preferences can be done in three ways (Branke, Deb, et al., 2008): posteriori, after retrieving the results from the calculations; a priori (Meignan, Knust, et al., 2015) (Adriana Debora Piemonti, Babbar-Sebens, et al., 2017), thus before results are available; or interactively, as the optimization progresses, by involving the human user in the search process. The decision-maker can directly influence the impact of the optimization procedure, using expert knowledge and experience (Meignan, Knust, et al., 2015), (Adriana D. Piemonti, Macuga, et al., 2017), (Liu, Dwyer, et al., 2018) focusing only on the most promising regions of the solution space, reducing thus the computational time (Liu, Dwyer, et al., 2018), (do Nascimento & Eades, 2005) and increasing confidence in the obtained solutions [59]. However, these methods are still scarcely used and lack a formalised visualization method. The use of parallel coordinates has attracted attention but was limited to an a posteriori illustration of Pareto solutions (Miettinen, Eskelinen, et al., 2010) (Ashour & Kolarevic, 2015) (Abi Akle, Minel, et al., 2017) (Sunith Bandaru, Amos H.C. Ng, 2017); or with a limited number of solutions. Eventually, a proper dissemination of LCSA approaches and demo cases is missing: some approaches are not designed to be used by others (e.g., PROSA (Grießhammer, R., 2007) is used as a label for products and no scientific publications regarding the methodology are published, while others published some scientific papers, but did not reveal every aspect of the methodology, e.g., weighing factors), while other are lacking in the visualization of the calculated indicators. For instance, a Life Cycle Sustainability Dashboard (LCSD) (Traverso, M.; Finkbeiner, 2009) has been proposed to compare sustainability performances of the same group of products as an effective supporting tool to present the results in dissemination activities or decision-making processes in which experts and non-expert stakeholders are usually involved.

In this articulated context, the following sections offer a more detailed vision on the assessment aggregation frameworks within the single areas of sustainability considering at the same time also the circularity evaluation and providing insights concerning the integration of the different areas.

4.1. Generic steps in aggregation phase

In the following, the main aggregation methods that are transversely applicable to all areas of sustainability have been listed, while in the §4.2, §4.3, §4.4, §4.5 domain-specific methods have been considered and cross-references to transversal methods have been given where appropriate:

- *Normalization*, it is the calculation of the magnitude of category indicator results relative to reference information. Also, to be considered as an alternative to normalization is the *Multiple-Criteria Decision Analysis methods (MCDA),* that explicitly evaluates multiple conflicting criteria in decision making;
- *Weighting*, it is the conversion and possibly the aggregation of indicator results across impact categories using numerical factors based on value-choices. LCIA data prior to weighting should remain available;
- *Aggregation/Grouping*, it is the sorting and/or the scoring and ranking of the impact categories based on value-choices;
- *Visual approaches*, it is the practice to show indicators addressing different areas of sustainability and circularity in one reference-model.

4.1.1. Normalization approaches

The impact normalisation phase, following the calculation phase, is a key step as it allows the impact data to be scaled or transformed to equalise the contribution of each impact category. By making a ratio between impact results and reference values, it is possible to normalise impact indicators.

Eq. 4.1 formulated by (Laurent & Hauschild, 2015), represents the normalization formula where NS_i^{SYS} is the normalized impact indicator scores for impact category *i* of the system (*SYS*), that result to be the ration between CS_i^{SYS}, the impact indicator score characterised for impact category *i* of the system (*SYS*) under consideration, and CS_i^{ref} and the normalization reference value for the impact category *i*:

$$NS_i^{SYS} = \frac{CS_i^{SYS}}{CS_i^{ref}} \qquad \text{(Eq. 4.1)}$$

Eq. 4.2 is an example of the use of normalisation in which the global normalisation factor for environmental impact: i = climate change per person, was calculated. The global normalisation factor reported here is built on a collection of data on emissions and resources extracted at global scale in 2010 (Sala, Crenna, et al., 2017).

$$8{,}40E+03_{kg\ CO_2\ eq.} = \frac{5{,}79E+13_{kg\ CO_2\ eq.}}{6{,}896E+09_{(World\ population)}} \qquad \text{(Eq. 4.2)}$$

Normalisation factors (NF) are calculated based on external resources such as results from regional/global inventories and data sources or by industry type and are characterised through impact assessment methods for a certain impact category in a reference year (Benini L, Mancini

L, Sala S, Manfredi S, Schau E, 2014) (Sala, Crenna, et al., 2017). Normalisation permits a comparison only in relation to the reference system considered at the level of the single impact category. To compare different impact categories, a weighting step is required. due to intrinsic modelling choices, normalisation is not recommended for presenting an evaluation to the general audience (Roesch, Sala, et al., 2020) (Wulf, Zapp, et al., 2017). Within the PEF Guide (European Commission, 2013), normalisation is an optional but recommended step.

Normalisation is distinguished into internal and external normalisation:

- Internal normalisation: exploits a comparative benchmark and is based on the difference between minimum and maximum values or comparison with a reference benchmark. Internal normalisation can also refer to pairwise comparison of criteria, which brings this methodology closer to multi-criteria decision analysis (MCDA) methods, making it rather an alternative method to normalisation than a normalisation approach per se (Wulf, Zapp, et al., 2017) (Wulf, Werker, et al., 2019). For this reason, it was decided to dedicate a separate chapter to MCDA methods.
- External normalization: External normalisation is based on reference systems with a worldwide or territorial boundary; on present, future, or potential scenarios; on LCI factors using the geometric mean for the same product stream in the database; or based on the absolute natural limits of the system, such as the maximum impacts that ecosystems can sustain and recover from without suffering permanent damage to functional integrity.

In Table 10**Errore. L'origine riferimento non è stata trovata.**, reconstructed on the basis of ORIENTING project (Horn & Zamagni, 2020), a list of possible approaches to standardisation are presented and the benefits and drawbacks have been catalogued for each of them. The table has more focus on the environmental domain, as it is the one where normalization approaches are more established. In the context of TREASURE, internal normalisation approaches, such as MCDA, can be used to obtain normalisation factors based on the preferences of the project partners, e.g., to define the goal and scope of the project in the various areas of sustainability. External normalisation approaches, on the other hand, are more suitable for obtaining normalisation factors on a more scientific basis, and can thus be used in LCA, LCC, SLCA and circularity assessment analyses. Among the external normalisation approaches, taking into account the boundary of the chosen system, global normalisation factors should be used when the impact categories considered describe global impacts (e.g., in the LCA the "climate change" category), vice versa if local impact categories are being considered, e.g. in a European context, territorial (EU) based normalisation factors should be used (e.g., for SLCA analysis, when measuring social impact categories, it would be appropriate to benchmark with European-level datasets to compare social performance). If databases are used to carry out assessments, and measured data are obtained on-site at a later stage, it must be ensured that it is possible to change the normalisation parameters set by default by the databases, this last method is presented in the Table 10**Errore. L'origine riferimento non è stata trovata.** under the name LCI-database factors.

Table 10. Normalization approaches from (Pizzol, Laurent, et al., 2017)

Type of normalization	Methods	Benefit	Drawbacks
Internal	Baseline / maximum / sum	Based on internal data	Only applicable in studies where alternatives are compared. Results fail to allow interpretation of the absolute magnitude of impacts. For these reasons, this approach is very controversial in LCA.
	Outranking methods	Avoids the need for additional weighting procedures and, consequently, decreases the risk of bias through offsetting. Qualitative or semi-qualitative impact categories can be evaluated.	It cannot represent an overview of the magnitude of impacts. This method is considered as an alternative method to normalisation, rather than a normalisation approach per se (Pizzol, Laurent, et al., 2017) (Prado, Rogers, et al., 2012) (Wulf, Werker, et al., 2019) (Wulf, Zapp, et al., 2017).
External	Global factors	The significance of the impacts in a global context can be evaluated, while the most relevant impacts can be identified.	It can include uncertainties, e.g., when using impact categories that describe local effects. against global values could cause over- or underestimated results, besides the uncertainties intrinsic to the global statistics (Benini L, Mancini L, Sala S, Manfredi S, Schau E, 2014).
	Territorial-based (production only)	The reference system is based on the total production within a territory boundary.	Some inconsistencies may occur, in case the boundaries of the reference system and the system under study are not equal (for example, the system includes raw materials that are produced in another territory;
	Territorial-based (consumption only)	The reference system is based on the total consumption within a territory boundary.	Export is excluded using this method.
	Status-quo	Allows comparison between the status quo and the current or future scenario that one wants to consider.	Uncertainties may arise concerning which status quo has to be considered.
	LCI-database factors	Many databases allow changes to the normalisation parameters set by default.	There might occur uncertainties including the lack of consistency in the scoping, LCI and LCIA modelling between the studied system and the normalization reference system and the datasets.
	Carrying capacity-based	Based on the absolute ecological limits, often referred to as absolute environmental sustainability assessment. Carrying capacity is the maximum impact that the ecosystems can sustain and recover, without suffering permanent damage to the functional integrity, and in the case of non-renewable resources, it represents the rate at which renewable substitutes can be developed. It can be applied to various spatial and temporal scale, but since it addresses the natural systems, it is usually based on planetary boundaries.	This is a method under development. An important issue regarding this approach is that the existing carrying capacity factors are context dependent, and the use of them outside the original context could be misleading (Bjørn, A., & Hauschild, 2015).

4.1.1.1. Multiple-criteria decision analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is used to evaluate different alternatives with the help of the stakeholders involved, allowing the construction of an aggregation model of multi-criteria evaluations of alternatives. This type of model is used to compare alternatives as the output consists of a ranking of alternatives or a priority ranking, thus supporting the decision-making process. This method is considered as an alternative method to normalisation, rather than a normalisation approach per se (Pizzol, Laurent, et al., 2017) (Prado, Rogers, et al., 2012) (Wulf, Werker, et al., 2019) (Wulf, Zapp, et al., 2017). The AHP method is also the MCDA most frequently used, according to (Thies, Kieckhäfer, et al., 2019), as can be seen in Figure 11, which shows the prevalence of MCDA methods in LCSA studies.

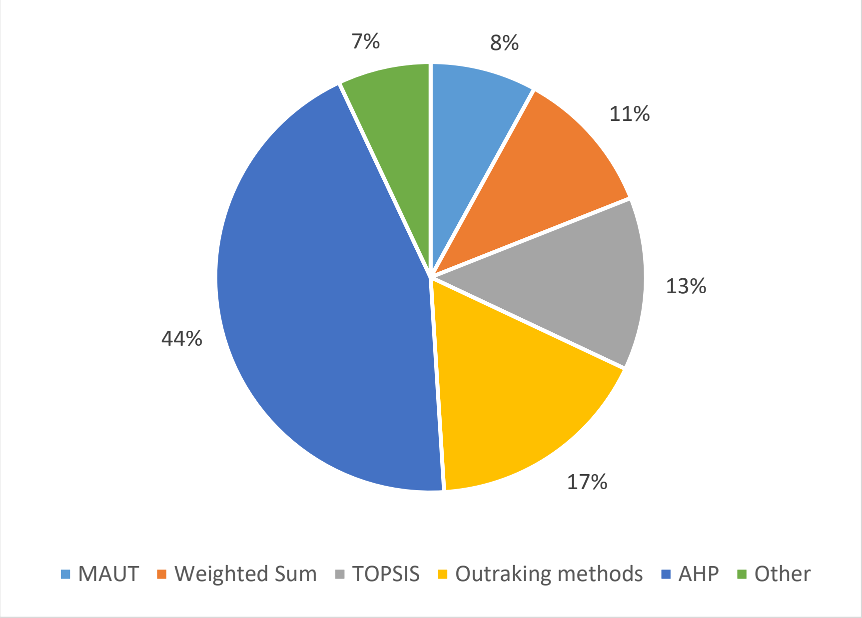

Figure 11. Most frequent MCDA methods in LCSA studies. Based on data from Thies, C., et al., 2019. Operations research for sustainability assessment of products: a review. Eur. J. Oper. Res. 274 (1) 1–21.

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making process introduced by (Saaty, 1977). The use of this approach has been stimulated by the fact that AHP matrix enjoys precise mathematical and methodical properties and requires input data that are easy to obtain. For the correct use of the tool, excel templates and free online tools can be used. As a first step, it is necessary to determine the main criteria to be evaluated, which should not be more than nine, so as not to affect the consistency of the grade, since it is complicated for human beings to compare more than nine criteria with each other while remaining consistent in their evaluations. If it is necessary to evaluate more than nine criteria, it is possible to nest the criteria in clusters, or to reduce the number of criteria. Reducing the number of criteria also enhances the consistency of responses by participants, thus reducing the risk of a high Consistency Ratio (CR). The CR is an indicator that precisely measures the consistency of the participants' answers; a high CR value means that that participant answered inconsistently. Usually, a CR value above 10% is considered too high. However, it is possible to use a balanced rating scale to determine whether the CR is too high, and there are online tools that help the participant to revise their ratings by suggesting changing the most inconsistent answers. It is also possible to assign a different weight to participants or leave an equal weight, depending on the context and who is participating. This method allows participants to compare criteria with each other, assigning a binary A or B value as to the preference of one criterion over the other. For each preference, it

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is also possible to assign an integer numerical value from 1 to 9 to quantify the intensity of importance of one criterion over the other, where e.g., 1 means equally important, and 9 means extremely more important. The CR is calculated using the following formula (Sala, Crenna, et al., 2017):

$$CR = \frac{CI}{RI} \qquad \text{(Eq. 4.3)}$$

Where CI represents the Consistency Index and is calculated for each participant using the following formula:

$$CI = \frac{\lambda \max - n}{n-1} \quad \text{(Eq. 4.4)}$$

RI is the Random Consistency Index and varies depending on the size of the matrix, e.g., for a 7-criteria matrix, RI = 1.32. There are literatures stating that generally only answers with CR<0.1 should be accepted. D. Goespel (Goepel, 2013), states that it is possible to accept CR values up to 0.2. Using special tools, such as the excel template developed by (Goepel, 2018), however, it is possible to indicate inconsistent answers to the participants so that they can change them to lower the CR score so that their grade can be considered valid. Once all participants have voted, it is possible to present the results in the form of an AHP matrix or other graphical representations highlighting preferences on the criteria to be evaluated. The AHP also makes it possible to calculate the S-indicator, which is an indicator used to measure the homogeneity of priorities among participants. The consensus indicator S can take values ranging from 0% to 100%, where 0% means that there is no consensus among the respondents regarding the available options and 100% means that there is full consensus among all respondents. The indicator S is calculated as follows:

$$S = \frac{\left[M - \frac{H_{\alpha_{min}}}{H_{\gamma_{max}}}\right]}{\left[1 - \frac{H_{\alpha_{min}}}{H_{\gamma_{max}}}\right]} \quad \text{(Eq. 4.5)}$$

Where:

$$M = \frac{1}{H_\beta} \qquad \text{(Eq. 4.6)}$$

$H_{\alpha,\beta,\gamma}$ are the Shannon entropic values of the different participants, with p_{ij} calculated priorities for criteria i = 1 to N and for decision maker j = 1 to K, and are defined as follows:

$$H_\alpha = \frac{1}{K} \sum_{j=1}^{K} \sum_{i=1}^{N} -p_{ij} \ln p_{ij} = \frac{1}{10} \sum_{j=1}^{10} \sum_{i=1}^{7} -p_{ij} \ln p_{ij} \qquad \text{(Eq. 4.7)}$$

$$H_\gamma = exp\left(\sum_{j=1}^{N} -\bar{p}_j \ln \bar{p}_j\right) = exp\left(\sum_{j=1}^{7} -\bar{p}_j \ln \bar{p}_j\right) \qquad \text{(Eq. 4.8)}$$

$$H_\beta = \frac{H_\gamma}{H_\alpha} \qquad \text{(Eq. 4.9)}$$

Using a linear scale, it is possible to calculate:

$$H_{\alpha_{min}} = \exp\left[-\frac{c_{max}}{N+c_{max}-1} \ln\left(\frac{c_{max}}{N+c_{max}-1}\right) - (N-1)\frac{1}{N+c_{max}-1} \ln\left(\frac{1}{N+c_{max}-1}\right)\right] \quad \text{(Eq. 4.10)}$$

and

$$H_{\gamma_{max}} = N \qquad \text{(Eq. 4.11)}$$

Now, having all the elements available, it is possible to first calculate M and then S, thus obtaining:

$$\mathrm{M} = \frac{1}{H_{\beta}} \qquad \text{(Eq. 4.12)}$$

$$\mathrm{S} = \frac{\left[\mathrm{M} - \frac{H_{\alpha_{min}}}{H_{\gamma_{max}}}\right]}{\left[1 - \frac{H_{\alpha_{min}}}{H_{\gamma_{max}}}\right]} \qquad \text{(Eq. 4.13)}$$

The obtained S-indicator has to be compared with Table 11 and allows the general consensus to be measured. A low level of general consensus may be related to the different opinions of the participants regarding the priorities on the criteria, and again justifies the use of the AHP instrument as an objective decision support method. At the same time, it shows the differences of opinion among participants. This indicator does not undermine the interpretation of the outcome of the AHP method but serves as a reminder that there is no general consensus for the selected criteria, when S have a low value; or vice versa, it serves as evidence of an outcome with high general consensus, when S have a high value (Vafaei, Ribeiro, et al., 2016).

Table 11. Interpretation of the general consensus indicator S

S	Consensus
≤50%	Very low
50% - 65%	Low
65% - 75%	Moderate
75% - 85%	High
85% - 100%	Very high

By applying the AHP method, a decision maker is able to structure the decision problem and break it down into a top-down hierarchical process. Then, he/she performs a matrix comparison of pairs of criteria using a scale [1-9] (corresponding to semantic interpretations such as 'A is much more important than B' with respect to a criterion). This step, performed by all participants, can be understood as a normalisation procedure. Priorities are then determined using Eigen vectors or a simplified version with weighted sum (SAW) (Vafaei, Ribeiro, et al., 2016).

4.1.2. Weighting approaches

Following the methodological flow, the next step in aggregation of results is the association of a certain weight to each environmental impact category, i.e., weighting. It, in fact, involves multiplying the normalized results of each impact category with a weighting factor that expresses the relative importance of the impact category.

It is important to emphasize how weighting is a key step in arriving at a single score. First, it makes it possible to identify the most relevant impact categories of life cycle stages, processes, and flows. Through this, it is useful in guiding decision makers, who, in line with their strategies and policies, can understand where to focus their efforts and identify solutions that can reduce impacts. In addition, the weighting phase allows for the presentation of aggregated results, making communication clearer and more effective.

Investigating this stage, there are various groups of approaches to identify weighting facts, listed in Table 12 below.

Table 12. Classification of weighting approaches and methods, modified from (Pizzol, Laurent, et al., 2017)

Approach	Method	Description
Distance-to-Target		In this approach, weighting is done according to how much closer the indicator in question is to the normative target.
	Normative targets	The weight assigned to each impact category is the ratio between the normalization reference value and the target value: $$w_i = \frac{N_i}{T_i}$$ Where: • w_i is the weight of the i_{th} impact category; • N_i is the normalization reference for the i_{th} impact category; • T_i is the target reference for the i_{th} impact category. In many cases, a power factor is inserted into the formula. In this way, the rationale remains the same, so give more weight to the impacts that turn out to be farther away from the goal, though, the results can be spread over a wider range of values (G. A. and H. E. M. Norris, 1995) (Hauschild, 2005) (Rüdenauer, I., C.-O. Gensch, R. Grießhammer, 2005) (Weiss, M., M. Patel, H. Heilmeier, 2007).
Panel-based		In this approach, the relative importance of impact categories is extrapolated from various groups of people (e.g., experts or stakeholders).
	Stakeholder panel	Regarding the weighting from stakeholders, stakeholders panel, the weighting is done according to the opinion of non-expert individuals. In order to collect the necessary data from stakeholders, based on their size, interviews, workshops or surveys can be used (Huppes, 2016).
	Expert Panel	About the weighting from expert, in this case the weighting can be performed involving expert individuals from different backgrounds (academic, industrial, political) (M. S. R. Goedkoop, 2001) (Soares, S. R., L. Toffoletto, 2006) (M. et al. Goedkoop, 2013).
Monetary weighting		In the monetary weighting approach, all impacts are weighted according to the estimated economic value product/system under analysis. There are 3 types of monetary weighting: observed preferences, revealed preferences, and stated preferences.
	Observed preferences	In the observed preferences, the marginal value of the asset is identified based on the market price. It includes the budget constraint method, a monetization method in which the marginal value of a Quality-Adjusted Life Year is identified based on the potential economic output per capita per year (Steen, 1999a) (Steen, 1999b) (Weidema, B., M. Z. Hauschild, 2008) (B. P. Weidema, 2009) (B. P. Weidema, 2015).
	Revealed preferences	In the revealed preferences, the marginal value of the good is identified on the basis of the market price of a surrogate good, that is, a good that is indirectly affected by changes in the availability of the primary good (Boardman, A. E., 2006) (Finnveden, G., Eldh P., 2006).
	Stated preferences	In the stated preferences, the marginal value of a good is identified on the basis of preferences expressed by a demographically representative panel in response to hypothetical trade-off questions (e.g., through contingent valuation survey methods or choice experiments) (Steen, 1999a) (Itsubo, N., 2004) (Itsubo, N., 2015).

