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fenix

WP1 – NEW BUSINESS MODELS IDENTIFICATION

T 1.2 – Business models circularity assessment

Person responsible / Author:	Paolo Rosa (POLIMI), Roberto Rocca (POLIMI), Claudio Sassanelli (POLIMI), Sergio Terzi (POLIMI)
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Author(s) contact information

Name	Organisation	E-mail	Tel
Paolo Rosa	POLIMI	paolo1.rosa@polimi.it	+39 0223999537
Roberto Rocca	POLIMI	roberto.rocca@polimi.it	+39 0223992729
Claudio Sassanelli	POLIMI	claudio.sassanelli@polimi.it	+39 0223992716
Sergio Terzi	POLIMI	sergio.terzi@polimi.it	+39 0223992803

ABSTRACT

The main aim of the FENIX project is the development of new business models and industrial strategies for three novel supply chains in order to enable value-added product-services. Through a set of success stories coming from the application of circular economy principles in different industrial sectors, FENIX wants to demonstrate in practice the real benefits coming from its adoption. In addition, Key Enabling Technologies (KETs) will be integrated within the selected processes to improve the efficient recovery of secondary resources. Deliverable 1.2 focuses on the implementation of a Circularity Product Assessment (CPA) methodology to be adopted within the FENIX project. This implementation activity was done into two steps. From one side, a state-of-the-art analysis of existing CPAs and related KPIs has been executed and the most common circularity assessment methods (and KPIs) were identified. Subsequently, a totally new CPA methodology was developed starting from the findings coming from the literature. This methodology, together with classic LCA and LCC methods, will be will be exploited in WP2 for the quantitative assessment of CBMs.

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Abbreviations and Acronyms:	
AHP/ANP	Analytic Hierarchic/Network Process
BOCR	Benefits, Opportunities, Costs, and Risks
BOL	Beginning of Life
BSC	Balanced Score Card
BWPE	BIM-based Whole-life Performance Estimator
CBM	Circular Business Model
CCA	Circularity Cost Assessment
CE	Circular Economy
CEA	Circularity Environmental Assessment
CEENE	Cumulative Exergy Extraction from the Natural Environment
CEPA	Circular Economy Performance Assessment
CI	Customer Involvement
CPA	Circularity Product Assessment
CPI	Circularity Performance Index
CSF	Critical Success Factor
CSR	Corporate Social Responsibility

DEA	Data Envelopment Analysis
DES	Discrete Event Simulation
DFD	Design for Disassembly
DfX	Design for X
DMC	Domestic Material Consumption
DMU	Decision-Making Unit
DPSIR	Drivers-Pressures-States-Impacts-Responses
EC	Embodied Carbon
ECEC	Ecological Cumulative Exergy Consumption
EE	Eco-Efficiency
ELCA	Exergetic Life Cycle Assessment
ELV	End-of-Life Vehicle
EOL	End of Life
EPI	Environmental Performance Index
ETV	Environmental Technology Verification
EYR	Emergy Yield Rate
GHG	Green House Gas
GSC	Green Supply Chain
GVBE	Green Virtual Enterprise Breeding Environment
ICEC	Industrial Cumulative Exergy Consumption
IELR	Improved Environmental Loading Ratio
IESI	Improved Energy Sustainable Index
IS	Industrial Symbiosis
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LD	Level of Disassembly
MADM	Multiple-Attribute Decision-Making
MC	Management commitment
MF	Material features
MFA	Materials Flow Analysis
MFCA	Material Flow Cost Accounting
MOL	Middle of Life
MSW	Municipal Solid Waste
PF	Productivity Factor
PSS	Product-Service System
RC	Recycling cost
RE	Recycling efficiency
RRBR	Recycling and Reuse Benefit Ratio
SC	Supplier commitment
SIC	Social Impact Coefficient
SME	Small and Medium Enterprise
SPA	Sustainable Performance Assessment
SPC	Sustainability Performance Criteria
SPD	Sustainable Product Development
SSC	Sustainable Supply Chain
SSCM	Sustainable Supply Chain Management
TBL	Triple Bottom Line
UEVE	Unit Energy Value of Economic output
UM	Urban Metabolism

1. INTRODUCTION

Deliverable 1.2 describes the implementation of a new Circular Economy Performance Assessment (CEPA) methodology to be adopted within the FENIX project to assess the three Circular Business Models (CBMs) selected in Deliverable 1.1. To do that, a multi-perspective procedure has been established. Firstly, a state-of-the-art analysis identified what are the available types of CPAs and how they can be classified (e.g. by comparing their focus and KPIs). Secondly, a totally new CPA methodology was implemented basing on key findings from the literature. Together with classic LCA and LCC assessments, its adoption in WP2 will allow the identification of the most suitable CBMs to be considered within the FENIX project. Deliverable 1.2 is structured as follows. Section 2 is dedicated to the literature assessment about CEPAs and related KPIs. Section 3 is dedicated to the circular economy assessment. Section 4 puts together results coming from the previous two sections and describes into detail the new CPA methodology to be adopted in FENIX and a set of dedicated KPIs to be exploited for the comparison of CBMs. Section 5 gives some concluding remarks and future activities.

2. STATE OF THE ART ON CIRCULAR ECONOMY PERFORMANCE ASSESSMENT (CEPA) METHODS

The intent of this section is the analysis of the state of the art about the circularity performance assessment methods available in literature. This literature review will be useful to conceive the positioning framework on which the methodology able to provide a set of Key Performance Indicators (KPI) suitable to the circularity context should then be built. Starting from a generic view on the main approaches used to measure circularity performances, the different perspectives of the Triple Bottom Line (TBL) of sustainability (WCED, 1987) have been adopted. This led to the detection and definition of those variables deserving more attention to circularity performances.

2.1. Current state of the art on circular economy performance assessment methods

Circular Economy (CE) research is continuously evolving. Especially in the last years, this led both researchers and practitioners to understand how to measure and quantify its impacts in a real context. Trying to sum up the results obtained so far and gather interesting details on current findings, a systematic literature review on scientific articles published up to the second quarter of 2018 and provided by the most popular academic search engines (i.e. Science Direct and Scopus) has been carried out. The main keywords, "circular economy" and its main synonym "end of life", were combined with "performance", "assessment" and "methodology" in a total of 6 searches, without considering any document type, time and field content limitations. Results of these queries are reported in Table 1, by evidencing that the item "end of life" has been explored more than the "circular economy" one.

Search	Science Direct	Scopus
"circular economy" AND "performance assessment" AND "methodology"	56	60
"circular economy assessment"	9	11
"circular economy performance"	9	30

"end of life" AND "performance assessment" AND "methodology"	316	186
"end of life assessment"	32	88
"end of life performance"	65	124
TOTAL	**487**	**499**

Table 1: Searches by keywords

The total amount of papers found have then been selected based on three main criteria:

1. by title, abstract and keywords analysis,
2. by entire manuscript analysis,
3. by redundancies detection and removal.

This led to a final set of 53 selected articles that have been deeply analysed.
All these papers have been categorized by:

- Authors
- Nation of the authors
- Keywords
- Year
- Title
- Main Content
- Document type
- Research type (theoretical assessment; Analytical Assessment; Case Studies; Surveys; Action Research; Other)
- Journal
- Framework/method/approach proposed
- Assessment Methodology used
- Index
- Triple Bottom Line perspective (Environmental, Economic, Social)
- Variables analysed (Energy, Material, Pollution)
- Industry and Industrial Symbiosis

As specified at the beginning of the paragraph, current findings show that authors' interest in CE topics rose especially during the last years. This trend can be explained by the fact that CE regulations are becoming always more restrictive and relevant in the international scenario. Figure 1 displays how the results of the queries performed are spread along the years, also by providing the general publications trend. Like reported by the picture, publications started in 2009, but the greatest part (73,5%) of them has been published only by 2016 onwards.

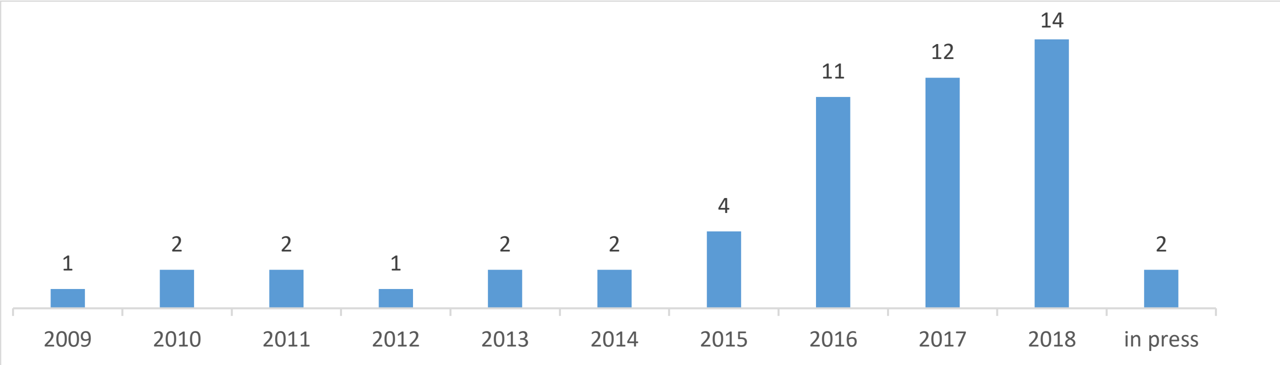


Figure 1 Historical series of results by year

A total of 46 articles were published in scientific journals and 7 in proceedings of scientific conferences. As shown in