Binary weighting		Regarding the binary weighting approach, two situations arise: either no weight is given to impact categories or it is given but equal weight to all of them, based on criteria decided by the practitioner. Therefore, it is called binary, as there are two mutually exclusive possible cases.
	Equal weighting	In the equal weighting the practitioner assumes all impact categories have equal weight, so the weight is equal to one
	Footprinting	In the Footprinting the practitioner selects one or more impact categories to which he or she associates equal weight of one, while deciding not to take into account other categories (equal weight of zero) (ISO, 2014) (Ridoutt, B., 2015).
Mid-to-endpoint		In the mid-to-endpoint approach, impacts are weighted according to average characterization factors that translate from mid-point indicators to end-point indicators.
	Mid-to-endpoint factors	The mid-to-endpoint factors is a method where characterization factors are applied to the midpoint indicators to obtain the endpoint indicator. The resulting indicator or indicators are one per Area of Protection (AoP), and additional weighting must be applied to obtain a single score (Humbert, 2015) (B. P. Weidema, 2009).
	Midpoint contribution	The midpoint contribution to endpoint is a method where characterization factors are applied to midpoint indicators in order to obtain endpoint indicators, for a specific normalization reference (e.g. EU totals, World totals). Then, the relative contribution of each midpoint indicator is calculated and used as weights. This can be performed for each of the AoP indicators, or for a single index resulting from the aggregation of the AoP indicators (Ponsioen, T.C., Goedkoop, 2015).
Meta-models	Meta-model	In the meta-model method, impacts are weighed by applying multi-pixel weight factors. So, multiple methods are used and averaged according to a defined weighting scheme (Soares, S. R., L. Toffoletto, 2006) (Huppes, G., 2012).

Following the mapping phase of existing weighting methodologies, it appears necessary to perform an evaluation of these by establishing criteria. To this end, following a review of available literature (Pizzol, Laurent, et al., 2017), a list of criteria for evaluating weighting methods was determined. The following are the criteria:

- *Scientific robustness,* it allows investigation of what is the science behind the development of the method. To do this, it is first necessary to assess the scientific robustness of the method, that is, to the ability of replications of the method to provide similar results. Another aspect that is part of this criterion is whether the method is peer-reviewed. In fact, if reviewed by experts in the field, the methodology has greater reliability and scientific validity. In addition, it is important to mention how another factor is the extent to which the objectives, underlying assumptions and principles of the method are clear and unambiguous.
- *Documentation,* it assesses whether the documentation provided enables the method to be understood and reproduced. Several aspects need to be investigated to define this criterion. First, assess accessibility, so how much effort is required to retrieve method documentation, whether it is available online, whether it is freely available, and whether it is also translated into English. Another aspect is the transparency of the algorithms, data, factors, and choices, to help the reader apply the method without mistakes.
- *Coverage*, it defines what is the scope of the method. First, this requires defining the extent to which the method allows for broad coverage of biophysical and/or social

impacts. Next, it is necessary to assess the coverage by normalization factors/weighting of midpoint categories and the coverage by normalization factors/weighting of endpoint categories. It is necessary, however, not to exclude the extent to which the method includes geographic and temporal differentiations and cultural differences, another key issue.

- *Uncertainty,* it analyzes how method uncertainties are addressed, managed, and described. First, it is necessary to assess the uncertainty of the model, so what are the main uncertainties in the theoretical structure of the method and the main assumptions and choices. In addition, it is also necessary to assess parameter uncertainty, i.e., what are the main uncertainties in the basic data used in the method. Next, the uncertainty of the results must also be considered, assessing the extent to which there is an explicit statement of uncertainty associated with the results, e.g., in terms of standard deviation, range of values, order of magnitude etc. Once these levels of uncertainty are determined, it is also necessary to assess whether any model parameters are identified that have greater influence on the results and how the model allows for natural variability beside uncertainty.
- *Complexity,* means a measure of what knowledge is needed to apply the method in practice. In fact, to define complexity, it is necessary to define what level of scientific knowledge base is needed (transdisciplinary, interdisciplinary). Another factor is to assess what technical support is needed to execute the method, such as dedicated software, mathematical models, and databases. Related to this criterion is also the extent to which the method has been tested on real case studies, where any difficulties encountered in application can be extrapolated.

Once the evaluation criteria were defined, each weighting method was evaluated by going to determine how well they met the criterion in question.

To do this, the following scale in Table 13 was applied.

Table 13. Criteria evaluation scale of weighting methods

Score	Description
+	Good performance of weighting method on assessment criteria
0	Medium performance of weighting method on assessment criteria
-	Poor performance of weighting method on assessment criteria

In addition to the application of the rating scale reported for each criterion, a comment is included for each weighting method where it is indicated in which cases the method is recommended or not recommended. Table 14 below contains the evaluation made of the weighting methodologies.

Table 14. Evaluation of weighting methods according to specific criteria from (Pizzol, Laurent, et al., 2017)

Weighting method		Scientific robustness	Documentation	Coverage	Uncertainty	Complexity	Comment
Distance-to-target	Normative targets	-	+	-	-	+	Recommended if weighting between targets is included, or the lack of this is explicitly mentioned; recommended for midpoint only
Panel-based	Stakeholder panel	0	+	+	0	0	Recommended for midpoint/endpoint if information on panel composition and criteria Expert for selection is provided
	Expert for selection is provided Panel	0	+	+	0	0	
Monetary-based	Observed preferences	-	+	-	0	+	Not recommended and if applied, recommended for midpoint only
	Revealed preferences	0	+	-	0	-	Not recommended in general, if applied recommended for midpoint only
	Stated Preferences	+	+	-	0	-	Recommended for endpoint only. Weights derived via choice experiment recommended over weights derived via contingent valuation (the former has higher consistency)
Binary	Equal weighting	-	-	+	-	+	Recommended for midpoint/endpoint, if explicit statement is provided that no weighting is really applied by the analysis
	Footprinting	-	-	0	-	+	Recommended for midpoint/endpoint, if explicit statement of implicit weighting is provided and motivations for selecting/excluding the categories are provided
Mid-to-endpoint	Mid-to endpoint	-	0	+	0	0	Not recommended if alternative robust endpoint methods are available for use
Meta-models	Meta-models	Depends upon used methods	Depends upon used methods	Depends upon used methods	Depends upon used methods	Depends upon used methods	They carry all the uncertainties and limitations of the underlying weighting methods. Recommended to midpoint/endpoint if information on the weighting amongst weighting methods is provided and units are coherently addressed

4.1.3. Aggregation/Grouping methods

After the normalization and impact weighting steps have been performed, it is crucial to conduct the aggregation step in order to provide a summary of the system's impacts, useful for decision making and to provide clear communication of the results.

Analysing the methods, according to (Gan, Fernandez, et al., 2017) and (Buchmayr, Verhofstadt, et al., 2021), three types of methods can be identified: additive aggregation methods (e.g., arithmetic), multiplicative methods (e.g., geometric), and non-compensative methods (e.g., some of the outranking methods for multicriteria analysis).

The following is a description of the aggregation methods and of a summary Table 15.

Additive aggregation methods

The most widely used aggregation methods are additive aggregation methods, which use functions that sum the normalized values of sub-indicators to form a single Sustainability Index (SI).

Among the various existing additive methods, the one that is most widely used is the weighted average. An important feature of the weighted average is the continuity characteristic, which implies that the limit for the sustainability index must be precisely defined in the case where the relative measurement error of a set of indicators is already known. In general, two important characteristics of additive aggregation emerge. The first characteristic is preferential independence, that is, if linear additive aggregation methods are used, sustainability indexes must be independent. This characteristic, therefore, means that in order to obtain a total value all the values of the individual indicators must be summed, implying that there are no conflicts between the various indicators, a rather unrealistic assumption (Chen, L., & Pu, 2004) (Nardo, M., 2005). The second feature is that the weights used in additive methods turn out to be substitution rates and not importance coefficients. This means that additive methods should not be used when interactions between indicators are significant.

Geometric aggregation methods

Analysing other types of aggregation methods, geometric aggregation methods emerge, which, unlike additive aggregation methods use multiplicative rather than additive functions. Among these, the most popular aggregation function turns out to be the weighted geometric mean.

Examining geometric aggregation methods as a whole and making a comparison with additive methods, the latter adopt a compensatory behavior, that is, a poor performance of certain indicators may not be detected in when compensated by the high performance of other indicators. This is not the case in geometric aggregation which uses a less compensatory approach, that is, it performs multiplication of indicators, limiting the ability of indicators with very low scores to be fully compensated by indicators with high scores.

An important point to note is the limitation of geometric aggregation methods. In fact, geometric aggregation methods are not completely non-compensatory techniques, and thus allow trade-offs between indicators, like additive methods, have the characteristic of being preferentially dependent (Keeney, 1973) (Keeney, 1974) (OECD, 2008). Furthermore, with geometric aggregation methods, sensitivity analyses and uncertainty quantifications cannot be analyzed using measurement errors of indicators (Calvo, Kolesárová, et al., 2002) (Beliakov, G., 2007).

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Non-compensatory aggregation methods

As a result of the analysis of additive and geometric aggregation methods, it has emerged that the use of these methods is often controversial because they imply compensation between sustainability sub-components, that is, the possibility of offsetting a disadvantage on some indicators with a sufficiently large advantage on other indicators.

For this reason, other aggregation methods emerge that are useful when substitution between sub-components is unacceptable, namely non-compensatory aggregation methods which allow the construction of composite indicators (Podinovskii V.V., 1994) using a non-compensatory multicriteria approach. The approach consists of using a mathematical formulation to rank in a complete pre-order (i.e., without any incomparability relationship) all units under analysis, from best to worst, following a pairwise comparison of units over the entire set of available indicators.

In order to make the operation of the method more understandable, a description of the algorithm is provided. Suppose you have three units, A, B and C, and you want to rank their overall performance according to N indicators. First, it is necessary to construct an "outranking matrix" whose entries eij tell us how much better unit "i" performs than unit "j." To understand better, eij represents the sum of all the weights of all the indicators for which unit "i" does better than unit "j."

Once the matrix is constructed, knowing all the possible permutations of the order of the units (ABC, ACB, etc.), the second step is to calculate for each of them the ordered sum of the scores, so taking ABC as an example, the ordered sum of the scores will be $Y = eAB + eAC + eBC$. Having performed this calculation for all permutations, it is possible to create a multicriteria ranking of the units following the order from the highest total score Y. Through this process it is possible to show that the unit with better performance on many indicators is ranked higher, as it cannot compensate for deficiencies in some dimensions with excellent performance in others.

Thus, this aggregation method has the advantage of overcoming some of the problems raised by additive or multiplicative aggregations: preference dependence. In addition, there are no restrictions on the type of variables or indicators that can be used, which means that both quantitative and qualitative data can be used (European & Commission, n.d.).

Two possible disadvantages of this method are the computational limitations associated with the increasing number of units or indicators and the loss of information on the intensity of sustainability (Munda G., 2005) (Nardo M., 2005).

Strengths, weakness and exemplification calculation formulas are summarized in Table 15.

Table 15. Description of the methods of aggregation highlighting – formulas, benefits and drawbacks

Methods for aggregation	Formulas	Benefits	Drawbacks
Additive aggregation	$$SI = \omega_1 I_1 + \omega_2 I_2 + .. + \omega_m I_m = \sum_{i-1}^{m} \omega_i I_i$$ Where SI is the sustainability index, ω_i the weight of the i^{th} indicator, and I_i the normalized score of the i^{th} indicator	Transparent and simple. Easy to execute sensitivity analysis and uncertainty quantification.	Rigorous prerequisites exist, such as mutually preferentially independence.
Geometric aggregation	$$SI = I_1^{\omega_1} I_2^{\omega_2} .. I_m^{\omega_m} = \prod_{i=1}^{m} I_i^{\omega_i}$$ Where SI is the sustainability index, ω_i the weight of the i^{th} indicator, and I_i the normalized score of the i^{th} indicator	Transparent and simple. Can be used for all kinds of ratio-scale variables.	Rigorous prerequisites exist, such as mutually preferentially independence.
Non-compensatory aggregation methods	Rank(*Unit$_i$*) $$s.t. \varphi_* = max \sum e_{jk}$$ $$i = 1, \ldots, n$$ Where Rank(*Unit$_i$*) is the overall ranking of the n researched units, φ_* the corresponding score fo the final ranking of the researched units, and e_{jk} the generic of the outranking matrix	No ad hoc restrictions.	Computational problems may be caused by the increasing number of units or indicators. Losing information on the intensity of sustainability.

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4.1.4. Graphical Visualisation as an integrated visual Approach

Beside the normalization, weighting and aggregation methodologies that allow to obtain a unique indicator resuming the impacts generated along different sustainability compartments, it is worth to cite the possibility to display single or aggregated indicators through a graphical approach, such as a panel, a 2D or 3D graph, a radar chart or other graphical representation models. This could be included as an optional step after the aggregation to support communication and performance evaluation between multiple products or processes visualizing the results of the assessment of the single sustainability domains or of the entire LCSA. This approach, like other approaches to aggregation, is oriented towards communication with the end user and can lead to more immediate communication of the result than other methods that only produce a numerical value. The representation of assessment results by graphic approaches is not in itself a numerical aggregation of impacts into a single result, but rather an aggregation of impacts through a single picture. Areas of application include for example: Type III ISO14025 compliant declarations such as the EPDs (Enso, 2020) or Type I ISO14024 compliant declarations such as Ecolabel Regulation (REGULATION (EC) No 66/2010 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 November 2009 on the EU Ecolabel, 2009). Also, the PEF, although not providing a clear communication guideline, suggests that it is possible to use different means of communication, such as: product labels, reports, web pages, videos, info-graphics, and so on. In Figure 12, as an example, disaggregated environmental mid-point impacts are presented through an environmental performance label with a communicative approach designed to raise consumer awareness. The value of the environmental indicators is paired with a concrete example of the impact effect related to the reported emissions.

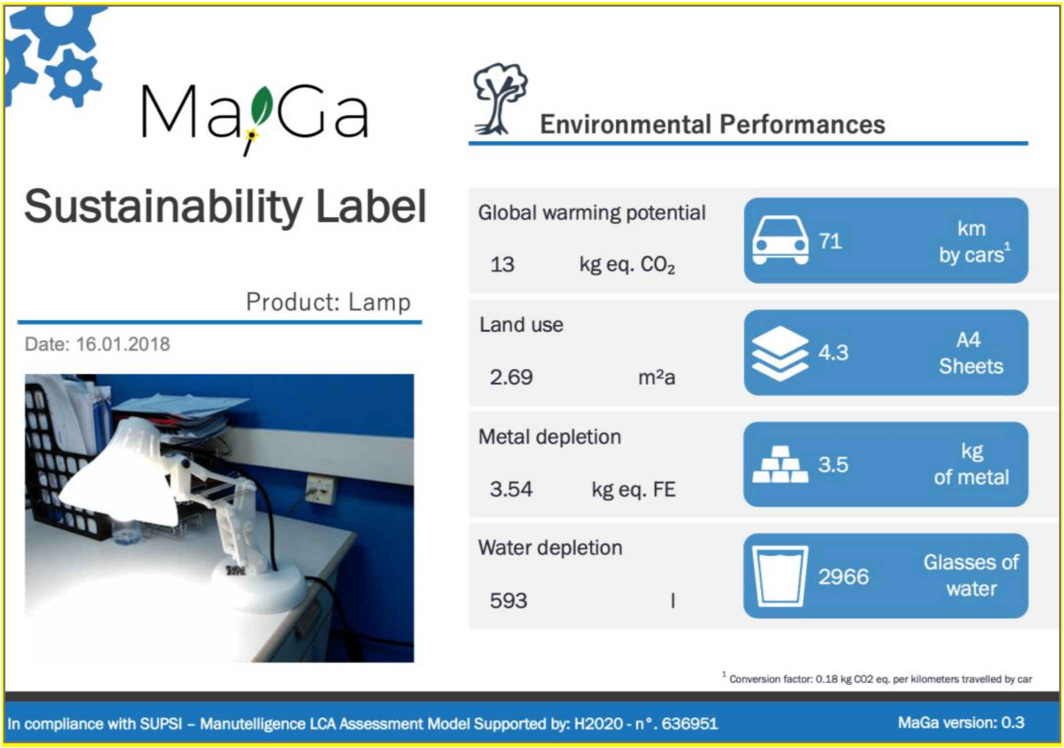

Figure 12. Example of an environmental performances label

Various examples of visual approaches to aggregation can be found in the literature for all domains of sustainability. Figure 13 shows a further example in which the label developed within the SAM Innosuisse project[23] (Menato, S., 2015) is presented.

The label offers a vision on several areas of sustainability, thus presents in an integrated way all the different aspects concerning the environmental, economic and social issues. Moreover, exploiting a reference product, it defines "impact classes" similarly to energy efficiency classes, which allow a more effective understanding of the impacts of a product, considering its weakness and strengths in respect to the reference one, and a more rapid possibility to compare different product when a label for each of them is available.

Figure 13. A guided product label design for effective sustainability communication

More examples of LCSA graphical integration approaches can be found in section §4.6, where the aggregation of the different sustainability domain is described more in detail.

4.2. CE integrated indicator aggregation framework

Scoring systems can be used to aggregate CE indicators. (Bracquené, E., n.d.) used an Ease of Repair Rating Matrix (AsMeR) to assess the repairability of a product by scoring the various criteria; the aggregate score gives more weight to parts that are more likely to be repaired and/or replaced. (Alfieri, F., 2018) states that scores assigned to individual parameters can be normalised, weighted and aggregated into overall circularity or thematic evaluation scores (e.g., assessing eligibility for repair); however, this process adds subjectivity to the evaluation.

In literature, the most widely used and state-of-the-art recommended circular approaches were considered. Among these, some result in a single score indicator or in a one indicator and can be considered for aggregation within the CE domain. Some of these approaches are not only limited to the domain of circularity but also merge into other domains of sustainability, so they

[23] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjw2KG-gMf-AhUWUKQEHfnoCnwQFnoECEkQAQ&url=https%3A%2F%2Fwww.aramis.admin.ch%2FTexte%2F%3FProjectID%3D31994%26Sprache%3Den-US&usg=AOvVaw0fSXLBh551cJEUQzoCgxQc

have not been considered in this moment. In ORIENTING project (Bachmann, Till, 2022), the approach (Circ(T)) approach (Pauliuk, S., 2017) results to be unsuitable to be operational as it requires too much data has not been considered too, together with the Value-based resource efficiency (VRE (Di Maio, F., 2017)) approach that was found to be insufficiently transparent and not sufficient credible. The 3 remaining approaches selected and evaluated for aggregation within the CE domain in TREASURE were previously identified and classified by the analysis of CE indicators. An earlier description of these single-score indicators can be found in §3.4 and they are resumed below:

- The Material Circularity Indicator (MCI) is an indicator for products and was proposed by the Ellen MacArthur Foundation in 2019 (Measuring Circularity, 2019). The MCI measures how much linear flows have been minimised and how much restorative flows have been maximised for the materials that compose the product. It also considers the use phase, comparing the lifetime and intensity of use compared to similar products on the market. The result is a single value between 0 and 1, where 1 means that the maximum level of circularity has been reached. The methodology relies on similar values (mass and rates) as used by practitioners conducting LCA and criticality assessment. For these interest groups, the method is transparent and easily understandable, and it is recommended for the decision-makers in industries.
- The Circular Footprint Formula (CFF) from (Zampori, L., & Pant, 2019b) is recommended by the European Union for dealing with materials and end-of-life allocation problems in LCA, in the context of the product environmental footprint (PEF). CFF makes it possible to account for the benefits and burdens of recycling processes, energy recovery, and the use of secondary materials, considering the boundaries between the first and second production systems.
- The Product Circularity Indicator (PCI) is a further development of the Material Circularity Index from Ellen MacArthur Foundation (Bracquené, Dewulf, et al., 2020). PCI should overcome the main limitations identified in the MCI. It differs from the MCI since the recycled content is defined at the material level and not at the product level, considers and assigns more benefits to the reuse of components than to direct recycling, material recovery and material recycling are fully part of the product system, and flow exchanges of material with the external boundaries of the system are not treated as completely circular in the PCI calculation method. Although this method is presented as an improvement on the MCI, it scored lower in literature, in ORIENTING project (Bachmann, Till, 2022) this is mainly due to the criterion of “stakeholder acceptance, credibility, and suitability”.

The approaches were evaluated on various criteria, namely: stakeholder acceptance, credibility, and suitability; applicability/complexity; transparency; scientific robustness; comprehensiveness; and compatibility with the life cycle approach. Table 16 summarises the results obtained in ORIENTING project (Bachmann, Till, 2022) by the various CE approaches but excludes those that result in more than one indicator, those that also cover other areas of sustainability, and those that are not considered due to their lack of transparency, credibility and operability.