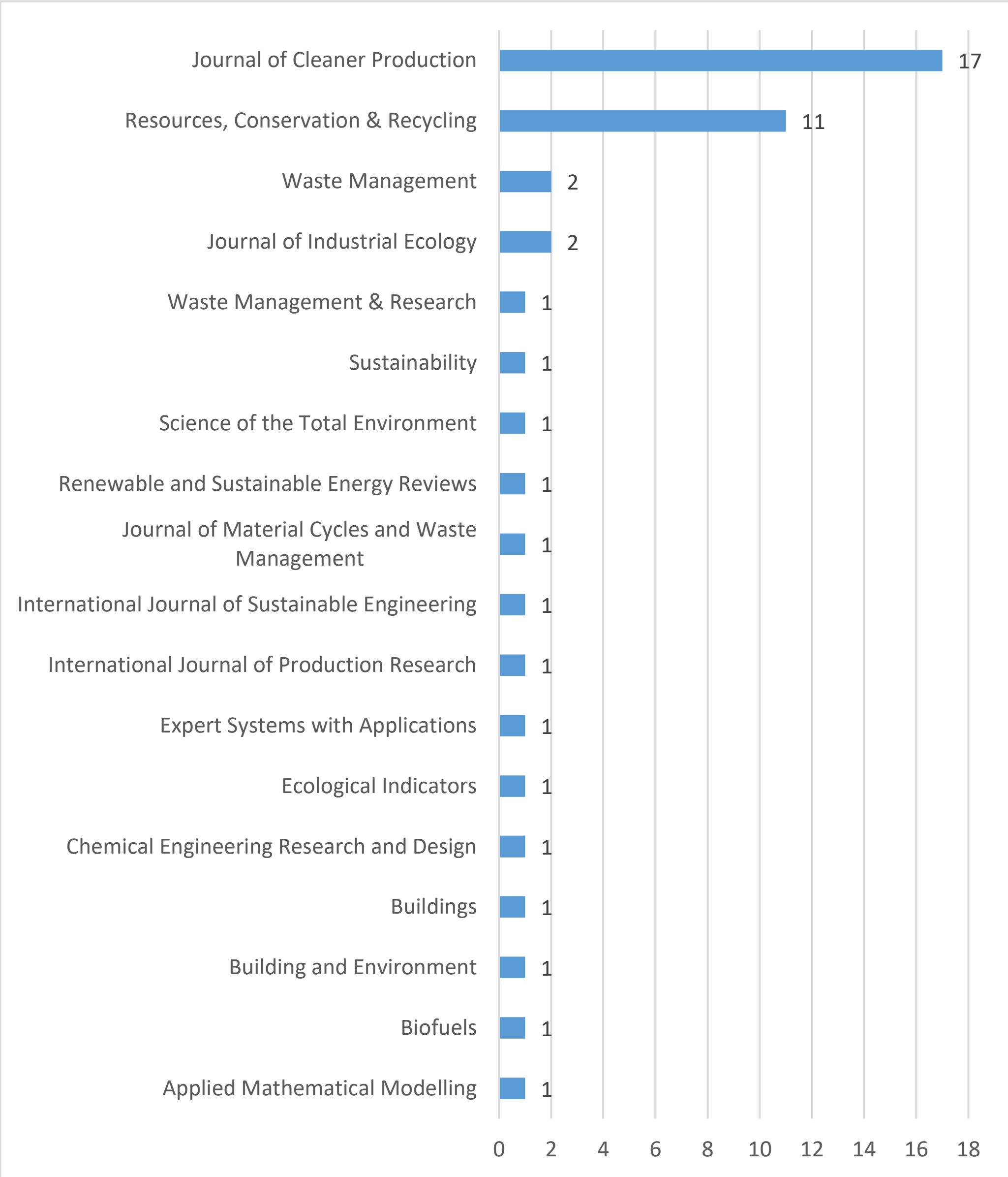


Figure 2, two journals are the most impacting in terms of publication in the CE field (*Journal of Cleaner Production* and *Resources, Conservation and Recycling)* with 52,8% of the total amount of papers taken into account. The great part of other contributions have been published in different journals, probably due to their focus in specific industries or to specific research approaches.

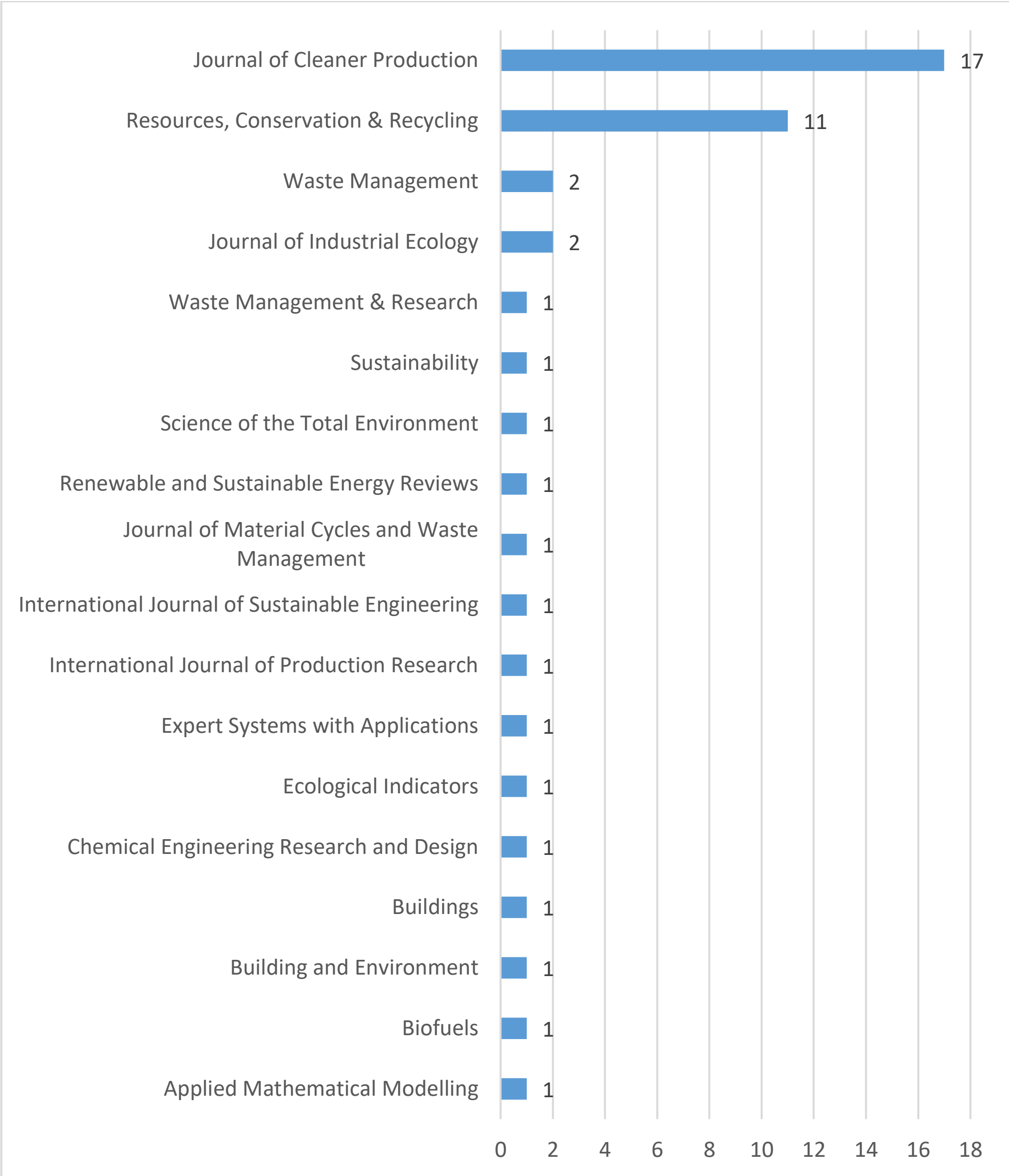


Figure 2 Journals

Considering the nationality of the authors, the highest number of contributions come from the European countries (52,8%), followed by China and USA. Instead, by considering the nationality of the articles' first author, China is the major contributor (15,1%), followed by Italy and France (both with 11,3%), Spain and UK (both with 7.5%) (Figure 3).

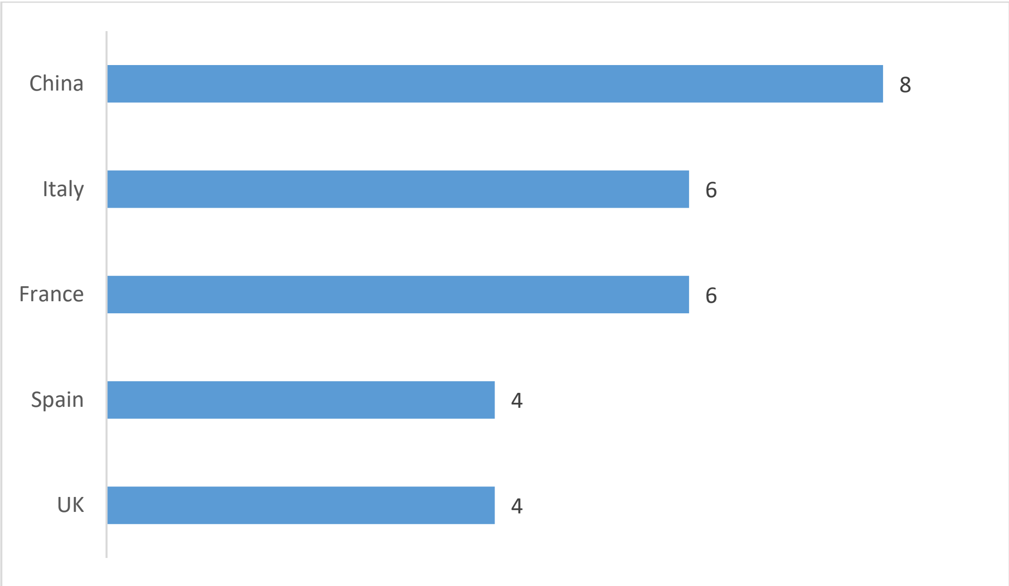


Figure 3: Top five publishing countries

The analysis reveals that most of the selected contributions (46 out of 53) provide not only a theoretical view for the evaluation of the circularity aspects of a system, but also suggest or report a practical context or industry in which to apply the frameworks and methods proposed. In addition,