Table 16. Evaluation of CE approaches resulting in a single score or a single indicator

Criteria	Stakeholder acceptance,	Applicability/ Complexity	Transparency	Scientific robustness	Comprehensiveness	Compatibility with LCA	**FINAL SCORE**

Approaches	credibility, and suitability						
MCI	A+	B	A	B	A+	A+	**A**
CFF	B	A	A	B+	B	A+	**A-**
PCI	B+	B	A	B	A+	A+	**A-**

The circular economy should be seen to achieve sustainable goals, not an end. CE results should therefore be paired with sustainability results, but kept separate, not integrated with them. In TREASURE the dimension of circularity to be considered is mainly the recycling, the other circular principles are less addressed. The 3 methods considered all scored very well and can therefore be considered equivalent. The choice of which method to use in TREASURE was therefore based on the project context and CFF was selected. The CFF contains within it the parameters R1, referring to the percentage of material in the product input that was recycled in a previous system, and R2, referring to the percentage of material in the product that will be recycled in a subsequent system. R2 also considers inefficiencies in the collection and recycling processes and must be measured at the exit of the recycling plant. These two parameters are compatible with the PEF methodology and PEFCR and could therefore be presented together with the results from the environmental sphere since, according to what has just been stated, CE results should not be an end in themselves, but should accompany results from the sustainability domains. In PEFCR there are default values for the parameter R2 to be used if no company data are available, while R2 should be set equal to 0 if this value is not present in PEFCR either. If the PEF methodology is being used and the value of R2 is not known, then an average value in line with the European average can be used or set to 0 if that is not available either. In TREASURE, however, the focus is not on the percentage of mass of recycled product that can be recovered or the mass content of recycled material in the product, but rather on the recovery of critical materials. The Material Recycling Index (Material-RI), the indicator, described in §2.3.2 and listed among circular indicators in §3.4.3, is therefore more suitable for the project even though it is not an aggregating indicator. Its graphical flower-like representation can be interpreted as a qualitative integration methodology (M. A. Reuter & van Schaik, 2016). This representation, already shown in Figure 9, makes it possible to visualise the Material Recycling Index of the various metals considered in a single instance. This model responds to the need for comparison of circularity in the TREASURE dimension and can be used to compare the circularity principle of recycling in different situations, such as comparison between different processes, between products, between two enterprises, and so on.

4.3. Environmental aggregation framework

The environmental sphere represents, compared to the social and economic ones, the most investigated and consolidated by research institutions and companies. It is in fact characterized by different impact categories, such as resource depletion, human health, climate change, etc., which allow different environmental impacts to be quantified.

In terms of aggregation, that is, moving from impacts related to individual categories to an overall impact representing the entire environmental sphere, what turns out to be a challenge is the heterogeneity of impact categories.

Analysing the impact categories individually, however, they assume a linear behaviour. Taking the impact category "Acidification", for example, which calculates the potential acidification of soil and water due to the release of gases such as nitrogen oxides and sulphur oxides, expressed in $equivalent\ kg\ of\ mol\ H+$ released, assumes linear behaviour. This is explained by the consideration that, zero is the reference and reducing value is the target, and linearity is expressed by the fact that the release of $2\ kg\ mol\ H+$ results in twice the release of $1\ kg\ mol\ H+$. Therefore, all indicators in the same impact category are easily aggregated because they follow the same linear behaviour.

Given these issues, in a macro perspective, each impact category turns out to be stand-alone and measuring environmental impacts by reporting separate results for each impact category is ineffective for the purpose of obtaining an overall assessment. This methodology, however, is able to produce less uncertain and more transparent assessments (Pizzol, Laurent, et al., 2017) since, when aggregation is performed, there is a risk that one product results better than another one despite this is not actually the case, because it has very low values in many impact categories that offset high impacts in others. Environmental assessment with non-aggregated impact categories is, however, more difficult to manage, for example, from a decision-making or communication perspective (Myllyviita, Leskinen, et al., 2014). For this reason, in relation to the TREASURE context, the aggregation of individual impact categories is crucial because it is the decision-making process that drives the choice of the best-performing alternative in terms of sustainability. Moreover, the aggregated outlook of environmental performances could also be exploited to better address final customer needs in terms of understandability and usability of environmental data, an additional aspect taken into account by the TREASURE vision.

Known the importance of the aggregation stage, it is necessary to understand which methods are best suited for aggregating environmental indicators. According to (Prado, Cinelli, et al., 2020), the most common practice appears to be the aggregation of LCA results by a combination of weighted sum and external normalization. This technique involves dividing the values of individual impact assessments by the values of external normalisation, and then multiplying them by importance weights coming from multiple sources. The weights can be derived in relation to the scope of the study using distance-to-target weighting techniques, and/or through the involvement of various stakeholders. In some cases, more for convenience and ease of use, default values taken from external sources are used (Ahlroth, Nilsson, et al., 2011).

It is important to highlight how Multi-criteria Decision Analyses methods (MCDA), that are decision-making methods used in operations research, are compatible with LCA analyses and can be used to obtain weights from stakeholders, produce individual scores and rank decision alternatives (Myllyviita, Leskinen, et al., 2014) (Prado, Cinelli, et al., 2020). Some examples of MCDA methods are the AHP method, outranking, TOPSIS, MAUT, etc. Relatively the last mentioned, it is considered the one with the most solid theoretical basis for dealing with normalisation, weighting, and calculation problems in LCIA (Seppala, J., 2002).

PEF aggregation process

As indicated in §3.1, the indicators considered for TREASURE's environmental assessment come from the PEF's default indicators. For this reason, it is essential to analyze how the aggregation process was addressed by the PEF.

Analysing the PEF guide, in early versions, both the normalization and aggregation steps were mentioned as optional steps, with the difference being that the normalization step was also recommended.

Later, as it evolved, it has become mandatory to produce a report where there are characterized, normalized and weighted results for each impact category. In fact, for this reason, predefined normalization and weighting factors were developed for the PEF method (Sala, S., 2018) and are applied to identify the most relevant environmental impact categories that together account for at least 80% of the total environmental impact. Regarding the product groups for which PEFCR is available, the most relevant environmental impact categories have already identified.

Concerning the steps, particularly the PEF normalization step, the LCIA results are multiplied by normalization factors that represent the total impact of an average citizen for a given impact category (e.g., climate change, eutrophication) in a reference year, which is an example of an external normalization approach (see §4.1.1).

As the final step, PEF results shall be multiplied by a set of pre-defined weighting factors, which reflect the perceived relative importance of the environmental impact categories. Weighted results can be compared across different impact categories and also summed up to in order to obtain a single overall environmental score (Zampori, L., & Pant, 2019a).

In the environmental footprint pilot phase, after characterization and normalization, an equal-weight approach was applied. Each of the 16 midpoint impact categories is similarly weighted (considered equally important). However, the weighting factors now recommended for PEF research include a robustness factor for each environmental impact category and an actual weighting factor representing the estimated importance of each environmental impact (Sala, S., 2018) (Zampori, L., & Pant, 2019a) . Weighting factors were developed based on input from citizen surveys, LCA expert surveys, and impact assessment expert webinars (Sala, S., 2018). Hence, this is an example of a so-called meta-model (see §4.1.2), where inputs from different groups of experts are used to develop the weights.

Exploring weighting factors, in the PEF the highest weighting factors are currently assigned to those impact categories that are the most robust impact assessment methods and represent the most severe environmental impacts. Currently, climate change is given the highest overall weight, followed by particulate matter, water consumption and use of fossil resources (Sala, S., 2018). Weighting factors are presented in two ways, including or excluding the three effect categories associated with toxic effects. This is because these three toxicity-related classes are currently considered immature and are being further developed (Sala, S., 2018). In addition, other environmental impact categories also need further development, such as those describing impacts on land use, water use and resource use (European Commission, 2018).

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4.4. Economic integrated indicator aggregation framework

The aggregation of values in the economic sphere is generally less problematic than in the other areas, as indicators can generally be reduced to a single monetary unit of measurement. There are, however, considerations to be made and elements to pay attention to, as introduced in §2.2.2. For example, it is necessary to consider if, once the individual indicators have been integrated into a single value, this result remains representative for the stakeholders involved, both those who bear the costs and those who benefit. Costs are often expressed on several levels for very specific reasons, in respect of the study conducted one should reflect if it makes sense to aggregate direct costs, indirect costs, social costs, and market costs into a single cost indicator. A manufacturer is interested in knowing the individual cost items, so that he has more elements to make a production decision, while the end user will not need to know this level of detail, it will be sufficient for him, for example, to visualise costs at the level of life cycle stages (Emblemsvåg, 2003). Given the same conditions in the other spheres of sustainability, the economic one is subject to mutuality in time and space. Attention must be paid to mutable economic elements such as changing interest rates, inflation, currency conversion, changing market prices, and so on. The history of prices and other economic characteristics can help as monitoring tools. The most frequently used analysis tool to help the decision maker decide within the economic domain is cost-benefit analysis.

Relative to the interaction with other sustainability domains, cost-benefit analysis can be expressed in terms of social benefits and social costs, where if, for example, a political decision must be made, then the social benefits are greater than the social costs. The same can be applied to environmental economic decisions, in this case it is verified that the environmental benefits are greater than the environmental costs (OECD, 2018).

(Schaubroeck, Petucco, et al., 2019), propose a single cost-benefit analysis (CBA) model applicable to linear and circular systems, from the perspective of different stakeholders such as companies, consumers, the public and administration. Costs are associated with the various processes, who must bear them, and who benefits. Taking the recycling process as an example, it is paid for by the company and sums up to the financial cost analysis sustained by the company each time a cycle is completed. The sales process, on the other hand, is paid by the customer to the company and thus adds to the sum of the financial cost analysis supported by the customer. Once all costs have been allocated to the stakeholders considering the beneficiaries, a CBA can be performed for each stakeholder by simply adding up the costs and subtracting the associated revenues. The CBA will result in a monetary value of a positive sign for the stakeholders who paid more than they received, while it will result in a monetary value of a negative sign for those who benefited more than the costs incurred. This model, however, considers a closed-loop approach and excludes the various financial costs and mechanisms such as taxes, depreciation over cycles, discounting over time, etc. In any case aggregation for the economic domain should relate back to the goal and scope of the project and be discussed in relation to it (Hunkeler, Lichtenvort, et al., 2008).

Like LCA and LCC, CBA can conduct comprehensive and complete sustainability assessments. Nevertheless, there are aspects to consider. LCA and LCC can be classified as product-related assessments, whereas CBA is essentially project- or policy-oriented (Ness, Urbel-Piirsalu, et al., 2007). A second key point of view is the time frame. LCA and LCC focus on the life cycles (complete or monetary) of the products to be evaluated, whereas CBA focuses on the life span of a project, making the life span of products secondary. A third factor is that LCA and LCC are evaluation devices that compare products, while CBA is commonly used for independent project evaluation. For CBA, the calculation of NPV is meaningful even without a comparison with other projects. A fourth fundamental point of view is that of work prerequisites. In sLCAs and sLCCs, the labour expected to produce a product is seen as an advantage because new jobs are created. The cost-benefit analysis always treats labour as a cost.

Since LCC is compatible with LCA and SLCA, and in TREASURE the product life cycle is considered and not the project one, as well as comparing product performance in the various areas of sustainability, LCC seems more suitable as an aggregation and cost integration methodology for the economic area. Indeed, the application of LCC results in a single monetary value with which it is possible to compare products, processes and recycling routes from a costing perspective. The additional financial indicators proposed in §3.2 do not necessarily have to be integrated with the LCC and can be presented in a disaggregated view.

4.5. Social integrated indicator aggregation framework

The UNEP methodology, selected as the social assessment methodology in TREASURE, consists of guidelines explaining, among other things, how to aggregate indicators into a single value. Aggregation and weighting occur during the impact assessment phase in several steps, starting with the aggregation of indicators into sub-categories first and into social impact categories afterwards. Finally, these impact categories can be aggregated into a single stakeholder performance evaluation, or into a single overall score. Especially in Social Life Cycle Impact Assessment (SLCIA), aggregation is a way of putting together different elements to produce a summary of complex processes to achieve a better interpretation and to communicate the relevant results. Aggregation results in the development of a single, possibly synthetic, score that involves two or more sub-components. Single indexes or scores are a strong instrument to combine and summarise multidimensional data and, as already cited in the environmental area, in TREASURE they could be exploited both for decision-making support and communication with stakeholder (more in general) and the final customer. At present, the SLCIA proposed by UNEP is to be seen as the shell within which methods and techniques of aggregation will be developed, which are currently still under discussion. This enclosure is divided into three phases:

- Selection of impact categories and methods, and characterisation models;
- SLCIA and classification;
- Calculation of results for indicator subcategories.

Two families of impact assessment approaches are then indicated, namely the "Reference Scale Assessment" (also called Type I or RS SLCIA), and the "Impact Pathway Assessment" (also called Type II or IP SLCA). The RS assessment is indicated for assessing social performance or social risks. The IP assessment is indicated to assess consequential social impacts through cause-effect chain modelling; however, few cause-effect chain models have been demonstrated to date, and UNEP Guidelines do not provide a definitive recommendation on how to implement this method. Both impact assessment families are used to aggregate subcategories of impacts, to be understood as what it is desired to be protected, into impact categories. For the reasons just mentioned, only the RS assessment implementation approach has been investigated.

Reference Scale Assessment Implementation

The UNEP Guidelines set out the steps to be taken to implement the RS SLCIA, stating that all steps are performed by SLCA databases such as SHDB and PSILCA. The steps and methods used by the databases are summarised below:

- *Step in Goal & Scope:* as a first step, it is indicated to decide on the impact assessment approach and the scope of assessment, thus to determine the stakeholders subcategories and the product system life cycle steps. See §2.2.3.4 for more information.
- *Step in Inventory:* a) it is indicated to establish the reference scales for impact assessment. Databases have a set of predetermined reference scales for each impact subcategory in their framework. b) Proceeding with data collection; the associated software collects data for the specific case, drawing on generic data from pre-selected databases or other data sources.
- *Step in SLCIA:* a) the evaluation of the data against the reference scale is carried out. The databases proceed with the evaluation of the collected data against pre-established reference scales. b) At this point, again using the databases, an impact assessment method can be applied to group by sub-category or impact category and aggregate the results on the value chain using an activity variable (this step is optional). (Blengini, G., 2019), for example, assessed the PSILCA sub-categories and selected impact categories for social risk assessment in the raw material industry from PSILCA by conducting a seven-criteria evaluation in which the relevance of the topic, the comprehensiveness of the impact assessment method, and the quality of the data in the database for their case study were assessed. They assigned individual scores for each criterion (good=2, medium=1, low=0). All criteria had the same weight. They then selected the 9 highest scoring sub-categories presented in Table 17Table 15 highlighted in green. Finally, databases provide users with the option of applying weighting to results (this step is optional).
- *Step in Interpretation:* presenting and interpreting the results. Databases provide some infographics to present the results. However, some users prefer to use the raw data to develop their own infographics for interpretation.

Table 17. Assessment by Mancini et al., 2019 of PSILCA impact subcategories

Impact category	Criteria					
	1. Relevance for the RM sectors	2. Policy relevance	3. Link between topic and the indicator	4. Link between indicator and risk assessment	5. Reliability of the data sources	6. Appropriate resolution
Child labour	2	1	2	0.5	2	1
Forced labour	1	1	2	0.5	1	2
Fair salary	2	2	2	1	1	2
Working time	1	1	2	1.5	2	2
Discrimination	1	1	1	0.5	2	2
Health and Safety	2	2	2	0.5	2	2
Social benefits, legal issues	1	1	1.5	0.5	2	1
Workers´ rights	2	2	2	1	2	2
Fair competition	0	0	1.5	0.5	1	1
Corruption	1	1	2	1	2	2
Contribution to economic development	2	2	0.7	0.5	2	1
Health and Safety (society)	0	0	1.5	0.5	2	1
Prevention and mitigation of conflicts	2	2	2	1		
Access to material resources	0	0	1	0.5	1	1
Respect of indigenous rights	2	2	1.5	1	2	1
Safe and healthy living conditions	2	2	1.5	0.65	1	0
Local employment	2	1	1.5	1.5	1	1
Migration	1	2	1.5	1	2	2
Health and Safety (consumers)	0	0	1	1	0	0
Transparency	0	0	1	1	0	0
End of life responsibility	0	0	1	1	0	0

Steps that could include aggregation and weighting are step 2, when the reference scales for impact assessment are established, and (optionally) step 3 if the activity variable is applied and the final weighting of the results is carried out. Finally, in step 4 graphical solutions are indicated to interpret the results. UNEP guidelines recommend not aggregating positive impacts with negative impacts; the opportunity to observe them separately should be given, so as not to compromise the transparency of analysis.

Figure 14 shows two generic reference scales, the generic ascending reference scale, and the generic descending reference. Reference scales are ordinal scales, typically composed of 1 to 5 levels, each of which corresponds to a Reference Point of Performance (PRP). The first is used to assess the social performance of a specific context, such as company-wide performance or individual indicator performance, by assigning scores from +2 to -2, where +2= Ideal performance, best in class; while -2= Starkly below compliance level. The second scale is used to detect the presence or absence of an impact, it does not use a numerical score but a coloured one, assigning for example the red indicator when the risk is very high.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

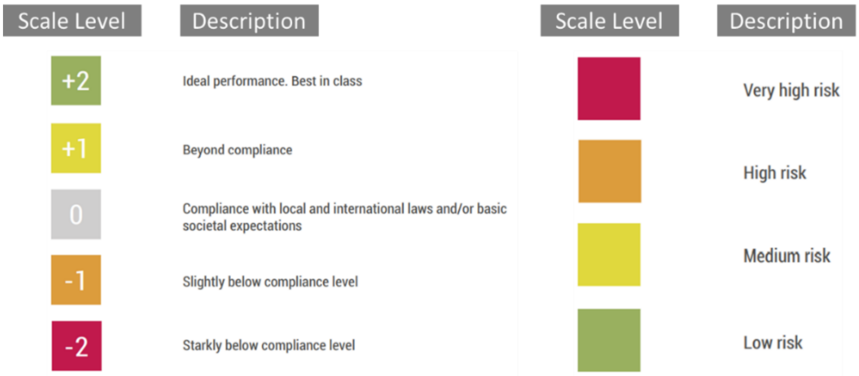

Figure 14. Generic ascending reference scale – social performance evaluation (left); generic descending reference scale – social risk evaluation (right)

The Guidelines recommend using specific data to measure a company's social performance, while they recommend using generic sector and country level data to assess social risk. From this comparison it is possible to better contextualize social performance, thus putting it in relation to the reference system. For example, having production activities that are free from child labour is a different result in countries and sectors where the risk is low compared to countries and sectors where the risk is high. When aggregating, it is recommended to express all impacts as positive or as negative, without mixing them together. This avoids misleading interpretations during evaluation, such as thinking that 0 equals a neutral social impact, when in fact it could be the sum of positive and the same number of negative impacts. SLCA databases operate according to the logic of converting impacts into positive values, to obtain more representative evaluations of results.

The aggregation of social indicators in TREASURE will be conducted with the help of the PSILCA database as aggregation software. The stakeholders to be protected and the impact categories to be monitored will be selected through a survey that will be circulated among the partners that will be designed in T2.2. The database will then calculate the social risk associated with the impact categories considered and the stakeholders selected, using generic sector and country data. This assessment will represent the social risk benchmark for the industry in the European context and will subsequently be used as a benchmark of TREASURE's social performance. TREASURE's social performance will be assessed by first collecting data on the specific indicators, and then exploiting the PSILCA database as aggregation software for the same impact and stakeholder categories previously considered by the social risk assessment. Not all the specific indicators identified can be entered manually into PSILCA, since some specific indicators has been introduced by the analysis carried out in T2.1 as they were not initially present in the list of PSILCA indexes. If, at the end of the indicator selection process, it is decided to also use the specific indicators not present in PSILCA, then it will be necessary to create an ad hoc aggregation methodology using the sequential steps described above such as normalisation, weighting, and aggregation.

4.6. Integration methods and aggregation approaches between sustainability domains and circularity

Given the assessments for each field of sustainability, a further step will be to generate a comprehensive interpretation of the results. To assess the sustainability and the circularity of a product in one absolute terms, it is necessary to consider the environmental, economic, and social impacts in an LCS&CA approach and then aggregate the results into a single sustainability indicator. A recurring problem with LCS&CA aggregation is that of offsetting a burden in one area with a benefit in another. Is it possible, for example, to offset an environmental impact with a social benefit, and if so, how? Therefore, trade-offs should be discussed in methods that accept them (compensatory methods), while they should be avoided in methods that use threshold values in compensation levels (non-compensatory methods). In accordance with the articles analysed in ORIENTING project (Horn & Zamagni, 2020), the aim of LCSA studies is primarily to compare alternatives (82%) and AHP lends itself to such studies. 14% of the studies aim to quantify sustainability in the analysis system while the remaining 4% aim to identify hotspots. The complex nature of the LCSA, in consideration of the various partners involved, requires that it is faced with a multi-criteria approach, to address decision-making, which goes beyond the sensitivity survey. MCDA strategies were perceived as a useful resource in literature, not only to aggregate LCSA results, but also to allow for trade-offs and to merge quantitative data with qualitative data. UNEP suggests involving stakeholders and decision-makers in the process of defining the desired assessment. In ORIENTING project an attempt to find a balance between environmental, economic, and social benefits, the integration approaches for the three areas of sustainability and circularity were identified by providing a critical evaluation and recommendations. A methodology is being created to co-ordinate and interpret product life-cycle data, enabling the formalisation of associations between environmental, economic, and social spheres. Information on trade-offs between different sustainability domains, life cycle stages, impact categories, protection areas and stakeholder groups are being formalised. Finally, a critical evaluation of the methods investigated was provided and recommendations were given. Nine integration procedures (Group 1) were identified and evaluated as integration methods across sustainability domains (as showed in Table 18Table), the same procedure has been done for two integration methods with a promising visualisation approach for LCSA (Group 2), and for four aggregative methods and sub-procedures mostly developed in the environmental domain but with potential to be extended in an LCSA integration approach (Group 3).