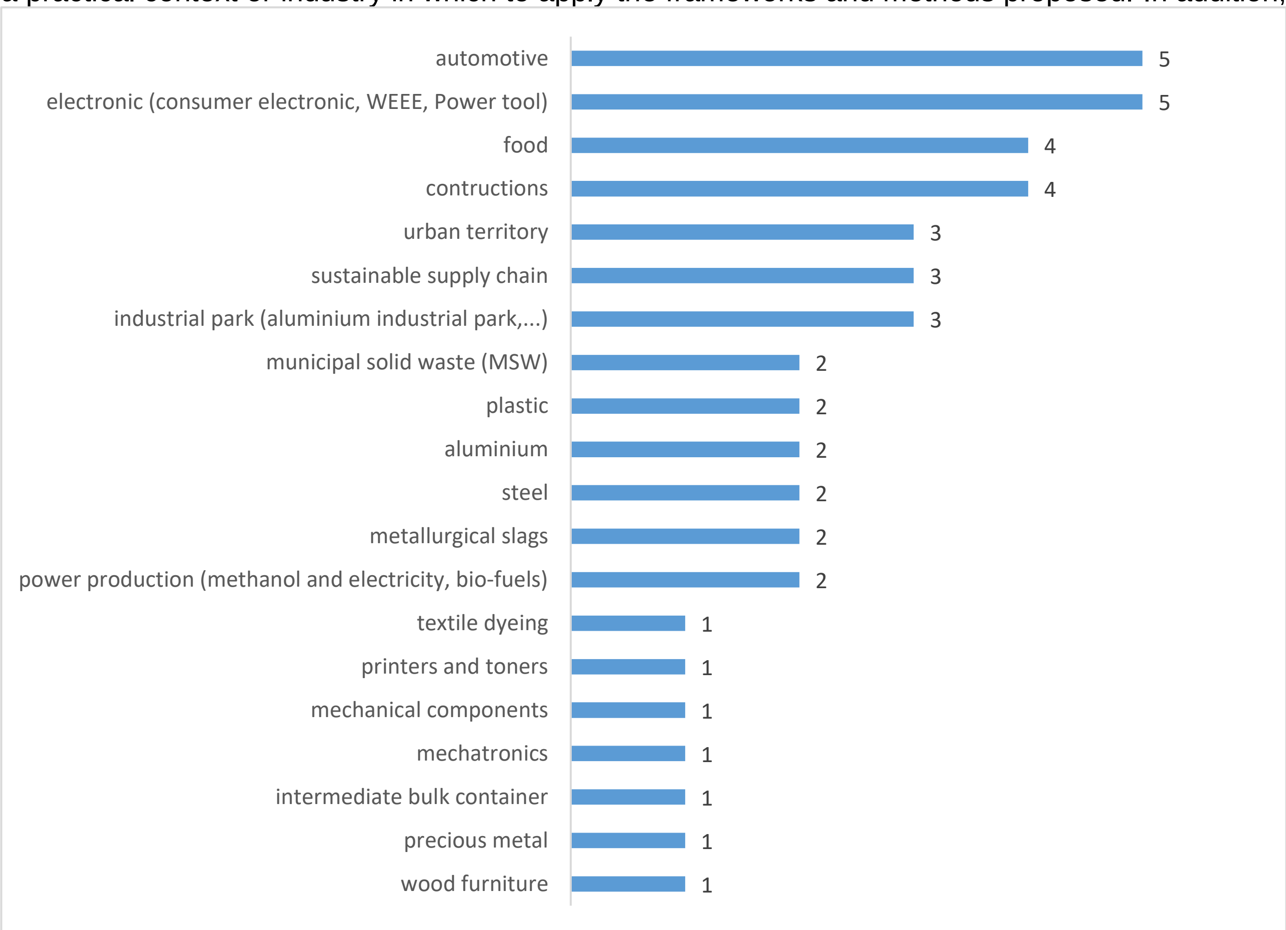


Figure 4 highlights the perspective adopted on the system analysed in terms industrial symbiosis. From this perspective, contributions can be divided in two groups:

- Those focused on intra-company links (35 contributions - 76%)
- Those focused on inter-company links (11 contributions - 24%)

In the first case, industries like metals (aluminium, precious metals, steel, metallurgical slags) (15,2%), automotive (10,8%), electronic (consumer electronic, WEEE, Power tool) (10,8%), food (8,7%), constructions (8,7%), plastic (4,3%) and others have been considered. In the second case, the analysis is done on wider and complex systems, like Urban Metabolism (UM) and Municipal Solid Wastes (MSW) (10,8%), Sustainable (Green) Supply Chains (SSC or GSC) (6,5%) and industrial parks (6,5%).

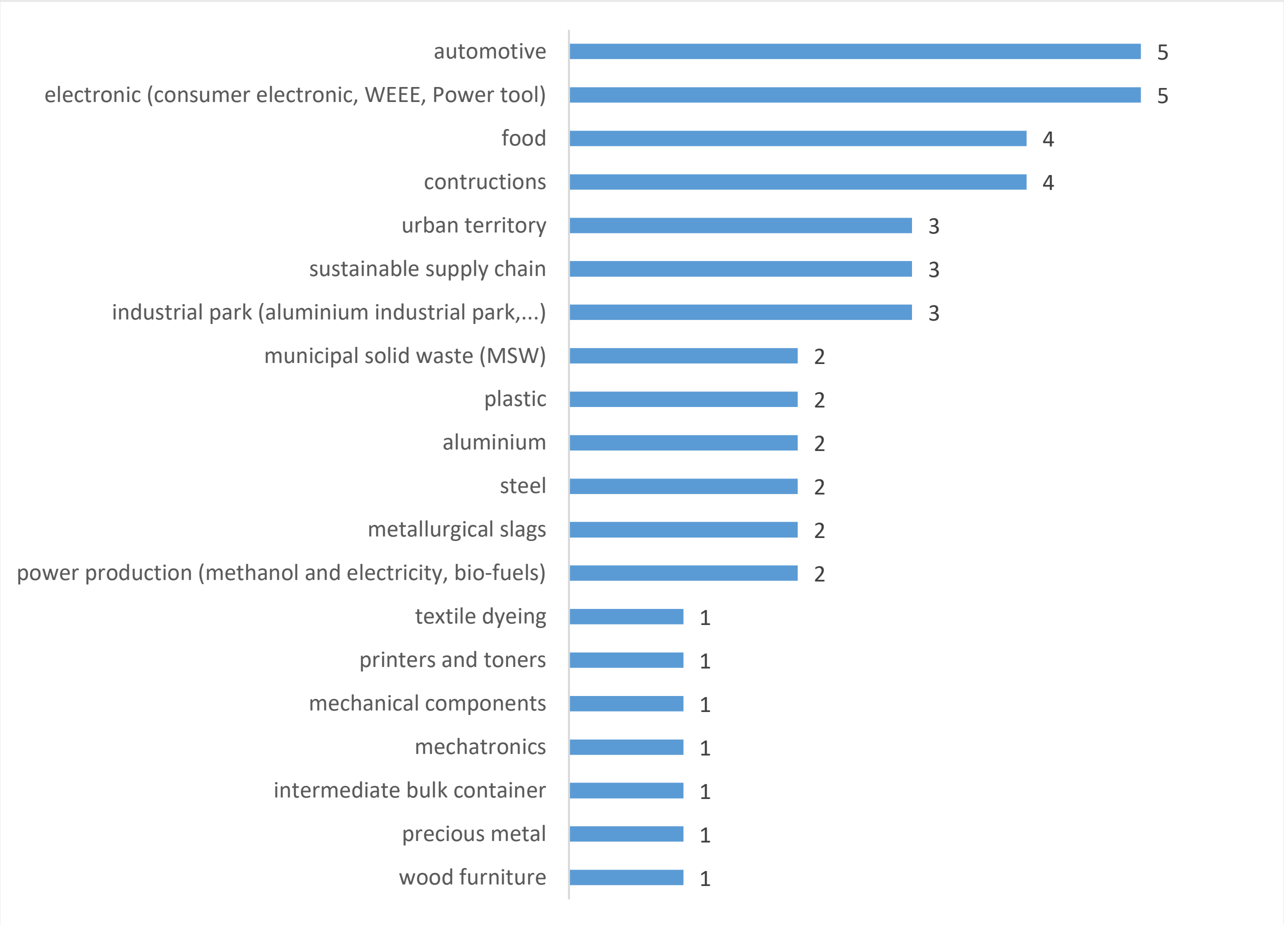


Figure 4 Industries

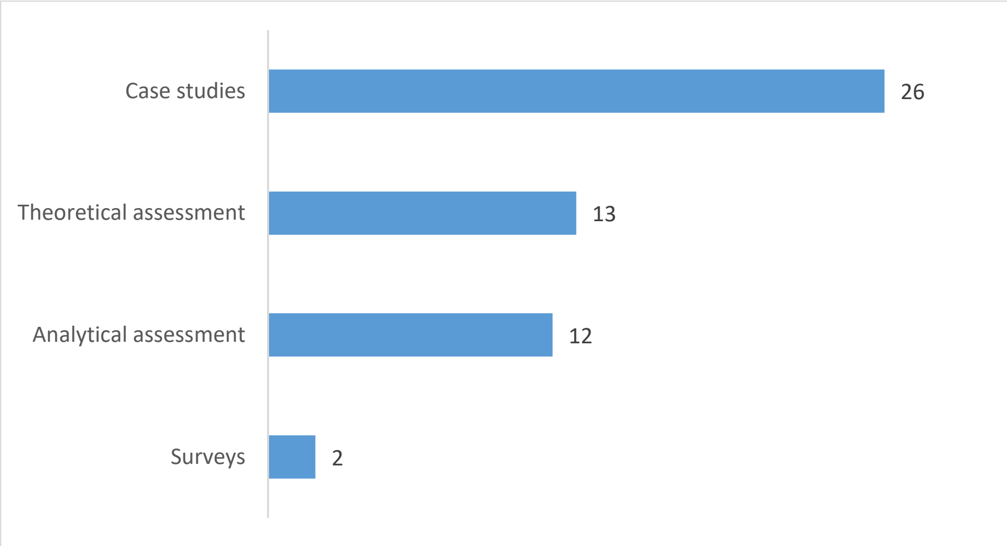


Figure 5 shows also the research approach adopted in studying such a context. Results confirm that most of the authors gave relevance to the industrial side in their studies, in order to practically validate the proposed theories. Case study is the most exploited research approach, followed by theoretical and analytical assessments and surveys.

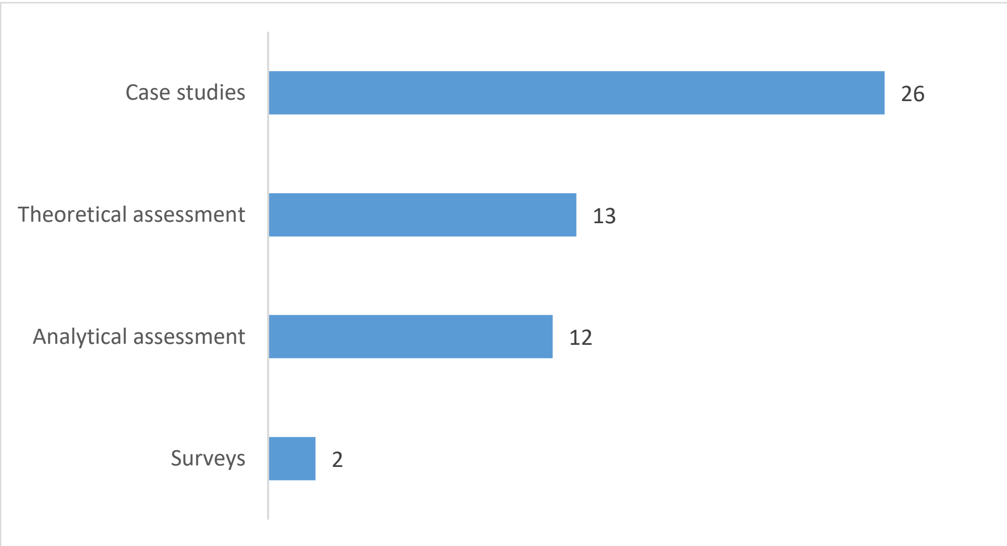


Figure 5 Main typologies of research

In general terms, all the papers proposed a new framework, method, index or approach by starting from the selection and mix of already existing ones. All of them were focused on measuring only specific aspects of CE. This led to the selection of specific methodologies suitable to their heterogeneous research aims. The most common methodologies available in literature have been listed in the following Table 2.

DEA/ input-output	DfX and Guidelines	LCA/ LCI/ LCIA	Multi-criteria approach / fuzzy methods	Energy (emergy, exergy) approach	Simulation / DES	MFA / MFCA	Others