Table 18. Aggregative methods considered by ORIENTING

Groups of procedures analysed in Orienting.	Sub-groups	Integration methods or sub-procedures
Group 1: Integration methods across sustainability domains	MCDA Methods	SAW (#1)
		AHP (#2)
		MAVT/MAUT (#3)
		TOPSIS (#4)
		ELECTRE (#5)
		PROMETHEE (#6)
		VIKOR (#7))
	MODM Methods	(#8; evaluated as a group of methods)
	DEA methods	(#9; evaluated as a group of methods)
Group 2: Integration methods with a promising visualization approach for LCSA		Life Cycle Sustainability Dashboard (#10)
		SEEBalance© (#11)
Group 3: Other aggregation methods or sub-procedures commonly used	environmental and/or social domains	PEF normalization (#12)
		PEF weighting approaches (#13)
	Distance to target weighting methods	evaluated as a group of methods (#14)
	Monetary weighting methods	evaluated as a group of methods (#15)

The methods were evaluated considering the criteria of 1) stakeholder acceptance, credibility, and suitability; 2) applicability/complexity; 3) transparency; 4) scientific soundness; 5) completeness. The results obtained by the methods in the different criteria have been summarised in Table 19.

Table 19. Summary of the results obtained by the methods in the various criteria

Criterion / Methods	Stakeholder acceptance, credibility, and suitability	Applicability/ complexity	Transparency	Scientific soundness	Completeness	Final Score
SAW (#1)	B-	A+	A	A	B+	**A-**
AHP (#2)	B-	A+	A	A	A+	**A**
MAVT/MAUT (#3)	C+	B+	A	A	B+	**B+**
TOPSIS (#4)	C+	B+	A	A	A	**A-**
ELECTRE (#5)	C+	B+	A	A	B+	**B+**
PROMETHEE (#6)	B	B+	A	A	B+	**A-**
VIKOR (#7)	B-	B+	A	A	B+	**B+**
MODM (#8)	C-	C+	B	B	B	**B-**
DEA (#9)	B+	C	A+	A	B+	**B+**
LCS Dashboard (#10)	A-	C+	B	B	C+	**B**
SEEBalance© (#11)	B+	C	C	B	C+	**B-**
PEF normalization (#12)	B+	C+	A	A+	D+	**B**
PEF Weighting (#13)	B+	C	C+	B	C+	**B-**
Distance to target weighting methods (#14)	B	C	C+	D+	D+	**C**
Monetary weighting methods (#15)	B	C	C+	C	B	**C+**

In general, MCDA methods scored better in the various evaluation criteria, except for "*Stakeholder acceptance, credibility, and suitability*", where they scored a little lower due to a poorer rating in the *"Allows visualization of trade-offs and benefits"* sub-criteria (not showed here), where most of them received an 'E' rating. Of all the MCDA methods considered, the AHP method is the one with the best score. The methods that ranked best in the *"Allow visualization of trade-offs and benefits"* sub-criteria were the PEF, LCS Dashboard and SEE-Balance, where they all achieved an 'A' rating.

The analysis of aggregation methods between sustainability domains revealed significant conceptual discrepancies that do not allow for immediate and meaningful integration without a clear understanding of these differences first. These discrepancies have been summarised in Table 20. Compared to what has been investigated in ORIENTING, a line was removed where *quantitativeness* was mentioned as a discrepancy, stating that the social domain did not yet have a quantitative methodology. The social dimension as defined in this deliverable, however, turns out to be quantitative, as indicators were selected based also on this criterion, and the assessment method adopted by PSILCA is quantitative as well.

Table 20. Differences between domains found in ORIENTING project (Horn & Zamagni, 2020)

Domains / Discrepancy	Environmental	Economic	Social	CE
Linear metrics	Adopt linear metrics (e.g., One kilogram of CO2 is half of two kilograms).	Adopt linear metrics (Note that a result reported in euros could incorporate hidden valuation and cover both costs (effects) and benefits).	The principle of linearity does not apply here (e.g., earning a part of the living wage is generally not as bad as earning the entire living wage. A large part of the living wage implies need and, surprisingly, 90% of the living wage can mean poverty.	CE indicators have different signs and meanings.

Stakeholders	The focus is generally on the health of society at large, ecosystems and future generations when dealing with resource scarcity.	In the economic domain, there are also various stakeholders who pay the costs or reap the benefits, as companies, consumers, public administration, and so on.	6 stakeholders to be safeguarded as defined by UNEP.	
Dealing with different units	In the environmental domain the units of measurement of all impact categories are different, which has led to the development of standardisation procedures.	In the economic sectors, all impacts are expressed in euros or other currencies, eliminating the need for standardisation to aggregate results within this domain.	In the social sectors, some authors propose expressing all impacts in terms of DALY or QALY, but as indicated there is no general agreement on this.	For CE indicators, scoring systems can be used to aggregate indicators.

When planning an aggregation technique, it is essential to manage and pay attention to these distinctions and what they might mean for possible weighting and aggregation when thinking about all aspects. In the ecological area, a typical practice is to use pre-characterised default values for weighting, and this methodology has also been proposed for PEF. However, no comparative weight sets, or pre-characterised strategies are yet available for the other areas analysed.

In addition to the aggregation methods investigated, the visualisation approach of LCS&CA results could also be taken into account, especially in the TRASURE context. Some studies combine aggregate strategies with an explicit visualisation. For example, a radar chart can be used to show normalised values without conglomerating them. Other studies use a more qualitative methodology, where the spider graph region is used to show the aggregated results. The possible exploitation of the visualization methodologies also emerged in TREASURE from the questionnaire that was distributed to project partners with expertise in sustainability to investigate aspects of the holistic interpretation of evaluation results. UNIZAR indicated a desire to maintain at least three separate indicators for the three areas of sustainability and a fourth graphical indicator to group the CE information, such as the MARAS flower. MARAS agreed that a graphical representation allows for greater clarity of interpretation for the general audience, but also emphasised that the values behind the model must remain visible and explorable. POLIMI also agrees that the multi-indicator approach is better to support decision-making, while the single-indicator approach for each area is more aimed at a general audience and suggests adopting a graphical panel to communicate the results. Graphical methods found in the literature to aggregate multiple domains of sustainability and evaluated in ORIENTING include the Life Cycle Sustainability DASHBOARD and the SEEBalance, which among other things performed best in the criterion of *"Stakeholder acceptance, credibility, and suitability"*. An explanation of these two approaches follows.

Life Cycle Sustainability Dashboard (LCSD)

This solution proposal, proposed by (Traverso, M.; Finkbeiner, 2009) and presented by UNEP and SETAC, aims to communicate and present LCSA results in a comprehensive manner that supports decision-making in the field of alternative comparison. The solution is presented as a colour scale combined with a scoring system. The LCSD integrates LCA, LCC and SLCA. The dashboard, presented in Figure 15, presents the results of the evaluations and the comparison of alternatives. The conditions are expressed with a colour scale ranging from dark red (critical conditions) to dark green (best conditions), passing through orange (average conditions) and touching on 7 different colour shades in all. To arrive at this representation, it is first necessary to calculate the LCA, LCC and SLCA indicators of the entire product portfolio to be compared. The product that scores best gets 1000 points and the worst 0. The software then uses weighting factors for each indicator included in the analysis and then, through an arithmetic sum of the topic in question, the final evaluation can be obtained.

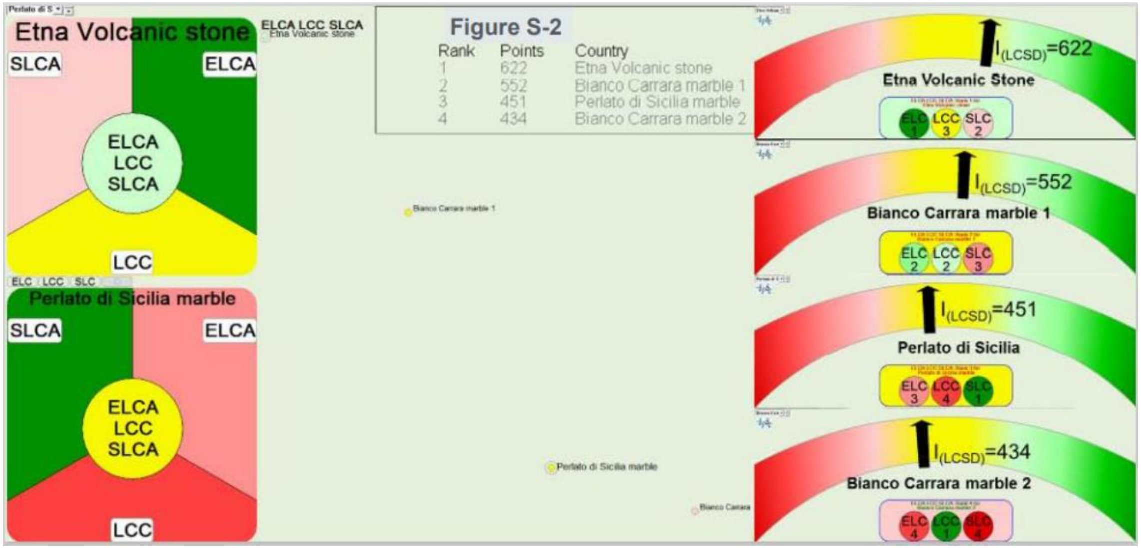

Figure 15. SLCA comparison between two products using the Life Cycle Sustainability Dashboard graphic methodology (Traverso, M.; Finkbeiner, M. Life Cycle Sustainability Dashboard. In Proceedings of the 4th International Conference on Life Cycle Management, Cape Town, South Africa, 6–9 September 2009.)

SEEBalance

BASF's SEEbalance method (Kolsch, Saling, et al., 2008) allows SLCA to be incorporated with the Eco-Efficiency Analysis (EEA). The method makes it possible to visualise the performance of different products or process in the 3 domains of sustainability thanks to a 3D graphical representation (see Figure 16) and can therefore be used to evaluate alternatives. The method also tries not to lack transparency, suggesting enabling an additional visualisation per domain through a radar graph; moreover, it offers the user the possibility to also visualise the behaviour in individual indicators through, for instance, a histogram representation (see Figure 17). The authors of the method indicate the integration of a weighting scheme for the social indicators as necessary since the importance of the different indicators is different. Thus, a result can be obtained by aggregating the social indicators. The weighting factors used were based on two different factors, the relevance factor, and the social weighting factor. The relevance factor indicates the contribution of a social indicator to the national amount and is derived from external statistics.

The social weighting factors reflect the relative position of society with respect to the various indicators. These factors are subjective and consider the probability of occurrence and the potential size of an indicator. These weighting factors were obtained from a series of interactions with experts within the scope of product development. The weighting scheme determined the impact of each indicator on the result, which was synthesised in the SEEcube.

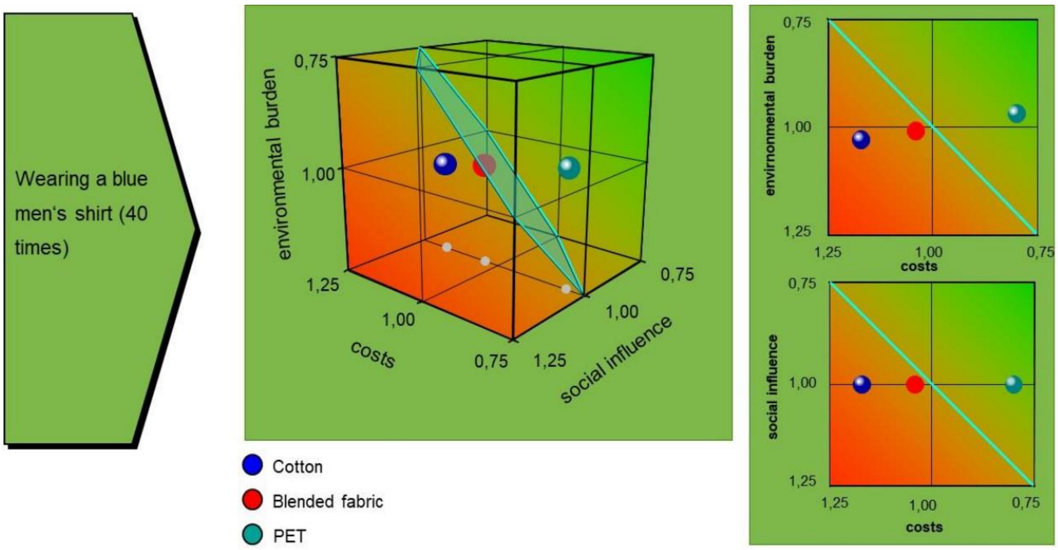

Figure 16. SEEbalance – evaluation of 3 alternatives of product

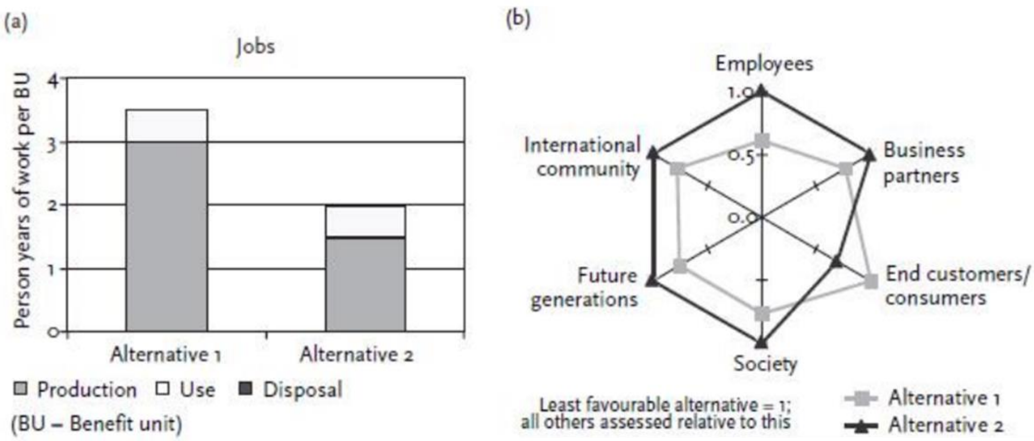

Figure 17. SEEbalance – alternatives' evaluation: a) histogram display for each indicator; b) single domain radar chart display

TREASURE dimension

Aggregation methods require the input of the stakeholders involved through the exchange of opinions and values by means of weighting factors for different impact categories or dimensions of stakeholder categories. However, even when adopting these evaluation and aggregation techniques, subjective choices cannot be avoided. MARAS has in the past used MCDA methods for decision support, not to try to aggregate different indicators into one universal indicator, but to enable decisions to be made with greater transparency. According to MARAS, a single indicator for sustainability does not do justice to a clear decision-making process, for which it is better to have several indicators.

Another aspect is that of the goal and scope behind the aggregation. What is the goal and scope of the sustainable assessment in TREASURE? To answer this question, it is necessary to understand the boundaries of TREASURE in the first place, considering the life cycle phases affecting the use cases and the stakeholders involved. The End of Life directly affects the use cases of disassembly and recycling, and indirectly the use case of eco-design, in its declinations: design for disassembly and design for recycling. It is also true that the design use case should consider all phases of the life cycle, including procurement and production. It could therefore be argued that all phases of the life cycle are concerned, with a focus on disassembly and recycling. Additional elements to be determined are the identification of the stakeholders to be protected, and what are the environmental, social, and economic objectives to be contained, avoided, and monitored. The indicators of the areas of sustainability and the circular indicators identified and selected in Section 3 allow to cover several goals and scopes. In T2.2, the advisory methodology framework is proposed which will support the decision-makers within the use cases, a possible filter may therefore be to check with them how they want to be supported. In parallel to this, it is intended to bring the discussion to the consortium level, to define the goal and scope of sustainability of the project. A survey will be presented in T2.2 to be circulated within the consortium to prioritise stakeholders and impacts, in the various areas of sustainability, on which to advise. Aggregation methods may then have to be revised at that time, if needs emerge that certain stakeholders or impacts, for example, should not be considered. Among the integration methods to be considered in LCSA, once assessments have been obtained in the individual areas of sustainability and circularity, we suggest the use of AHP, supported by a graphical and thus qualitative approach, such as a radar chart, a dashboard or the SEEBalance method.

5. Conclusion and next steps

T2.1 activities focused on the development of the TREASURE S&C assessment framework that is constituted by: i. environmental, economic, social and circularity indicators; ii. the related calculation methodologies; iii. the aggregation approaches of indexes within the single areas of sustainability; iv. the integration approaches to be exploited for an integrated and overall evaluation of all the S&C dimension. The framework will be mainly exploited to lay the foundation to the WP4 assessment and advisory services to be developed by SUPSI and TXT. The obtained results are briefly resumed in the following complemented with a summary table (Table 21). Eventually, this section closes with the identification of possible improvements to be carried out with a special attention of the framework application within the TREASURE context.

Methodologies and indicators selected for the environmental assessment

As detailed in §2.2.1.2, the approach adopted in the environmental assessment is the LCA methodology, based on the PEF initiative. Specifically, LCA in TREASURE will have the characteristics detailed in the following. LCA considers a “cradle-to-cradle” perspective that allows to take into account the circularity dimension. Moreover, it has a focus on BoL and EoL phases with this last one addressed by complementing LCA with the Exergy analysis and the Recyclability analysis to enhance the relevance of the circularity aspects in TREASURE context. The Bol phase will be addressed by delineating its strong interdependence with the EoL phase, with the aim of highlighting and quantifying the differential impacts created by BoL decisions on the EoL performances. The LCI phase will be strongly related to use cases, trying to gather as much as possible primary data. LCIA is performed using the PEF characterization methodologies and the related indicators. Moreover, the interpretation of the results will converge in the realization of a methodological foundation for the Advisory feedbacks (D2.2). Concerning the integration of circularity aspects into the LCA perspective, the End-of-life Recycling approach has been chosen, since the focus of the TREASURE activities is on the recyclability of materials at the EoL phase instead of on the use of recycled content in BoL phase.

Methodologies and indicators selected for the economic assessment

The assessment of the economic sphere is addressed in TREASURE through the eLCC approach, trying to account not only for the costs generated by the technological processes under analysis, but also for the externalities through the monetarization of the environmental impacts generated by the same technological processes. Being the CE a new economic framework, innovative LCC models that consider the multiple functionalities and extended uses of a product are needed. For this reason, the Circular Economy (CE-LCC), which builds on and extends the Total Life Cycle Costing Model (TLCCM), has been investigated. The CE-LCC leverages on the eLCC methodology as eLCC has been structured and designed to facilitate its use in conjunction with LCA in a multi-criteria assessment and incorporates costs’ perspectives of multiple stakeholders. With respect to other models addressing the economic measurements of products facing multiple life cycles, as for instance the TLCCM, the CE-LCC claims to be applicable to complex products on multiple scale levels rather than to products as a singular unit. Summarizing, TREASURE economic assessment is developed in increasing level of complexity, starting from the cLCC cost breakdown structure, trying to enlarge the costs by including the monetarization of the externalities (eLCC), and allocating costs in a circular economy perspective, considering multiple stages of the life cycles and multiple stakeholders’ perspectives.

According to §3.2, the economic indicators included in TREASURE are the costs indicators foreseen by eLCC methodology. The total cost indicator will be given by the sum of the costs arisen along the life cycle phases of the product in analysis and incurred by the stakeholders involved. In TREASURE, three life cycle phases are analyzed (i.e., BoL design, EoL disassembly and recycling phases), and the three main stakeholders involved correspond to the BoL actors (i.e., car and parts manufacturers) and to the EoL ones (i.e., disassemblers and recyclers). Concerning the environmental externalities, the Eco-costs approach is proposed for their inclusion in the cLCC model. The “Eco-costs” represents a single indicator where environmental mid-point indicators are translated into monetary end-point indicators via the monetary characterization factors, then the single monetary end-point indicators addressing the single areas of protection (i.e., human health, ecosystems, given carbon footprint, resource scarcity) are summed to obtain the single Eco-costs indicator. In addition to the LCC perspective suggested by the project DoA, an investigation on the economic evaluation from the financial point of view has been also carried out so that the economic evaluation is not only focused on the cost aspects. The adoption of financial indicators may be justified for the evaluation of KETs as enablers of the transition to a sustainable and circular approach in the processes of the automotive value chain. In this regard, the assessment of initial investments can be supported by indicators that not only consider the cost dimension, but also the financial sustainability of the case under consideration.