5	7	16	8	4	2	5	• SNA • Corporate Social Responsibility (CSR) • Regression model (2) • BIM-based approach (BWPE) and real estate (2) • Sustainable Product Development (SPD) and Sustainable Performance Assessment (SPA) • Factor analysis (2) • Process modelling • AHP/ANP (2) • Longevity based method • Balanced Score Card (BSC)
DEA= Data Envelopment Analysis, DfX= Design for X, LCA=Life Cycle Assessment, LCI= Life Cycle Inventory, LCIA= Life Cycle Impact Assessment, DES=Discrete Event Simulation, MFA=Material Flow Analysis, BWPE= BIM-based Whole-life Performance Estimator, AHP/ANP= Analytic Hierarchic/Network Process							

Table 2: Most used methodologies to assess Circular Economy in the extant literature

As reported in Table 2, the most common methodology is Life Cycle Assessment (LCA) (Angelis-Dimakis, Alexandratou, & Balzarini, 2016; Biganzoli, Rigamonti, & Grosso, 2018; Eastwood & Haapala, 2015; Fregonara, Giordano, Ferrando, & Pattono, 2017; Gbededo, Liyanage, & Garza-Reyes, 2018; Grimaud, Perry, & Laratte, 2017; Hadzic, Voca, & Golubic, 2018; Huysman, De Schaepmeester, Ragaert, Dewulf, & De Meester, 2017; Jamali-Zghal, Lacarrière, & Le Corre, 2015; J. Laso et al., 2016; Jara Laso et al., 2018; Martin, Wetterlund, Hackl, Holmgren, & Peck, 2017; Park, Egilmez, & Kucukvar, 2016; Pauliuk, 2018; Petit, Sablayrolles, & Yannou-Le Bris, 2018; van Schalkwyk, Reuter, Gutzmer, & Stelter, 2018).