Methodologies and indicators selected for the social assessment

The UNEP methodology has been identified in the social assessment domain as the most performing one in comparison to the other evaluated in this document since from the analysis performed it is the more complete (having more impact allocation categories more indicators); it is structurally more comprehensive and robust; it presents a comprehensive and understandable user guide and a document where it shows all classified social indicators with references to standards, data collection guidelines, and limitations and policy relevance of the topic in question with also several helpful examples of the methodology's application available in the literature; it provides quantitative indicators and especially quantitative results aggregation methodologies; it is fully compatible with available social database structure. The evaluation performed in TREASURE D2.1 has also been supported by those performed in the cited EU-funded ORIENTING project that shown the UNEP methodology meets more than other methodologies, criteria such as: stakeholder acceptance, applicability, transparency, scientific robustness, completeness, and compatibility with life-cycle approach.

Concerning SLCA indicators, UNEP methodology includes generic and specific analysis. Regarding the generic analysis, the use of the PSILCA database is recommended, which allows the calculation of social indicators for all the stakeholders and the related impact categories. Increasing the level of detail, social indicators belonging to the specific analysis are also analyzed. Since these are 162 indicators, they have been skimmed by selecting only quantitative indicators consistent with the European context. Despite the effort required to calculate them, it is recommended, where possible, to perform specific analysis as it is more precise.

Methodologies and indicators selected for the circularity assessment

The CFF and the CEPA methodologies provide a methodologic approach to the assessment of the materials and energy circularity level that could be adopted to evaluate the TREASURE performances. CFF has been proposed in the EF context and developed in the same framework of the PEF methodology, which is actually the common thread of the environmental TREASURE assessment. For this reason, the CFF methodology is the chosen one to be applied in the project context. CFF focuses on both the closing the loop on materials and the issue of retaining the quality of secondary material in the loop. An additional advantage of CFF is that the related indicator is a single one, thus it appears to be one of the major candidates to the role of aggregation's method for the circularity pillar.

In addition to the CFF methodology, the exergy analysis (through thermodynamic rarity indicator) and the recyclability assessment with the related Recyclability Index (RI) are also proposed to be added to the TREASURE circularity level evaluation. These indicators are based on the expertise of two partners of the consortium and especially fit the project objectives since are focused on the recyclability and the recoverability analysis of critical and precious raw materials, resources that are today disregarded in the automotive recycling process.

Thanks to a literature review mainly based on six literature review works, a set of additional circularity indicators suitable to support quantitatively the research activities of TREASURE project has been identified. After a first selection obtained considering the "nano" and "micro" indicators, since the project focus on material and product level, 106 indicators has been retrieved, including online, excel spreadsheet and analytical tools. For further analysis and selection, these indicators have been classified according to ad-hoc defined taxonomy. Exploiting this classification, a first screening of the indicators list has been carried out considering only the indicators providing a measurable output. A second screening has been applied considering the need of fitting TREASURE context and the possibility to integrate the indicators as assessment instruments in an advisory logic scheme. 15 are the resulting indicators identified after this analysis. Amongst them, a special attention has been dedicated to MCI and PCI indicators since they provide an aggregation vision of CE aspect (refer to §4.2).

Methodologies selected for the aggregation of the indicators within the single areas of S&C

The aggregation methodologies for circularity and for the individual sustainability domains were addressed and discussed in the sections §4.2, §4.3, §4.4, §4.5 can be summarized as follows:

- *Circularity*: for this area, CFF is suggested as an aggregation approach in combination with Material-RI as an integration support. Circularity in TREASURE assumes importance in the EoL and BoL phases, and CFF is a PEF-compatible single score indicator able to measure circularity in absolute terms, and for this reason able to aggregate several aspects of circularity into a single value. The Material-RI allows to evaluate the performance of the recycling process through the graphical visualisation of the different metals recovered; in this case, it does not make sense to aggregate the results and a disaggregated visualisation gives more insight.
- *Environmental:* From an environmental perspective, it is recommended to approach aggregation using the PEF guidelines. They contain the steps for normalisation, weighting and finally aggregation.
- *Economic:* LCC can effectively be considered an aggregation method as it assesses economic sustainability from a cost perspective. In addition to this methodology, financial indicators have been suggested as a supplement to the LCC. These indicators will be reported in a disaggregated way from the LCC.
- *Social:* UNEP, the methodology chosen for the social area, contains within it guidelines to aggregate the results of the impacts. This process can be automated with the support of a database, such as PSILCA. At the same time PSILCA allows you to modify the parameters, such as the default normalization ones, by accessing them directly. It remains to be established how the supplementary social indicators not supported by

UNEP can be aggregated, one possibility is to follow the various steps that lead to the aggregation reported in the sections §4.1.1, §4.1.2, and §4.1.3.

Integration methods and aggregation approaches between sustainability domains and circularity

When it comes to aggregation between areas of sustainability and circularity, the purpose of what is being done and the opinion of all stakeholders involved must be taken into account. MCDA methods are for this reason the most suitable, and among the existing methods, AHP is recommended. However, it is important that it is always possible to transparently trace the method and raw data used to derive an aggregated result. In terms of presenting results, rather than aggregation, it is better to adopt an integration approach; for example, by using a graphical model such as those presented in the sections §4.6, with which it is possible, for example, to compare the performance between two products or processes in each area of sustainability, using a single graphical support that integrates various aspects into a single presentation model.

A summary of the different approaches selected in TREASURE for the CE&LCSA domains in terms of goal and scope, methodologies, indicators, aggregation approaches can be found by consulting Table 21.

Table 21. Summary of the approaches selected in TREASURE for the CE & LCSA domains in terms of goal and scope, methodologies, indicators, aggregation, and integration.

CE&LCSA domains Selected approaches	Circularity	Environmental	Economic	Social
Goal and Scope	Measuring the performance of EoL and BoL management through the recycling.	Environmental assessment of EoL and BoL management plus design recommendations	Accounting for the costs of environmental externalities; the costs supported by stakeholders at different stages of the life cycle; and providing financial sustainability statements.	Define the stakeholders to be protected and the social impact categories to be monitored in relation to the TREASURE context.
Methodology	• CFF • Exergy analysis • Recyclability assessment	• LCA cradle to cradle • PEF	• cLCC • eLCC • CE-LCC	• SLCA (UNEP)
Indicators	• 15 circular indicators	• PEF midpoint indicators (14 default indicators)	• Total cost • Eco-costs • Financial indicators	• 79 social indicators
Aggregation	• CFF • Material-RI (Integration)	• PEF • MCDA (AHP)	• LCC	• UNEP guidelines • PSILCA database
CE&LCSA Aggregation and Integration	• MCDA -> AHP (Aggregation) • Graphical integration approach (Integration)			

Framework improvement for the framework application

Task T2.1 addressed the identification and inventorying of the indicators of the different areas without, however, arriving at a definitive selection of them. A partial selection has been performed with a high-level analysis that considers different aspects such as if the indicators are relevant to the use cases (disassembly, recycling, eco-design), if they are relevant to the project's goals and scopes and the life cycle phases mainly considered (BoL and EoL), and if they are relevant to the European context. A further selection was made by considering elements such as quantitativeness, the relevance with electronic products, the type of data required and the availability of the data. An additional filter is thus needed via the involvement of partners, discarding those indicators which are less relevant or require unavailable or uncertain data. At the current stage of the project, however, it may be premature to proceed this way, and this can be done when a more mature state of the pilots (faced in WP3 and WP5) is available together with the first picture provided by the advisory framework (T2.2) on the decisions to be supported.

Also in the case of aggregation and integration methodologies, supplementary analysis are needed within the pilot, investigating their applicability, their limit and the possible support to the advisory to be provided. From what can be learnt in Section 4, the integration of LCS&CA into a graphical model are effective for communication, but a technician who has to make a decision needs more elements and transparency, which is why he or she also needs to have access to a higher, disaggregated level of detail. When aggregating, it is also important to consider the discrepancies pointed out in the analysis above presented: not all areas use metrics that are linear; it is necessary to establish who the stakeholders involved are in order to understand whether aggregation may influence the interpretation of a result depending on who consults it; and finally, to make sure that the difference in units of measurement of the various indicators is taken into account in the various steps of aggregation.

Moreover, the framework developed in this deliverable lays the foundation for building a decision-support advisory model. However, not even the most effective aggregation and integration methods can unequivocally provide all the tools for the decision maker to actually make the 'right' decision. There will always be the possibility that indicators, e.g. from different areas of sustainability, will conflict with each other. Aggregation methods, e.g. MCDA, suggest involving and collecting the assessments of several stakeholders, so as to make at least a collective choice. However, these methods introduce subjectivity to the evaluation and do not exclude the possibility of doing errors of judgement and in fact the possibility of making one decision that turns out to be less sustainable than another. These aspects has to be taken into account in the pilot application.

An additional stimulus to be considered in the further development of the framework and in its applicability in the project is the automation of the assessment process. One of the TREASURE goals is to ease the S&C evaluation both in the calculation and in the interpretation phase. This could be supported by software tools that, supported by the TREASURE platform, are assuring a semi-automatic performance evaluation. In this regard, the assessment framework has to be evolved mainly considering the availability of primary and secondary data and the possibility that the procedure is carried out minimizing a manual intervention. This could especially affect the indicators selection that is directly linked to data availability. Again, concerning this aspect and the assessment automation, the use of primary data is always the suggested choice in terms of calculation accuracy, but this has not to be in contrast to the actual possibility to perform some evaluation in a time horizon compliant with decision making process. The use of secondary data (i.e., from eternal sources), is for sure more oriented to be plugged in an automatic calculation process, but obviously those data have to be available and with high quality and specificity.

Eventually, the selected methodological framework, in addition to ensuring a coexistence and integration of the different methodologies, should also avoid or mitigate the critical issues emerged in Sections 2, 3 and 4, such as: allocation problem (§2.2.1.2, §2.3.1), multi-stakeholders perspective (§2.2.2.1), externalities monetarization problem (§2.2.2.1), double counting (§2.3.1), handle difference in quality between secondary and primary material (§2.3.1), perform social assessment with both PSILCA indicators and new indicators (§3.3.2, §4.5), with 'global factors' normalisation method uncertainties may be introduced (§4.1.1), circular aggregation could introduce subjectivity to the evaluation (§4.2). However, being a new and not previously tested framework, it is advisable to keep these critical aspects in mind and make sure they are avoided.

6. Abbreviations

LCS&CA	Life Cycle Sustainability & Circularity Assessment
CE	Circular Economy
LCSA	Life Cycle Sustainability Assessment
S&C	Sustainability and Circularity
MCDA	Multi-Criteria Decision Analysis
UNEP	Unep Nations Environmental Programme
SETAC	Society of Environmental Toxicology and Chemistry
LCT	Life Cycle Thinking
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
SLCA	Social Life Cycle assessment
CEPA	Circular Economy Performance Assessment
KPI	Key Performance Indicators
CPA	Product Circularity Assessment
CEA	Environmental Circularity Assessment
CCA	Cost Circularity Assessment
GRI	Global Reporting Initiative
OEF	Organization Environmental Footprint
PEF	Product Environmental Footprint
PCR	Product Category Rules
ILCD	International Life Cycle Data system
PSIA	Product Social Impact Assessment
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
SLCIA	Social Life Cycle Impact Assessment
PEFCR	Product Environmental Footprint Category Rules
EoL	End of Life
BoL	Beginning of Life
RC	Recycled Content
EOR	End of life Recycling
CFF	Circular Footprint Formula
EPD	Environmental Product Declaration
SETAC	Society of Environmental Toxicology and Chemistry
cLCC	conventional Life Cycle Costing
eLCC	environmental Life Cycle Costing
sLCC	societal Life Cycle Costing
TCO	Total Cost of Ownership
R&D	Research and Development
EPS	Environmental Priority Strategies
CE	Circular Economy
BAU	Business As Usual
VRP	Value Retention Processes
CE-LCC	LCC method for the Circular Economy
TLCCM	Total Life Cycle Costing Model
PSILA	Product Structure-Based Integrated Life Cycle Analysis
TC	Total Cost
TCMAN	Total Cost of Manufacturer

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TCCUS	Total Cost of Customer
TCEUA	Total Cost of the End of Use Actors
MP	Mainstream Production
NPV	Net Present Value
MFCA	Material Flow Cost Accounting
SF	Social Footprint
LCSDGA	Life Cycle Sustainable Development Goals Assessment
SHDB	Social Hotspots Database
PSILCA	Product Social Impact Life Cycle Assessment
RS	Reference Scale
IP	Impact Pathway
DSM	Director Sustainability Methods
ESG	Environmental, Social and Governance
QALY	Quality Adjusted Life Years
SDG	Sustainable Development Goal
LCSS	Life Cycle SDG screening
LCSA	Life Cycle SDG assessment
EC	European Commission
CPI	Cost Product Indicator
RI	Recycling Index
Material-RI	Material Recycling Index
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
AE	Accumulated Exceedance
P	Fraction of nutrients reaching freshwater end compartment
N	Fraction of nutrients reaching marine end compartment
ADP ultimate reserves	Abiotic resource depletion
CTU_e	Comparative Toxic Unit for ecosystems
CTU_h	Comparative Toxic Unit for humans
WEEE	Waste Electrical and Electronic Equipment
KET	Key Enabling Technologies
RBR_{RI}	Recycling Index from Recyclability Benefit Rate
MCI	Material Circularity Indicator
PCI	Product Circularity Indicator
CC_C	Circular Calculator – Circularity
CR	Collection Rate
CTI	Circularity Transition Indicators
MECI	Material and Energy Circularity Indicators
MCEM-PLCS	Multi-Criteria Evaluation Method of Product-Level Circularity Strategies
REAPro	Assessment of Products
SPI	Sustainability Performance Indicators
PRDI	Product Recycling Desirability Index
MSI	Material Security Index
TRL	Recycling Technology Readiness
RRR	Rusability/Recyclability/Recoverability
MIS	Multidimensional Indicator Set
APL	Assessment of Circular Economy Strategies at the Product Level

MIPS	Material Input Per Service Delivered
QC	Circularity of Material Quality
CPEI	Circular-process energy intensity
CPFI	Circular-process feedstock intensity
Rrecov	Recoverability rate
RCR	Recycled content rate
RNL	Relative net loss
LCSD	Life Cycle Sustainability Dashboard
AHP	Analytic Hierarchy Process
CR	Consistency Ratio
CI	Consistency Index
SAW	Simple Additive Weighting
SI	Sustainability Index
AsMeR	Ease of Repair Rating Matrix
VRE	Value-based resource efficiency
EMF	Ellen MacArthur Foundation
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
CBA	Cost-Benefit Analysis
PRP	Reference Point of Performance
ELECTRE	ELimination and Choice Expressing REality
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
VIKOR	Multi-criteria optimization and compromise solution
SEEBalance	Socio-Eco-Efficiency Analysis
DEA	Data Envelopment Analysis
EEA	Eco-Efficiency Analysis

7. References

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ANNEX 1

T2.1 Post Kick-Off Questionnaire

Lead: SUPSI

Main Recipients: UNIZAR, MARAS, POLIMI, TNO

T2.1 Kick-Off Meeting recap

The objective of T2.1 is to develop the sustainability and circularity impact assessment framework to be adopted by TREASURE. The main goals of the T2.1 kick-off meeting were: 1) developing a common understanding of the assessment methods/approaches to be used and 2) defining the contributors and the expected contributions to the task activities. With this aim, expertise on sustainability assessment methods was explored during the meeting consortium. UNIZAR, MARAS, POLIMI and SUPSI presented the sustainability assessment methods they have experienced and they are meant to exploit in TREASURE project. To summarize:

- **UNIZAR:** deals with identifying the most critical components of vehicles by performing a thermodynamic analysis. The analysis measures the scarcity of metals used in the components, difficulty of extraction and difficulty of refining, measured through an indicator called thermodynamic rarity. The data required for the analysis has been provided by Seat.
- **MARAS:** analyses and processes the exact composition of components, calculates recycling and recovery rates (for both product and elements), optimizes recycling processing flowsheet architectures related to an improved disassembly strategy, simulates and evaluates recycling routes, links design to recycling through digitization, and develops physics-based recycling labels.
- **POLIMI:** presented the Circular Economy Performance Assessment (CEPA) methodology. This method allows assessing the circularity of a product by considering: the circularity product assessment, the circularity environmental assessment, and the circularity cost assessment.
- **SUPSI:** presented the methodologies and indicators for the sustainability assessment already adopted in previous projects:
  1. Environmental area – LCA approach, inventory level indicators according to GRI and OEF, impact indicators retrieved from PEF, OEF and EPD (PCR) in the fields of furniture and energy efficiency of manufacturing processes;
  2. Economic area – LCC approach;
  3. Social area – no experience in a project yet, first investigation on the S-LCA approach proposed by UNEP and on the PSIA methodology Handbook;
  4. Circular area – State of the Art for existing indicators' frameworks, especially focusing on circularity assessment at product level.
  5. From SUPSI point of view, whatever the calculation methods and indicators used in the assessment, a **life cycle approach** should be adopted: this allows comparing the sustainability of two systems considering their entire life cycle, thus avoiding problem shifting.

Purpose of the questionnaire

During the kick-off meeting, due to the limited available time, a planned open discussion with the participants has not been carried out. To follow-up the meeting, the questionnaire reported in Table 22 which lists the topics to be addressed (first and second columns), presents the related questions (third column) and, for each question, leaves room to the answers from the main involved partner (fourth column).

Please fill in the fourth column with your contributions in the space dedicated to your institution.

Table 22. Integrated consortium approach and vision on sustainable evaluation topics

Open Issue	Topics	Questions	Consortium expertise Approach/Vision (Supsi, Maras, Unizar, Polimi, TNO)
1 - Environmental assessment through LCA approach	LCA and allocation of impacts in closed-loop lifecycles Open issue: allocation of the impacts generated/avoided by the End-of-Life operations (e.g., recycling, refurbish, reuse etc. processes) from the first life to the second, third… ones, concerning the entire product, its components and assemblies, its constituting materials.	Within the TREASURE context on electronic components for automotive EoL: 1. Which approach of allocation (open VS closed-loop)[24] do you think is preferable? 2. Are you aware of some sector-specific decision/standard on that?	1) The closed-loop approach was chosen for the Treasure methodology. The closed-loop approach really has to do with the product under consideration, it expresses the true recycling of the materials of a product. Design for recycling, and recycling treatment options with a view to circularity take on more importance with this approach. Closed-loop is a prerequisite to allow open-loop recycling. Open-loop has little value if recycling of the recycled content is not considered. For the environmental assessment of the whole product life cycle, the LCA approach was chosen. The recyclability assessment is managed by Maras with the support of the HSC Chemistry software, it concerns the end-of-life phase of the LCA and it is based on achieved recycling/recovery rates, losses, emissions, energy/exergy etc. The impacts of the other LCA phases such as: procurement of virgin materials, production, assembly, transportation, use phase, etc. They will be calculated with an LCA software such as GaBi (yet to be decided). The final assessment is then given by: HSC Chemistry + LCA tool (such as GaBi).

[24] **Brief explanation to answer #1 topic – question 1**

Concerning the allocation of the impacts generated/avoided and the possible "credits" created by an End-of-Life (EoL) strategy, different approaches could be applied depending on the implemented strategy. In the case of recycling strategy, the closed-loop and the open-loop approaches have been defined:

- In open loop approach, the environmental credits generated by recycling are assigned to the product that use the recycled material, while
- In the closed-loop approach, recycling credits are attributed to the product that sends the material to recycling, no matter which kind of material is constituting it.

The approach selection is related to which kind of EoL scenario has to be promoted. For instance, metal industry opts for the closed-loop approach since it is meant to promote that the producer is responsible of the product EoL rather than being focalized on purchasing recycled material (currently a quite standard situation concerning metals).

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			2) No, even if standards would be available, the argumentation as given above, would prefer.
	LCA and circularity assessment Open issue: LCA is not so much sensible on materials savings, recyclability and reusability, material rarity and other aspects related to the availability of natural resources.	1. Do you have experience in combining LCA and circularity assessment? 2. How to integrate the circularity assessment and LCA results? (e.g., how to integrate the Recycling Index developed by MARAS and the circularity product assessment (CEPA) by POLIMI with the calculation of environmental indicators?)	1) Yes 2) After the recyclability assessment has been performed by MARAS, obtaining the actual recycling rates that can be achieved with the best recycling technologies, UNIZAR will then use the rarity indicator to further assess the recovery rates considering the quality of the recovered materials and not the mass terms. The result of these two analyses will be used as input for the LCA analysis and will cover the need to consider circularity within the LCA analysis. LCA can complement the thermodynamic assessment by introducing new indicators such as GhG emissions, etc. Another methodology able to relate the circularity of a product with the LCA is the CEPA methodology developed by Polimi, however it remains an open point to understand how/if to integrate it.
	Alternative methodologies to LCA Open issue: considering the above-mentioned issues and possible addition ones, is LCA the best methodology to be applied in a circular economy context?	1. Apart from the impact allocation of the EoL phase, do you see any other concern in the application of LCA in circular contexts? 2. Do you know/apply alternative/additional methodologies to the ones presented in the introduction for assessing environmental impacts within the circular economy context? 3. Is it possible to combine/integrate these methodologies with LCA? (e.g., how to integrate the thermodynamic rarity presented by UNIZAR and LCA?)	1) LCA is the best methodology to compare the environmental loads of different circular scenarios, but not the specific performance of a circular economy (e.g. recyclability, maintenance, renewable energy and resources, product life extension, input circularity vs output circularity, etc.). Furthermore, LCA for Eol is often not representative of the real performance and impact of recycling (energy, losses, emissions, etc.), as this is generally calculated from average and non-representative data. This means that a general LCA approach that is not based on the actual details of recycling/recovery, the quality of materials/elements recovered and lost, etc. will lead to incorrect calculations and will not lead to a correct representation and optimisation of circularity. The approach described above will allow this (LCA and recycling linked). 2) Evaluation of exergy in the Eol phase. 3) Possible integration of LCA and other CE methodologies: - Combining the different methodologies into a single algorithm (e.g. taking as input the environmental indicators from LCA and calculating CE performance from these). - Integrating the environmental impact calculation within an existing CE methodology (e.g. CEPA methodology). - See previous answers (combination of recyclability assessment, rarity indicator and LCA).

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2 - Economic assessment (LCC approach)	LCC, as well as LCA, has been largely adopted for the evaluation of linear cases, but not as much in circular ones. Thus, it is worth exploring consortium expertise in order to manage the choice of economic assessment methodology in circular field. For instance, the POLIMI circularity cost assessment (of CEPA) could be integrated in the economic assessment. However, if LCC will be the chosen assessment methodology, the integration of CEPA results into LCC approach shall be investigated.	1. Do you have experience with LCC? 2. Is LCC the only methodology to be considered, or are other economic evaluation methodologies more appropriate in the circular economy (CE) context? 3. Who can support us on economic indicators identification / development in the field of CE?	1) No one within the consortium is a leading expert but the LCC methodology has already been adopted in other projects: - SUPSI - MARAS did not apply LCC directly, but LCC was combined with recycling/recovery simulation modelling within the EU 6th Framework Project SuperLightCar[25] (project leader Volkswagen). See: 256) Van Schaik, A., M.A. Reuter (2009). Recycling and design for recycling of multi-material vehicles (as part of "Life cycle assessment and recycling of innovative multi-material applications" by S. Krinke (Volkswagen), A. van Schaik (MARAS), M.A. Reuter (Ausmelt) and J. Stichling (PE International)). In: Proceedings of the international conference 'Innovative developments for lightweight vehicle structures'. 26-27 May 2009, Wolfsburg, Germany (Volkswagen Head Office). pp. 196-208 (ISBN 978-3-00-027891-4). - POLIMI has adopted LCC in a past EU project related to cooling systems. 2) We do not have a precise answer to this question at the moment, but economic aspects will certainly be assessed in the circular steps, e.g. a cost assessment (rather an effort assessment) will be carried out for disassembly rates compared to recovery, to analyse where to stop disassembly in order to be "cost effective". SUPSI proposal is to adopt a LCC approach by addressing social and environmental impacts' costs, and allocating costs along multiple lifecycles Considering: product, and components constituting the product. 3) - Polimi can ask for support internally within its research team.
3 - Social assessment (S-LCA)	SUPSI has limited previous experience in the evaluation of social impacts and not carried out via the S-LCA indications. Thus, it is worth exploring possible expertise in the consortium in order to make a more aware selection of the assessment	1. Do you have any expertise on S-LCA or are you aware of someone in the consortium knowing having it? 2. If yes, could you provide us with some examples of S-LCA studies you have experienced? 3. If you answered affirmatively to the first questions, is in your view S-LCA	1) No one in the consortium is an S-LCA expert. Polimi has partly adopted S-LCA in an EU project related to WEEE. SUPSI proposal is to exploit S-LCA approach through: UNEP S-LCA – Guidelines for Social Life Cycle Assessment of Products and Organizations (2020). PSIA - Handbook for Product Social Impact Assessment (2020). PSILCA – Product Social Impact Life Cycle Assessment Database (2020). SHDB – Social Hotspot Database (2012).

[25] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi36brM_8b-AhW6TKQEHe5nAh4QFnoECBEQAQ&url=https%3A%2F%2Fcordis.europa.eu%2Fdocs%2Fresults%2F516%2F516465%2F127976541-6_en.pdf&usg=AOvVaw1pco4nXIUvLM_QHq8LmARe

	methodology and indicators for TREASURE case.	able to capture product/process changes from a societal perspective?	2) Polimi offered to share a past product with some social data on it. 3) Yes, only if based on a correct evaluation of products/processes and not on generalised data.
4 - Holistic interpretation of assessments results	Given the assessments for each field of sustainability, a further step will be to generate a comprehensive interpretation of the results. It is necessary to discuss on possible expertise in the consortium. The aim is gathering suggestions on how to manage results that could be conflicting to support decision-making.	1. Do you have expertise on multi-criteria decision-making? 2. How do you usually manage the coexistence of several indicators, even providing different and conflicting advice? For instance, @POLIMI, how do you manage the three indicators of the CEPA methodology? @MARAS, how do you integrate recyclability indexes and exergy results with those of LCA? 3. In order to support the decision-making process, would you rather prefer several indicators to be merged in one single sustainability indicator, or maintain different independent indicators juxtaposed in a proper graph? 4. In the latter case, would you adopt a scoring method, a graphical display (such as a cockpit), or do you have any other suggestion?	1) Yes 2) A multi-criteria approach will be preferred. Independent indicators could be social, environmental, economic and rarity/exergy assessment. This choice will be reflected in the graphical representation of the indicators through a multi-panel board. Maras: Multi-criteria decision making should not lead to trying to push all indicators into a single figure but use the different indicators/KPIs derived from the different studies (Recycling Index (total and per element! LCA, etc.) for correct and transparent decision making as also proposed by UNIZAR. Many indicators cannot be compared or combined into one value. Exergy is an elegant way to express several technical indicators in one value, without compromising detail and transparency. Polimi: On the CEPA methodology, there is a process of weighing several indices into a final indicator. The weighing is done according to the characteristics of the resource flows. However, the final indicators for the different sustainability characteristics (degree of circularity, economic aspects and environmental aspects) remain separate and we think this is the right way to proceed when assessing the different aspects of sustainability. 3) The advantage of having a single index is that it might be more understandable for a public. Conversely, several indices could allow experts to see how their decisions might affect each sustainability/circularity parameter. Considering that a single "sustainability" indicator will not do justice to a clear decision-making process. We will probably adopt the approach of "a few but distinct indicators", which have yet to be defined but could be: exergy, economic, social, environmental. However, the user will be given the possibility to view the indicators in detail.

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			4) This depends very much on which indicators we will use. A graphic way of presentation is clear for the public to grasp; however, the values behind must remain visible.

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5 – Sustainability Assessment Advisory	The Sustainability Assessment framework developed in T2.1 has a direct connection with the advisory module of TREASURE platform designed in T2.2. For this reason, during the development of the assessment framework, it is worth to focus on the pilots' assessment and advisor needs and the related possible features requested.	Considering the interactions you already had with pilots: 1) Which area of sustainability are the pilots more interested in (environmental, economic, social, circularity)? 2) What is the object of the assessment? A single component, a set of several components, a product, the comparison of different technologies…? 3) Who is the user of the assessment? 4) Should we foresee different sets of indicators varying the user of the assessment? 5) At what stage of the object of the analysis (a product, a technology…) life cycle does he/she view it? For what purposes? 6) What decisions can he/she make based on this assessment? 7) Does this decision target existing products or products under design? 8) Do we have to provide some "algebra" when considering multiple components (e.g., relevance of each component to the performance of products combining multiple components)?	The focus of the advisory is on environmental, economic and circular assessment of different disassembly procedures and prototyping technologies at single component and set of components levels. **(Q&A 1-2)** The indicators to be developed must be dedicated depending on the user type, which can be either the carmaker and part supplier/producer that must be supported at the BoL mainly or the dismantler that must be supported at the EoL phase. **(Q&A 3-4-5)** Examples of decisions supported by the Advisory based on the sustainability assessment are: disassembly components/ procedures/ depth, recycling architecture, Design for Recycling specifics, comparison of different strategies/scenarios, additional measures for improved recyclability, potential adjustment of processes or materials. **(Q&A 6)** The decisions target mainly under design products but also existing ones (for dismantlers and recyclers), and should be able to present the complexity of decision making in this field as a function of multiple indicators/KPI's in a clear and understandable manner, but without compromising the depth and knowledge required to understand and truly achieve circularity. **(Q&A 7- 8)**

ANNEX 2

Table 23 below reports the complete list of social indicators with appropriate selection criteria.

They are divided into "Generic" and "Specific" (column "Type") and are classified according to whether quantitatively, if suitable for the European context, whether related to the product, and in which company department the required data can be found.

A description of the application of the selection criteria is given below:

- Generic indicators: all generic indicators, as they are derived from the PSILCA database (Maister, K., Di Noi, C., Ciroth, A., & Srocka, 2020) are considered quantitative (see column "Quantitative indicators?). The only filter applied results column "Suitable for the European context?", while the criterion correlation with the product and the company section where to find the information were not found to be necessary since the data are derived directly from the database.
  It is important to specify that indicators related to the sphere of environmental sustainability are reported in the database, which were excluded (indicated with "Env.");
- Specific indicators: specific indicators, derived from UNEP (United Nations Environment Programme, 2021) and (Barni, Capuzzimati, et al., 2022), were first selected based on whether quantitative. Next, the filter was applied if consistent with the European context, followed by if related to the product.
  Finally, the relevant company department was indicated.

Indicators, generic and specific, that meet the selection criteria are highlighted in blue.

Table 23. Overall social indicators (Selected indicators are highlighted in blue)

Stakeholder	Category	Indicator	Type	Unit of Measurement	Data Sources / Methodology	Quantitative indicators?	Suitable for the European context?	Product related?	In which department of the company /organization can the data be found?
Local Community	Delocalization and Migration	International migrant workers in the sector	Generic	% (of total workers in the sector)	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	International Migrant Stock	Generic	% (of total population)	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	Net migration rate	Generic	‰ (= per 1,000 persons)	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	Asylum Seekers Rate	Generic	‰ (= per 1,000 persons)	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	Emigration rate	Generic	% (of total population)	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	Immigration rate	Generic	% (of total population)	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	Human rights issues faced by migrants	Generic	Yes/No	PSILCA	Yes	Yes	-	-
Local Community	Delocalization and Migration	Number of individuals who resettle (voluntarily and involuntarily) that can be attributed to the organization	Specific	-	! Site visit or site-specific audit ! Interviews with community members, Governmental agencies, management and NGOs ! Review of organization-specific reports, such as COP reports or audits	No	-	-	-
Local Community	Delocalization and Migration	Strength of organizational policies related to resettlement (e.g. due diligence and procedural safegaurds)	Specific	-	! Site visit or site-specific audit Interviews with community members, governmental agencies, management and NGOs ! Review of organization-specific reports, such as COP reports, audits and Social Impact Assessments	No	-	-	-

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Local Community	Delocalization and Migration	Strength of organizational procedures for integrating migrant workers into the community	Specific	-	! Site visit or site-specific audit Interviews with community members, employees, governmental agencies, management and NGOs ! Review of organization-specific reports, such as COP reports or audits	No	-	-	-
Local Community	Community Engagement	Strength of written policies on community engagement at organization level	Specific	-	! Site visit or site-specific audit ! Interviews with community members, employees, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	No	-	-	-
Local Community	Community Engagement	Diversity of community stakeholder groups that engage with the organization	Specific	-	! Site visit or site-specific audit ! Interviews with community members, employees, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	No	-	-	-
Local Community	Community Engagement	Number of meetings with community stakeholders (residents, community groups, developers, government workers (and the agencies they represent), etc.)	Specific	# of meetings	! Site visit or site-specific audit ! Interviews with community members, employees, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Management
Local Community	Community Engagement	Indicate the percentage [%] of employees that participate in social initiatives	Specific	Percentage [%]	! Site visit or site-specific audit ! Interviews with community members, employees, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Human Resources

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Local Community	Community Engagement	Indicate the extent [€. If hours, please convert them in €] of organization's support for community initiatives	Specific	Euro [€]	! Site visit or site-specific audit ! Interviews with management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Accounting
Local Community	Cultural Heritage	Are there policies/management plans in place to protect and/or support cultural heritage? [Yes/No]	Specific	Y/N	! Site visit or site-specific audit ! Interviews with community members, management and NGOs ! Review of organization-specific reports, such as GRI reports and Social Impact Assessments	Yes	Yes	No	Management
Local Community	Cultural Heritage	Presence of relevant organizational information to community members in their spoken language(s)	Specific	-	! Site visit or site-specific audit ! Interviews with community members, management and NGOs ! Consultation of documents/reports	No	-	-	-
Local Community	Cultural Heritage	Indicate the economic size of investments [€] in place to protect and/or support cultural heritage	Specific	Euro [€]	! Site visit or site-specific audit ! Interviews with community members, management and NGOs ! Consultation of documents/reports	Yes	Yes	No	Accounting
Local Community	Respect of Indigenous Rights	Presence of indigenous population	Generic	Y/N	PSILCA	Yes	No	-	-
Local Community	Respect of Indigenous Rights	Indigenous People Rights Protection Index	Generic	Score	PSILCA	Yes	No	-	-
Local Community	Respect of Indigenous Rights	Strength of Policies in Place to Protect the Rights of Indigenous Community Members	Specific	-	! Site visit or site-specific audit ! Interviews with community members, governmental agencies, management and NGOs ! Review of organization-specific reports, such as GRI reports	No	-	-	-

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Local Community	Respect of Indigenous Rights	Annual Meetings Held with Indigenous Community Members	Specific	-	! Site visit or site-specific audit ! Interviews with community members, management and NGOs ! Review of organization-specific reports, such as GRI reports	No	-	-	-
Local Community	Respect of Indigenous Rights	Number of reported and/or documented illegal activities	Specific	-	! Site visit or site-specific audit ! Interviews with community members, management and NGOs ! Review of organization-specific reports, such as GRI reports	No	-	-	-
Local Community	Respect of Indigenous Rights	The organization committed to accepting indigenous land rights	Specific	-	! Site visit or site-specific audit ! Interviews with community members, management and NGOs ! Review of organization-specific reports, such as GRI reports	No	-	-	-
Local Community	Local Employment	Unemployment rate in the country	Generic	% of the population	PSILCA	Yes	Yes	-	-
Local Community	Local Employment	Indicate the percentage [%] of workforce hired locally	Specific	Percentage [%]	! Site visit or site-specific audit ! Interviews with management ! Review of organization-specific reports, such as GRI or COP reports	Yes	Yes	No	Human Resources
Local Community	Local Employment	Strength of policies on local hiring preferences	Specific	-	! Site visit or site-specific audit ! Interviews with community members, employees, governmental agencies, management and NGOs ! Review of organization-specific reports, such as GRI or COP reports	No	-	-	-

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Local Community	Local Employment	Indicate the percentage [%] of local suppliers (within a radius of 150 km)	Specific	Percentage [%]	! Site visit or site-specific audit ! Interviews with management ! Review of organization-specific reports, such as GRI or COP reports	Yes	Yes	No	Purchase
Local Community	Access to Immaterial Resources	Annual arrests connected to protests of organization actions	Specific	-	! Site visit or site-specific audit ! Interviews with governmental agencies, management and NGOs ! Review of organization-specific reports, including GRI and COP reports and audits	No	-	-	-
Local Community	Access to Immaterial Resources	Indicate the economic size of investments [€] made in community education initiatives	Specific	Euro [€]	! Site visit or site-specific audit ! Interviews with community members, employees, governmental agencies, management and NGOs ! Review of organization-specific reports, including GRI and COP reports, audits and social impact assessments	Yes	Yes	No	Accounting
Local Community	Access to Material Resources	Level of industrial water use (related to total withdrawal)	Generic	% of total water withdrawal	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Level of industrial water use (Related to renewable water resources)	Generic	% of renewable water resources	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Extraction of biomass (related to area)	Generic	t/km^2	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Extraction of biomass (related to population)	Generic	t/cap	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Extraction of fossil fuels	Generic	t/cap	PSILCA	Yes	Yes	-	-

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Local Community	Access to Material Resources	Extraction of industrial and construction minerals	Generic	t/cap	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Extraction of ores	Generic	t/cap	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Certified environmental management systems (CMEs)	Generic	t/cap	PSILCA	Yes	Yes	-	-
Local Community	Access to Material Resources	Has the organization developed infrastructures with access to material resources and mutual benefit for the community? [Yes/No]	Specific	Y/N	! Site visit or site-specific audit ! Interviews with community members, employees, governmental agencies, management and NGOs ! Review of organization-specific reports, including GRI and COP reports and audits	Yes	No	-	-
Local Community	Access to Material Resources	If yes, please indicate how much the plant has invested [€] in it in the last year	Specific - added	Euro [€]	! Site visit or site-specific audit ! Interviews with management	Yes	No	-	-
Local Community	Access to Material Resources	Strength of organizational risk assessment with regard to potential for material resource conflict	Specific	-	! Site visit or site-specific audit ! Interviews with community members, governmental agencies, management and NGOs ! Review of organization-specific reports, including GRI and COP reports and audits and social impact assessments	No	-	-	-
Local Community	Access to Material Resources	Does the organization have a certified environmental management system? [Yes/No]	Specific	Y/N	! Site visit or site-specific audit ! Interviews with management ! Review of organization-specific reports, including GRI and COP reports and audits	Yes	Yes	No	Management

Local Community	Safe and Healthy Living Conditions	Pollution level of the country	Generic	Index	PSILCA	Yes	Yes	-	-
Local Community	Safe and Healthy Living Conditions	Drinking water coverage	Generic	% of the population	PSILCA	Yes	Yes	-	-
Local Community	Safe and Healthy Living Conditions	Sanitation coverage	Generic	% of the population	PSILCA	Yes	Yes	-	-
Local Community	Safe and Healthy Living Conditions	Management oversight of structural integrity	Specific	-	! Site visit or site-specific audit ! Interviews with management, community members, employees, governmental agencies and NGOs ! Review of organization-specific reports, such as GRI or COP reports	No	-	-	-
Local Community	Safe and Healthy Living Conditions	Indicate the organization efforts [€] to strengthen community health (e.g., through shared community access to organization health resources)	Specific	Euro [€]	! Site visit or site-specific audit ! Interviews with management, community members, employees, governmental agencies and NGOs ! Review of organization-specific reports, such as GRI or COP reports and social impact assessments	Yes	No	-	-
Local Community	Safe and Healthy Living Conditions	Indicate management effort [€] to minimize use of hazardous substances	Specific	Euro [€]	! Site visit or site-specific audit ! Interviews with management, community members, employees, governmental agencies and NGOs ! Review of organization-specific reports, such as GRI or COP reports	Yes	Yes	No	Accounting
Local Community	Secure Living Conditions	Management policies related to private security personnel	Specific	-	! Site visit or site-specific audit ! Interviews with management, community members, employees, governmental agencies and NGOs ! Review of organization-specific	No	-	-	-

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					reports, such as GRI or COP reports and social and/or human rights impact assessments				
Local Community	Secure Living Conditions	Number of legal complaints per year against the organization regarding security concerns	Specific	# of legal complaints	! Site visit or site-specific audit ! Interviews with management, governmental agencies and NGOs	Yes	Yes	No	Management
Local Community	Secure Living Conditions	Number of casualties and injuries per year ascribed to the organization and occurred in the local community (except employees)	Specific	# of casualties and injurie	! Site visit or site-specific audit ! Interviews with management, governmental agencies and NGOs	Yes	Yes	No	Management
Local Community	GHG Footprints	Embodied CO2 footprint	Generic	t per $	PSILCA	Yes - Env	Yes	-	-
Local Community	GHG Footprints	Embodied CO2-eq footprint	Generic	t per $	PSILCA	Yes - Env	Yes	-	-
Local Community	Environmental Footprints	Embodied agricultural area footprint	Generic	ha/$1	PSILCA	Yes - Env	Yes	-	-
Local Community	Environmental Footprints	Embodied forest area footprint	Generic	ha/$1	PSILCA	Yes - Env	Yes	-	-
Local Community	Environmental Footprints	Embodied water footprint	Generic	Mm3/$	PSILCA	Yes - Env	Yes	-	-
Local Community	Environmental Footprints	Number of threatened species	Generic	# species/$1	PSILCA	Yes - Env	Yes	-	-
Local Community	Labor Footprints	Embodied value-added total	Generic	$/$	PSILCA	Yes	Yes	-	-
Value Chain Actors	Fair Competition	Presence of anti-competitive behavior or violation of anti-trust	Generic	Cases per 10,000	PSILCA	Yes	Yes	-	-

		and monopoly legislation		employees in the sector					
Value Chain Actors	Fair Competition	Indicate the number of legal actions pending or completed during the reporting period regarding anticompetitive behavior and violations of anti-trust and monopoly legislation in which the reporting organization has been identified as a participant (GRI SO7)	Specific	# of legal actions	! Interviews with community members, employees, governmental agencies, union branch, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Management
Value Chain Actors	Fair Competition	Membership in alliances that behave in an anti-competitive way? [Yes/No]	Specific	Y/N	! Interviews with community members, employees, governmental agencies, union branch, OECD contact points, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Management
Value Chain Actors	Fair Competition	Do you have documented statements or procedures (policy, strategy, etc.) to avoid engaging in or being complicit in anti-competitive behavior? [Yes/No]	Specific	Y/N	! Interviews with community members, employees, governmental agencies, union branch, OECD contact points, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Management
Value Chain Actors	Fair Competition	Employee awareness of the importance of compliance with competition legislation and fair competition	Specific	-	-	No	-	-	-

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Value Chain Actors	Wealth distribution	Have contractual mechanisms been put in place in the supply chain to ensure the equitable distribution of value added and/or profit between the different supply chain actors (e.g.: maximum level of profits allowed, mutual aid fund in case of financial problems...)? [Yes/No]	Specific	Y/N	! Interviews with community members, management and NGOs ! Review of organization-specific repots, such as GRI reports and annual reports	Yes	Yes	Yes	Management
Value Chain Actors	Wealth distribution	Are there organizations, unions or sector representatives protecting the interests of those business entities with less bargaining power in the supply chain? [Yes/No]	Specific	Y/N	! Interviews with community members, management and NGOs ! Review of organization-specific repots, such as GRI reports and annual reports	Yes	Yes	Yes	Management
Value Chain Actors	Wealth distribution	Does your organization define a fair price, i.e. a price that covers all production costs and returns an acceptable profit margin? [Yes/No]	Specific	Y/N	! Interviews with community members, management and NGOs ! Review of organization-specific repots, such as GRI reports and annual reports	Yes	Yes	Yes	Management
Value Chain Actors	Respect of Intellectual Property Rights	Organization's policy and practice	Specific	-	! Interviews with community members, management and NGOs ! Review of organization-specific repots, such as GRI reports and annual reports	No	-	-	-

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Value Chain Actors	Respect of Intellectual Property Rights	Use of local intellectual property	Specific	-	! WIPO ! WIPONET ! Interviews with community members, employees, governmental agencies, management and NGOs ! Review of organization-specific repots, such as GRI reports and annual reports	No	-	-	-
Value Chain Actors	Supplier Relationships	Is there a coercive communication with suppliers? [Yes/No]	Specific	Y/N	! Interviews with management and procurement department ! Interviews with suppliers	No	-	-	-
Value Chain Actors	Supplier Relationships	Sufficient lead time	Specific	-	! Interviews with management and procurement department ! Interviews with suppliers	No	-	-	-
Value Chain Actors	Supplier Relationships	Reasonable volume Fluctuations	Specific	-	! Interviews with management and procurement department ! Interviews with suppliers	No	-	-	-
Value Chain Actors	Supplier Relationships	Does the organization pay its suppliers on time? [Yes/No]	Specific	Y/N	! Interviews with management and procurement department ! Interviews with suppliers	Yes	Yes	Yes	Accounting
Value Chain Actors	Promoting Social Responsibility	Membership in an initiative that promotes social responsibility along the supply chain	Generic	Number of companies	PSILCA	Yes	Yes	-	-
Value Chain Actors	Promoting Social Responsibility	Is there an explicit code of conduct in your plant that protects the human rights of workers among suppliers? [Yes/No]	Specific	Y/N	! Interviews with management ! Review of organization-specific reports, such as GRI reports or COP reports	Yes	Yes	Yes	Management
Value Chain Actors	Promoting Social Responsibility	Indicate the percentage [%] of suppliers the enterprise has audited with regard to social responsibility in the last year	Specific	Percentage [%]	! Interviews with management ! Review of organization-specific reports, such as GRI reports or COP reports	Yes	Yes	Yes	Management

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Value Chain Actors	Promoting Social Responsibility	Does the organization adhere to an initiative that promotes social responsibility along the supply chain? [Yes/No]	Specific	Y/N	! Interviews with management ! Review of organization-specific reports, such as GRI reports or COP reports	Yes	Yes	Yes	Management
Value Chain Actors	Promoting Social Responsibility	Is there integration of ethical, social, environmental and gender equality criteria in purchasing policy, distribution policy and contract signing? [Yes/No]	Specific	Y/N	! Interviews with management ! Review of organization-specific reports	Yes	Yes	Yes	Management
Value Chain Actors	Promoting Social Responsibility	Support to suppliers in terms of consciousness-raising and counselling concerning the social responsibility issues	Specific	-	! Interviews with management ! Interviews with suppliers	No	-	-	-
Value Chain Actors	Corruption	Public sector corruption	Generic	Score (Corruption Perceptions Index score of the country)	PSILCA	Yes	Yes	-	-
Value Chain Actors	Corruption	Active involvement of enterprises in corruption and bribery	Generic	%	PSILCA	Yes	Yes	-	-
Consumer	Health and safety	Violations of mandatory health and safety standards	Generic	Cases of Violation	PSILCA	Yes	Yes	-	-
Consumer	Health and safety	Presence of commissions or institutions to detect violations of standards and protect consumers from health and safety risks	Generic	Y/N	PSILCA	Yes	Yes	-	-

Consumer	Health and safety	Presence of management measures to assess consumer health and safety	Generic	Y/N or #	PSILCA	Yes	Yes	-	-
Consumer	Health and safety	Indicate the total number of customer complaints related to compliance with health and safety regulations and code-of-conducts	Specific	# of customer complaints	! Interviews or questionnaire filled by management, retailers and NGOs ! Review of enterprise-specific reports, such as GRI reports or audits ! Consumer organizations	Yes	Yes	Yes	Customer service
Consumer	Health and safety	Indicate the percentage [%] of products returned by customers due to health and safety problems	Specific	Percentage [%]	! Review of enterprise-specific reports, such as audits and/or GRI reports	Yes	Yes	Yes	Customer service
Consumer	Health and safety	is the product included with health and safety labels? [Yes/No]	Specific	Percentage [%]	! Labels on the product	Yes	Yes	Yes	Management
Consumer	Health and safety	Is there a Quality and/or Product Safety Management System in place in the plant (such as ISO 9001:2015, British Retail Consortium (BRC), Halal, International Food Standard (IFS), ISO 10377:2013, etc.)? [Yes/No]	Specific	Y/N	! Review of enterprise-specific documents ! Interviews or questionnaire filled by management, retailers, consumers, and NGOs	Yes	Yes	Yes	Management
Consumer	Feedback Mechanism	Are there any feedback mechanisms from the customers (e.g. after-sales services, customer satisfaction practices, ...)? [Yes/No]	Specific	Y/N	! Site visit or site-specific audit ! Interview with directors or marketing officer ! Verification of enterprise documents ! Consumer protection office ! Consumers organizations	Yes	Yes	Yes	Customer service

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Consumer	Feedback Mechanism	Indicate the total number of customer complaints	Specific - added	# of customer complaints		Yes	Yes	Yes	Customer service
Consumer	Consumer Privacy	Strength of internal management system to protect consumer privacy, in general	Specific	-	! Site visit or site-specific audit ! Interviews with employees, governmental agencies, management and NGOs ! Review of organization-specific reports and audits, such as GRI or COP reports	No	-	-	-
Consumer	Consumer Privacy	Do you hold a certification/label for your products or plant on privacy assurance? [Yes/No]	Specific	Y/N	-	Yes	Yes	Yes	Management
Consumer	Consumer Privacy	Number of consumer complaints related to breach of privacy or loss of data within the last year	Specific	# of customer complaints related to privacy	! Site visit or site-specific audit ! Interviews with governmental agencies and management ! Review of organization-specific reports and audits, such as GRI or COP reports	Yes	Yes	Yes	Customer service
Consumer	Consumer Privacy	Does your organization comply with current legislation on privacy (e.g. General Data Protection Regulation (EU) 2016/679)? [Yes/No]	Specific	Y/N	! Site visit or site-specific audit ! Interviews with governmental agencies and management ! Review of organization-specific reports and audits, such as GRI or COP reports	Yes	Yes	No	Management
Consumer	Transparency	Does your plant comply with current transparency regulations (e.g. Directive 2004/109/EC for EU countries)? [Yes/No]	Specific	Y/N	! Interviews with consumer protection agencies, governmental agencies, management and NGOs	Yes	Yes	No	Management

Consumer	Transparency	Indicate the number of customer complaints related to transparency	Specific	# of customer complaints related to transparency	! Interviews with consumers, employees, consumer protection agencies, governmental agencies, management and NGOs ! Review of enterprise-specific reports, such as GRI reports or audits	Yes	Yes	Yes	Customer service
Consumer	Transparency	Do you publish a sustainability report? [Yes/No]	Specific	Y/N	! Organization's Website	Yes	Yes	No	Health Safety and Environment
Consumer	Transparency	Quality and comprehensiveness of the information available in the sustainability report or other documents regarding to the social and environmental performance of the organization	Specific	-	! Review of organization-specific reports ! Interview with management	No	-	-	-
Consumer	Transparency	Do you communicate your results of the environmental and social impact assessment (if carried out) of your plant? [Yes/No]	Specific	Y/N	! Interview with management ! Review of enterprise-specific reports, such as GRI reports or audits	Yes	Yes	Yes	Marketing
Consumer	Transparency	Do you hold a certification/label for your products or organization on transparency assurance? [Yes/No]	Specific	Y/N	! Review of organization-specific reports ! Interview with management	Yes	Yes	Yes	Management
Consumer	Transparency	Company rating in sustainability indices (Dow Jones Sustainability Index, FTSE4Good, ESI, HSBC,	Specific	-	! Dow Jones Sustainability Index ! FTSE	No	-	-	-

		Corporate Sustainability Index, etc.)							
Consumer	End-of-Life Responsibility	Number of annual incidents of noncompliance with regulatory labelling requirements	Specific	# of annual incidents of noncompliance	! Site visit or site-specific audit ! Interviews with governmental agencies and management ! Review of organization-specific reports and audits, such as GRI reports	Yes	Yes	No	Management
Worker	Freedom of Association and Collective Bargaining	Trade union density	Generic	% of employees organised in trade unions	PSILCA	Yes	Yes	-	-
Worker	Freedom of Association and Collective Bargaining	Right of Association	Generic	score of ordinal 0-3 scale	PSILCA	Yes	Yes	-	-
Worker	Freedom of Association and Collective Bargaining	Right of Collective bargaining	Generic	score of ordinal 0-3 scale	PSILCA	Yes	Yes	-	-
Worker	Freedom of Association and Collective Bargaining	Right to strike	Generic	score of ordinal 0-3 scale	PSILCA	Yes	Yes	-	-
Worker	Freedom of Association and Collective Bargaining	Employment is not conditioned by any restrictions on the right to collective bargaining	Specific	-	! Interview with directors or human resources officer ! Interview with workers and trade union representatives ! NGOs reports ! Regulations	No	-	-	-

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Worker	Freedom of Association and Collective Bargaining	Number of hours [h] spent in trade union meetings and to adequately support trade unions in the company (Availability of facilities to Union, Posting of Union notices, time to exercise the representation functions on paid work hours)	Specific	Hours [h]	! Interview with directors or human resources officer ! Interview with workers and trade union representatives ! NGOs reports	Yes	Yes	No	Human Resources
Worker	Freedom of Association and Collective Bargaining	Check the availability of collective bargaining agreement and meeting minutes (e.g., copies of collective bargaining negotiations and agreements are kept on file)	Specific	-	! Interview and/or questionnaire filled out by directors or human resources officer	No	-	-	-
Worker	Freedom of Association and Collective Bargaining	Indicate the percentage [%] of employees joining unions	Specific	Percentage [%]	! Regulation ! Verification of organizations' documents ! Interview with workers and trade union representatives ! Interview with NGO and Trade Union association	Yes	Yes	No	Human Resources
Worker	Freedom of Association and Collective Bargaining	GRI LA5 Minimum notice period(s) regarding significant operational changes, including whether it is specified in collective agreements	Specific	-	! Organizations GRI Sustainability	No	-	-	-

Worker	Freedom of Association and Collective Bargaining	Workers have access to a neutral, binding, and independent dispute resolution procedure	Specific	-	! Verification of organizations' documents ! Interview with NGOs and Trade Union association	No	-	-	-
Worker	Freedom of Association and Collective Bargaining	Are facilities available for trade union meetings, display of trade union notices, etc.? [Yes/No]	Specific	Y/N	-	Yes	Yes	No	Management
Worker	Freedom of Association and Collective Bargaining	Indicate the percentage [%] of employees covered by collective bargaining agreements	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Child Labour	Children in employment, male	Generic	% of male children ages 7-14	PSILCA	Yes	No	-	-
Worker	Child Labour	Children in employment, female	Generic	% of female children ages 7-14	PSILCA	Yes	No	-	-
Worker	Child Labour	Children in employment, total	Generic	% of all children ages 7-14	PSILCA	Yes	No	-	-
Worker	Child Labour	Indicate the percentage [%] of working children under the legal age or 15 years old (14 years old for developing economies)	Specific	Percentage [%]	! Visit to facility ! Interview with directors or human resources officer ! Verification of organization documents ! NGOs reports ! Verification with workers interviews or audits ! Interview with community members	Yes	No	-	-
Worker	Child Labour	Children are not performing work during the night (an example of unauthorized work	Specific	-	! Visit to facility ! Interview with directors or human resources officer ! Verification of organization documents	No	-	-	-

		by the ILO conventions C138 and C182)			! NGOs reports ! Verification with workers interviews or audits				
Worker	Child Labour	Are there any records kept that show the names and ages or dates of birth of all workers? [Yes/No]	Specific	Y/N	! Visit to facility ! Interview with directors or human resources officer ! Verification of organization documents	Yes	No	-	-
Worker	Child Labour	Working children younger than 15 and under the local compulsory age are attending school	Specific	-	! Interview with directors or Human resources officer ! Verification with workers interviews or audits ! NGOs reports ! Interview with local schools	No	-	-	-
Worker	Fair Salary	Living wage, per month	Generic	USD	PSILCA	Yes	Yes	-	-
Worker	Fair Salary	Minimum wage, per month	Generic	USD	PSILCA	Yes	Yes	-	-
Worker	Fair Salary	Sector average wage, per month	Generic	USD	PSILCA	Yes	Yes	-	-
Worker	Fair Salary	Indicate the ratio between the average wage of lowest-paid employees compared with the average wage of the industry&country where the plant is located [%]	Specific	Percentage [%]	! Country minimum wage ! Interview with directors or Human resources officer ! Verification of organization documents: e.g., wage records ! Review of organization-specific reports, such as GRI reports or audits	Yes	Yes	No	Human Resources
Worker	Fair Salary	Indicate the ratio between the average wage of employees compared with the average wage of the industry&country where the plant is located [%]	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources

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Worker	Fair Salary	Number of employees earning wages below poverty line	Specific	-	! Interviews with workers ! Interview with local NGO's	Yes	No	-	-
Worker	Fair Salary	Presence of suspicious deductions on wages	Specific	-	! Interviews with employees, management and human resources ! Review of organization-specific reports, such as GRI reports or audits agreement or contracts between organizations and employees ! Review of wage records	No	-	-	-
Worker	Fair Salary	Indicate the percentage [%] of employees paid regularly and documented (at least monthly)	Specific	Percentage [%]	! Interviews with employees, governmental agencies, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits ! Review of wage records	Yes	Yes	No	Human Resources
Worker	Working hours	Hours of work per employee, per week	Generic	h	PSILCA	Yes	Yes	-	-
Worker	Working hours	Number of hours effectively worked by employees	Specific	Hours [h]	! Interviews with workers, governmental agencies, management and NGOs ! Review of audits ! Review of time records	Yes	Yes	No	Human Resources
Worker	Working hours	Number of holidays effectively used by employees (at each level of employment).	Specific	-	! Interviews with workers, governmental agencies, management and NGOs ! Review of audits ! Review of time records	No	-	-	-
Worker	Working hours	Respect of contractual agreements concerning overtime	Specific	-	! Interviews with workers, governmental agencies, management and NGOs ! Review of audits ! Review of time records	No	-	-	-

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Worker	Working hours	Clear communication of working hours and overtime arrangements	Specific	-	! Interviews with workers, governmental agencies, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits and agreement or contracts between organizations and workers ! Review of employee contracts and collective bargaining agreement	No	-	-	-
Worker	Working hours	Does the organization provide flexibility (e.g. flexible entry/exit times)? [Yes/No]	Specific	Y/N	! Interviews with employees, governmental agencies, management and NGOs ! Review of organization-specific reports, such as GRI reports or audits agreement or contracts between organizations and employees	Yes	Yes	No	Human Resources
Worker	Working hours	Indicate the percentage [%] of employees receiving regular performance and career development reviews	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Working hours	Indicate the percentage of training hours [%] spent on skills management and lifelong learning programs that support employees' continued employability	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Working hours	Indicate the percentage [%] of FTE employees who left (voluntarily or involuntarily) the plant	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources

Worker	Working hours	Indicate the percentage [%] of FTE employees who were hired by the plant	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Forced Labor	Goods produced by forced labor	Generic	Number of goods in the sector	PSILCA	Yes	No	-	-
Worker	Forced Labor	Frequency of forced labor	Generic	Cases per 1,000 inhabitants in the country	PSILCA	Yes	No	-	-
Worker	Forced Labor	Tier placement referring to trafficking in persons	Generic	Tier placement	PSILCA	Yes	No	-	-
Worker	Forced Labor	Average % of overtime hours (compared to ordinary hours) worked by employees	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Forced Labor	Workers voluntarily agree upon employment terms. Employment contracts stipulate wage, working time, holidays and terms of resignation. Employment contracts are comprehensible to the workers and are kept on file	Specific	-	! Interview with directors or Human resources officer ! Verification of organization documents ! NGOs reports ! Verification with workers interviews or audits	No	-	-	-
Worker	Forced Labor	Birth certificate, passport, identity card, work permit or other original documents belonging to the worker are not retained or kept for safety reasons by the organization neither upon hiring nor during employment	Specific	-	! Interview with directors or Human resources officer ! Verification of organization documents ! NGOs reports ! Verification with workers interviews or audits	No	-	-	-

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Worker	Forced Labor	Average ratio between the notice period granted to employees in the event of their voluntary contract termination and that required by the contract	Specific	-	! Interview with directors or Human resources officer ! Verification of organization documents ! NGOs reports ! Verification with workers interviews or audits	Yes	No	No	-
Worker	Forced Labor	Workers are not bonded by debts exceeding legal limits to the employer	Specific	-	! Interview with directors or Human resources officer ! Verification of organization documents ! NGOs reports ! Verification with workers interviews or audits	No	-	-	-
Worker	Equal opportunities/ discrimination	Women in the labor force (total)	Generic	% of economically active population	PSILCA	Yes	Yes	-	-
Worker	Equal opportunities/ discrimination	Women in the sectoral labor force	Generic	ratio	PSILCA	Yes	Yes	-	-
Worker	Equal opportunities/ discrimination	Gender wage gap	Generic	%	PSILCA	Yes	Yes	-	-
Worker	Equal opportunities/ discrimination	Indicate the percentage [%] of FTE employees coming from foreign countries	Specific - added	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Equal opportunities/ discrimination	Indicate the percentage [%] of FTE employees who have disabilities	Specific - added	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Equal opportunities/ discrimination	Indicate the percentage [%] of FTE employees that are women	Specific - added	Percentage [%]	-	Yes	Yes	No	Human Resources

Worker	Equal opportunities/ discrimination	Announcement of open positions happen through national/regional newspapers, public job databases on the internet, employment services or other publicly available media ensuring a broad announcement.	Specific	-	! Review of enterprise-specific reports ! Interview with NGOs ! Interviews with human resources and management	No	-	-	-
Worker	Equal opportunities/ discrimination	Composition of governance bodies and breakdown of employees per category according to gender, age group, minority, group membership, and other indicators of diversity	Specific	-	! GRI Sustainability reports ! Interviews with human resources and management ! Review of enterprise-specific reports ! Publicly available information	No	-	-	-
Worker	Equal opportunities/ discrimination	Indicate the entity (in percentage [%]) of the gender wage gap (ratio of basic salary of men to women)	Specific	Percentage [%]	! GRI Sustainability reports ! Interviews with human resources and management ! Review of enterprise-specific reports	Yes	Yes	No	Human Resources
Worker	Equal opportunities/ discrimination	Indicate the percentage of training hours [%] dedicated to non-discrimination	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources
Worker	Health and safety	Accident rate at workplace	Generic	Cases per 100,000 employees and year	PSILCA	Yes	Yes	-	-
Worker	Health and safety	Fatal accidents at workplace	Generic	Cases per 100,000 employees and year	PSILCA	Yes	Yes	-	-

Worker	Health and safety	DALYs due to indoor and outdoor air and water pollution	Generic	DALYs per 1,000 inhabitants in the country	PSILCA	Yes	Yes	-	-
Worker	Health and safety	Presence of sufficient safety measures	Generic	OSHA cases per 100,000 employees in the sector	PSILCA	Yes	Yes	-	-
Worker	Health and safety	Workers affected by natural disasters	Generic	%	PSILCA	Yes	Yes	-	-
Worker	Health and safety	Indicate the number of accidents occurred in the plant	Specific	# of injuries # of incidents # of fatalities	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Interview with workers and union	Yes	Yes	Yes	Health, Safety and Environment
Worker	Health and safety	Hours of injuries per level of employees	Specific	-	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Interview with workers and union	No	-	-	-
Worker	Health and safety	Indicate the number of work-related fatalities occurred in the plant	Specific	-	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Interview with workers and union	Yes	Yes	Yes	Health, Safety and Environment
Worker	Health and safety	Indicate the number of injuries occurred in the organization	Specific	-	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Interview with workers and union	Yes	Yes	Yes	Health, Safety and Environment

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Worker	Health and safety	Indicate the number of formal policies, Standard Operating Instructions or Procedures concerning health and safety that are adopted	Specific	-	! Interviews and or questionnaire filled by management and human resources ! Review of organization-specific web site and reports	Yes	Yes	No	Health, Safety and Environment
Worker	Health and safety	Does the plant have an occupational health and safety management system? [Yes/No]	Specific	Y/N	-	Yes	Yes	No	Health, Safety and Environment
Worker	Health and safety	Indicate the hours [h] of total occupational diseases	Specific	Hours [h]	-	Yes	Yes	No	Human Resources
Worker	Health and safety	Indicate the number of near misses registered (an incident in which no property was damaged and no personal injury was sustained, but where damage or injury easily could have occurred)	Specific	# of near miss	-	Yes	Yes	No	Health, Safety and Environment
Worker	Health and safety	Do you currently carry out a Near Miss analysis in order to identify whether the measures planned and implemented as a result of the risk assessment are adequate and effective and can prevent recurrence? [Yes/No]	Specific	Y/N	-	Yes	Yes	No	Health, Safety and Environment
Worker	Health and safety	Indicate the percentage [%] of workers operating in hazardous working conditions	Specific	Percentage [%]	-	Yes	Yes	No	Health, Safety and Environment

		(e.g., risky for health: exposure to chemical, carcinogenic, mutagenic, physical and biological agents; for safety; cross-cutting: psychological or ergonomic factors)							
Worker	Health and safety	Indicate the hours [h] of unexcused absences (neither for illness nor for holidays, also including absences that were not requested to and/or accepted by the employer)	Specific - added	Hours [h]	-	Yes	Yes	No	Human Resources
Worker	Health and safety	What is the ratio: product-related investment in general safety measures / total cost of the product [%]?	Specific	Euro [€]	! Interviews and or questionnaire filled by management, workers, governmental agencies and NGOs ! Review of organization-specific web site and reports	Yes	Yes	Yes	Accounting
Worker	Health and safety	Indicate the percentage [%] of employees wearing appropriate protective equipment in all applicable situations	Specific	Percentage [%]	! Interviews and or questionnaire filled by management, workers, governmental agencies and NGOs ! Review of organization-specific web site and reports	Yes	Yes	No	Health, Safety and Environment
Worker	Health and safety	Preventive measures and emergency protocols exist regarding pesticide & chemical exposure	Specific	-	! Interviews and or questionnaire filled by management, workers, governmental agencies and NGOs ! Review of organization-specific web site and reports	No	-	-	-
Worker	Health and safety	Appropriate protective gear required in all applicable situations	Specific	-	! Interviews and or questionnaire filled by management, workers, governmental agencies and NGOs ! Review of organization-specific web site and reports	No	-	-	-

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Worker	Health and safety	Indicate the number of (serious and nonserious) Occupational Safety and Health Administration (OSHA) violations reported within the last year	Specific	# of OSHA violations	! Questionnaire filled by management, government violation records, news articles	Yes	Yes	No	Health, Safety and Environment
Worker	Health and safety	Indicate the percentage of training hours [%] devoted to education, prevention and control of health and safety risks	Specific	-	! GRI Sustainability reports ! Interviews and or questionnaire filled by management, workers, governmental agencies, local communities and NGOs ! Review of organization-specific reports	No	-	-	-
Worker	Social Benefit/Social Security	Social security expenditures	Generic	% of GDP	PSILCA	Yes	Yes	-	-
Worker	Social Benefit/Social Security	Evidence of violations of laws and employment regulations	Generic	Violation cases	PSILCA	Yes	Yes	-	-
Worker	Social Benefit/Social Security	Indicate the percentage of the wage [%] referring to the social benefits provided to workers	Specific	Percentage of wage [%]	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Review of audits ! Interview with workers/union (s)	Yes	Yes	No	Human Resources
Worker	Social Benefit/Social Security	Indicate the percentage [%] of FTE employees who say they are satisfied (through surveys measuring employees' satisfaction or similar)	Specific	Percentage [%]	-	Yes	Yes	No	Human Resources

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Worker	Social Benefit/Social Security	Evidence of violations of obligations to workers under labor or social security laws and employment regulations	Specific	-	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Review of audits ! Interview with workers/union (s)	No	-	-	-
Worker	Social Benefit/Social Security	Indicate the percentage [%] of FTE employees receiving paid time-off	Specific	Percentage [%]	! Interviews or questionnaire filled by management and Human resources ! Review of enterprise-specific reports ! Review of audits ! Interview with workers/union (s)	Yes	Yes	No	Human Resources
Worker	Employment relationship	Indicate the percentage [%] of employees for whom there is a written employment contract defining the relationship between employers and employees (rights and responsibilities of each)	Specific	Percentage [%]	! Employment contract ! Interviews with directors or human resources officer ! Interviews with workers and trade union representatives ! Regulations	Yes	Yes	No	Human Resources
Worker	Employment relationship	Presence of contracts' essential elements	Specific	-	! Employment contract ! Interviews with directors or human resources officer ! Interviews with workers and trade union representatives ! Regulations	No	-	-	-
Worker	Employment relationship	Workers have a copy of the signed contract	Specific	-	! Employment contract ! Interviews with directors or human resources officer ! Interviews with workers and trade union representatives ! Regulations	No	-	-	-
Worker	Sexual harassment	Number of sexual harassment incidents	Specific	-	! Interviews with directors or human resources officer ! Interviews with workers and	No	-	-	-

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		reported on a grievance helpline			trade union representatives ! Interviews with community members ! Interviews with governmental agencies and NGOs ! Organization-specific reports and audits				
Worker	Sexual harassment	Existence of clear responsibilities for matters of sexual harassment within the organization	Specific	-	! Interviews with directors or human resources officer ! Interviews with workers and trade union representatives ! Interviews with community members ! Interviews with governmental agencies and NGOs ! Organization-specific reports and audits ! Regulations	No	-	-	-
Worker	Sexual harassment	Efforts by the organization to reduce the risk of sexual harassment	Specific	-	! Interviews or questionnaire filled by management and human resources ! Review of enterprise-specific reports	No	-	-	-
Worker	Smallholders including farmers	• Days and months without sufficient food in past year • Access to domestic services (e.g., water for domestic use; electricity)	Specific	-	! Interviews with management, procurement department, smallholders, and workers ! Visit to facility ! Verification of organization documents and with workers interviews or audits	No	-	-	-
Worker	Smallholders including farmers	• Participation in farmers organization • Ownership of the farm/company	Specific	-	! Interviews with management, procurement department, smallholders, and workers ! Visit to facility ! Verification of organization documents and with workers interviews or audits	No	-	-	-

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Worker	Smallholders including farmers	• Evidence of crop yield (e.g., crop yield calculated by estimated production/ estimated cultivation area; crop revenue calculated from farmer estimated sales; net crop income) • Evidence of production per year	Specific	-	! Interviews with management, procurement department, smallholders, and workers ! Visit to facility ! Verification of organization documents and with workers interviews or audits	No	-	-	-
Worker	Smallholders including farmers	• Evidence of access to services (e.g., inputs such as fertilizer and seeds (planting material); affordable credit and capital; use of credit (in a given year); to agronomic assistance)	Specific	-	! Interviews with management, procurement department, smallholders, and workers ! Visit to facility ! Verification of organization documents and with workers interviews or audits	No	-	-	
Worker	Smallholders including farmers	• Membership in or access to a farmer organization • Evidence of quality of relationship with primary buyer (e.g., length of relationship; number of options for buyers; presence of benefits from trade; percent of harvest sold; knowledge of certifications held) • Traceability and understanding of quality standards & price premiums (if they exist)	Specific	-	! Interviews with management, procurement department, smallholders, and workers ! Visit to facility ! Verification of organization documents and with workers interviews or audits	No	-	-	

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Worker	Smallholders including farmers	• Level of education completed by household/family members • Age of farm/company manager or the person who generally makes the decisions • Age of household/family members concerning for example age of member doing primary work in target commodity or agribusiness chain; attending training around the target; receiving the money from the sale; receiving credit around the target, joining the farmer group/cooperative	Specific	-	! Interviews with management, procurement department, smallholders, and workers ! Visit to facility ! Verification of organization documents and with workers interviews or audits	No	-	-	-
Society	Public Commitment to Sustainability Issues	Complaints issued related to the non fulfilment of promises or agreements by the organization by the local community or other stakeholders at OECD contact points or Global Reporting Initiative.	Specific	-	! Interviews with community members, employees, governmental agencies, union branch, OECD contact points, management and NGOs ! Review of enterprise-specific reports, such as GRI reports or audits	No	-	-	-

Society	Public Commitment to Sustainability Issues	Presence of mechanisms to follow-up the realisation of promises	Specific	-	! Interviews with community members, employees, governmental agencies, union branch, OECD contact points, management and NGOs ! Review of enterprise-specific reports, such as GRI reports or audits	No	-	-	-
Society	Public Commitment to Sustainability Issues	Have you implemented or signed up to any principles or other codes of conduct such as: Sullivan Principles, Caux Roundtable, UN Principles, etc.? [Yes/No]	Specific	-	! Sullivan Principles ! Caux Round Table ! United Nations ! Global Compact	Yes	Yes	No	Human Resources/Management
Society	Prevention and Mitigation of Conflicts	Risk of conflicts	Generic	Score	PSILCA	No	No	-	-
Society	Prevention and Mitigation of Conflicts	Organization's role in the development of conflicts	Specific	-	! Interviews with community members and NGOs ! Internet research	No	-	-	-
Society	Prevention and Mitigation of Conflicts	Disputed products	Specific	-	! Sector statistics ! Labelling	No	-	-	-
Society	Contribution to Economic Development	Public expenditure on education	Generic	% of GDP	PSILCA	Yes	Yes	-	-
Society	Contribution to Economic Development	Adult illiteracy rate (15+ years), male	Generic	% of male population	PSILCA	Yes	No	-	-
Society	Contribution to Economic Development	Adult illiteracy rate (15+ years), female	Generic	% of female population	PSILCA	Yes	No	-	-

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Society	Contribution to Economic Development	Adult illiteracy rate (15+ years), total	Generic	% of total population	PSILCA	Yes	No	-	-
Society	Contribution to Economic Development	Youth illiteracy rate, male	Generic	% of male population, 15-24	PSILCA	Yes	No	-	-
Society	Contribution to Economic Development	Youth illiteracy rate, female	Generic	% of female population, 15-24	PSILCA	Yes	No	-	-
Society	Contribution to Economic Development	Youth illiteracy rate, total	Generic	% of total population, 15-24	PSILCA	Yes	No	-	-
Society	Contribution to Economic Development	Contribution of the product to economic progress (revenue generated by the product, earnings, R+D costs relative to revenue, etc.)	Specific	-	! Interviews with community members, governmental agencies, management and NGOs ! Review of enterprise-specific reports, such as GRI reports or audits	No	-	-	-
Society	Poverty alleviation	The organization carries out a poverty alleviation program	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	Yes	No	No	-
Society	Poverty alleviation	Contingency planning measures, disaster, emergency management plan, training programs, and recovery/ restoration plans	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	Yes	No	No	-
Society	Poverty alleviation	Formalized commitment of the organization to reduce poverty	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	Yes	No	No	-

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Society	Corruption	Are you carrying out an anti-corruption programs? [Yes/No]	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports and annual reports	Yes	Yes	No	Management
Society	Corruption	Have you introduced internal or external controls to prevent corruption? [Yes/No]	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports and annual reports	Yes	Yes	No	Management
Society	Corruption	Financial damages	Specific	-	-	No	-	-	-
Society	Ethical treatment of animals	Presence of regular check-ups and frequency of animals welfare conducted by specialists (veterinaries, animal biologists, or others)	Specific	-	! Interviews with management ! Interviews with animal specialists (veterinaries, animal biologists or others)	No	-	-	-
Society	Ethical treatment of animals	Presence/number of serious injuries, illnesses, and unforeseen fatal casualties reported by workers and animal specialists	Specific	-	! Interviews with workers ! Interviews with animal specialists (veterinaries, animal biologists or others) ! Interviews with civil society organizations represeting animal walfare issues	No	-	-	-
Society	Ethical treatment of animals	Presence/number of behavioral disorders or occupational diseases reported by workers, animal specialists, and/or civil society members	Specific	-	! Interviews with workers ! Interviews with animal specialists (veterinaries, animal biologists or others) ! Interviews with civil society organizations representing animal welfare issues	No	-	-	-
Society	Ethical treatment of animals	Complaints from consumers or civil society organizations representing animal welfare issues	Specific	-	! Interviews with consumers ! Interviews with civil society organizations representing animal welfare issues	No	-	-	-

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Society	Ethical treatment of animals	Actions in response to complaints or serious unforeseen cases putting the lives or welfare of the animals at risk	Specific	-	! Interviews with management ! Interviews with consumers or civil society organizations representing animals' welfare issues	No	-	-	-
Society	Ethical treatment of animals	Presence of any label certifying the fair treatment of animals	Specific	-	! Interviews with management ! Interviews with consumers	No	-	-	-
Society	Ethical treatment of animals	Improvements over time concerning the prevention of injuries, illnesses, and unforeseen fatal casualties	Specific	-	! Interviews with management and procurement department ! Interviews with smallholders	No	-	-	-
Society	Ethical treatment of animals	Improvements over time concerning the prevention of behavioral disorders and occupational diseases	Specific	-	! Interviews with management ! Reports from NGOs ! Interviews with civil society organizations representing animal welfare issues	No	-	-	-
Society	Ethical treatment of animals	Quality, dimension and hygiene of livestock farming conditions; Livestock density	Specific	-	! Interviews with management and workers ! Interviews with civil society organizations representing animal welfare issues ! Comparison against specifications of animal welfare organizations ! Comparison against country/sector specific regulations	No	-	-	-
Society	Technology Development	Are you involved in technology transfer programs or projects? [Yes/No]	Specific	-	! Interviews with management ! Reports on technology development of the organization ! Project reports	Yes	Yes	Yes	Management

Society	Technology Development	Do you have partnerships in research and development? [Yes/No]	Specific	-	! Interviews with management ! Reports on technology development of the organization ! Reports of collaborating organizations on the technology development of the organization	Yes	Yes	Yes	Management
Society	Health and safety	Health expenditure, total	Generic	% of GDP	PSILCA	Yes	Yes	-	-
Society	Health and safety	Health expenditure, public	Generic	% of total health expenditure	PSILCA	Yes	Yes	-	-
Society	Health and safety	Health expenditure, out-of-pocket	Generic	% of total health expenditure	PSILCA	Yes	Yes	-	-
Society	Health and safety	Health expenditure, external resources	Generic	% of total health expenditure	PSILCA	Yes	Yes	-	-
Society	Health and safety	Domestic and External Health Expenditure	Generic	% of total health expenditure	PSILCA	Yes	Yes	-	-
Society	Health and safety	Domestic General Government Health Expenditure	Generic	% of total health expenditure	PSILCA	Yes	Yes	-	-
Society	Health and safety	Life expectancy at birth	Generic	Years	PSILCA	Yes	Yes	-	-
Children	Education provided in the local community	Community involvement programs and opportunities as a consistent goal for schools	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit ! NGO reports ! Regulations	No	-	-	-
Children	Education provided in the local community	Presence of systems promoting human and financial resources	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit	No	-	-	-

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					! NGO reports ! Regulations				
Children	Education provided in the local community	Presence of strategies addressing demand-side gender-related and disability barriers to education	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit ! NGO reports ! Regulations	No	-	-	-
Children	Education provided in the local community	Presence of equitable access to education	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit ! NGO reports ! Regulations	No	-	-	-
Children	Education provided in the local community	Presence of policy, leadership, and budget for early learning	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit ! NGO reports ! Regulations	No	-	-	-
Children	Education provided in the local community	Presence of education systems promoting accountability to communities	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit ! NGO reports ! Regulations	No	-	-	-
Children	Education provided in the local community	Presence of provisions of local community involvement in monitoring of school activities	Specific	-	! Interviews with community members, employees, governmental agencies, management, and NGOs ! Site visit or site-specific audit ! NGO reports ! Regulations	No	-	-	-

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Children	Health issues for children as consumers	The organization carries out programs to promote leisure and family time for the children	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-
Children	Health issues for children as consumers	The organization carries out programs to promote health impact to children	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-
Children	Health issues for children as consumers	Formalized commitment of the organization to improve the health of children	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-
Children	Children concerns regarding marketing practices	The organization has a policy on responsible marketing	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-
Children	Children concerns regarding marketing practices	The organization performs audit on the implementation of responsible marketing	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-
Children	Children concerns regarding marketing practices	The organization receives monitoring and evaluation from the governing body on the implementation of responsible marketing	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-
Children	Children concerns regarding marketing practices	The number of incidents of non-compliances with regulations and/or voluntary codes concerning product and service information/	Specific	-	! Interviews with management ! Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports	No	-	-	-

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		marketing/ advertising and labeling, by incidents of noncompliance with regulations resulting in a fine or penalty; incidents of non-compliance with regulations resulting in a warning; and incidents of non-compliance with voluntary codes							

ANNEX 3

Mass of Virgin Raw Materials ($M\%_{virgin}$)

This section describes the calculation of the mass of Virgin Raw Materials.
Firstly, it is necessary to understand the input data needed to obtain the requested value:

- Product mass in kilograms.
- Number of Products delivered to the market, in all time.
- Percentage of Virgin Raw Materials.

Using the above data, it is possible to determine a first value of the mass (Table 24): Quantity of Virgin Raw Materials) which however needs to be adjusted according to the characteristics of the case study treated.

In fact, if refurbishing, remanufacturing or closed loop recycling actions are carried out, it is necessary to consider the impact they have on the mass of Virgin Raw Materials used.

Table 24. Calculation of the mass of Virgin Raw Materials

Quantity of Virgin Raw Materials	Quantity to be discounted
$Mass\ of\ Virgin\ Raw\ Materials = Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * (1 - \%\ of\ Recycled\ input\ in\ the\ Product\ [\%])$	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Refurbished\ used\ Products\ [\%] * (1 - \%\ of\ Recycled\ input\ in\ the\ Product\ [\%])$
	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Remanufactured\ used\ Components\ [\%] * (1 - \%\ of\ Recycled\ input\ in\ the\ Product\ [\%])$
	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Closed\ loop\ Recyled\ Materials\ [\%] * (1 - \%\ of\ Recycled\ input\ in\ the\ Product\ [\%])$

If there is a refurbishing action
If there is a remanufacturing action
If there is a closed loop recycling action

Mass of Wasted Materials ($M\%_{wasted}$)

This paragraph reports the calculation of the mass of Wasted Materials used.
In order to obtain the required value, the necessary input data are:

- Product mass in kilograms.
- Number of Products delivered to the market, in all time.
- Percentage of non-collected used Products.
- Percentage of Wasted Materials.

Using the above data, it is possible to determine the value of the mass of Wasted Materials.

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In this case, unlike the Virgin Raw Material mass calculation described above, circularity actions such as refurbishing, remanufacturing, closed and open loop recycling do not influence the value of the mass of Wasted Materials.

Below is the calculation.

$$Mass\ of\ Wasted\ Materials = Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * (1 - \%\ of\ Collected\ used\ Products\ [\%]) * (1 - \%\ of\ Downcycled\ Waste\ [\%])$$

Mass of Downcycled Waste ($M\%_{downcycled}$)

This section describes the calculation of the mass of Downcycled Waste.
The input data needed to obtain the requested value are:

- Product mass in kilograms.
- Number of Products delivered to the market, in all time.
- Percentage of non-collected used Products.
- Percentage of Downcycled Waste.

Knowing the above data, it is possible to determine the value of the mass of Downcycled Waste, using the following formula.

$$Mass\ of\ Downcycled\ Waste = Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * (1 - \%\ of\ Collected\ used\ Products\ [\%]) * \%\ of\ Downcycled\ Waste\ [\%]$$

Mass of Scrap from Collected Products ($M\%_{scrap}$)

This part explains the calculation of the mass of Scrap from collected Products.
To obtain the required value, the necessary input data are:

- Product mass in kilograms.
- Number of Products delivered to the market, in all time.
- Percentage of Collected used Products.

Using the above data, it is possible to determine a first value of the mass (Table 25Table): Quantity of Scrap from Collected Products), which however needs to be adjusted according to the characteristics of the case study treated.
In fact, if refurbishing, remanufacturing, closed loop recycling or open loop recycling actions are carried out in the reference scenario, it is necessary to consider the impact they have on the mass of Scrap from Collected Products.

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Table 25. Calculation of the mass of Scrap from Collected Products

Quantity of Scrap from Collected Products	Quantity to be discounted
$Mass\ of\ Scrap\ from\ Collected\ Products = Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%]$	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Refurbished\ used\ Products\ [\%]$
	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Remanufactured\ used\ Components\ [\%]$
	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Closed\ loop\ Recyled\ Materials\ [\%]$
	$Product\ mass\ [Kg] * Number\ of\ Products\ delivered\ to\ the\ market\ [\#] * \%\ of\ Collected\ used\ Products\ [\%] * \%\ of\ Open\ loop\ Recyled\ Materials\ [\%]$

If there is a refurbishing action
If there is a remanufacturing action
If there is a closed loop recycling action
If there is an open loop recycling action

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