In particular, (Angelis-Dimakis et al., 2016) conducted a LCA to develop a methodological framework for the eco-efficiency assessment of water-use systems in the textile dyeing industry. Here, appropriate metrics for measuring the performance of a given system were proposed and the most promising alternative solutions (eco-innovations) were identified. A lifecycle-oriented approach, incorporating principles of functional unit, life cycle inventory (LCI) and life-cycle impact assessment (LCIA), is used to evaluate the environmental performance, while the economic performance is assessed through the total value added to the product because of water use.

(Pauliuk, 2018) proposed a general system for deriving CE indicators. Indeed, a dashboard of new and established quantitative indicators for CE strategy assessment in organizations have been defined, mostly based on material flow analysis (MFA), MFCA, and LCA. Four main index categories have been detected: 'Circular Economy', 'Life Cycle Resource Efficiency', 'Climate, Energy & other', 'Stock & sufficiency'.

(J. Laso et al., 2016) method assesses the treatment and valorisation of anchovy wastes, combining LCA, LCI and LCIA. Then, (Jara Laso et al., 2018) built a two-step eco-efficiency methodology assessment based on LCA and LCC. They provided environmental (Global Warming Potential, Acidification Potential, Eutrophication Potential and the ReCiPe Single Score Endpoint) and economic (Value Added) indicators and proposed a composite eco-efficiency index in the attempt to gauge the fish canning industry from both an environmental and economic perspective.

(Hadzic et al., 2018) proposed an LCA to perform an assessment of wastes, but in an urban context. Instead, (Martin et al., 2017) used LCA to assess the use of materials and the environmental benefits of by-products in biofuels industry.

(Biganzoli et al., 2018) proposed a LCA to assess the environmental impacts of intermediate bulk containers re-use in the circular economy.

(Fregonara et al., 2017) combined different approaches (Real Estate Appraisal, Economic Evaluation of Project Environmental Design, LCA, LCC) to develop a methodology for supporting decision-making in design activities in the construction industry, by considering indexes related to the different aspects of sustainability, like Total Embodied Energy (EETOT,j), Embodied Carbon (EC), Level of Disassembly (LD), recycled materials index (RM). Also (Grimaud et al., 2017) contributed to the design phase. They built a decision-support methodology by combining LCA, Material Flow Analysis (MFA) and Environmental Technology Verification (ETV) to support designers.

(van Schalkwyk et al., 2018) traced a baseline for the evaluation of the true economic viability of the CE paradigm. They combined LCA and process simulation for assessing the challenges of digitalizing the CE of metallurgical slags.

LCI, one of the four iterative phases of a life cycle assessment, received a particular attention by (Eastwood & Haapala, 2015). They developed a methodology to assist product sustainability assessment during design for manufacturing. In this research economic, environmental and social metrics were selected. The economic metric was based on operating costs, an estimate of the production-related expenses (including materials and consumables used), on-site energy consumption, and labour. Instead, the environmental metric was based on input material non-fly away content, on-site energy consumption, water use, water discharge, greenhouse gas emissions, pollutant emissions, waste to landfill, waste to recycle, and hazardous waste. The selected social metric was based on acute injuries, lost work days and chronic illnesses.

(Park et al., 2016) proposed an integrated framework consisting of the Eco-LCA framework, the ReCiPe method (for midpoint and endpoint impact quantification by using emission results of Eco-LCA) and linear programming-based ecological performance assessment. The Eco-LCA model was used for calculating industrial cumulative exergy consumption (ICEC), ecological cumulative exergy consumption (ECEC), and emission, water and land-use. Ecological performance assessment has been conducted by focusing on four performance metrics, namely: ecological/industrial cumulative exergy consumption (ECEC/ICEC) ratio, loading ratio (LR), renewability index (RI) and eco-efficiency (EE). The aggregation approach (ECEC) used to quantify the ecological resource consumption, being an input–output-based method, involved uncertainty and thus has been integrated with quantitative performance assessment metrics. Indeed, industrial eco-efficiency is increasingly assessed through a combination of life cycle assessment (LCA) and data envelopment analysis (DEA).

(Petit et al., 2018) used a combination of LCA, Corporate Social Responsibility (CSR) and Multiple-Attribute Decision-Making (MADM)-specific frameworks to introduce a conceptual framework for value chain sustainability assessment. The DPSIR (Drivers-Pressures-States-Impacts-Responses) model has been adopted, taking it by the European Environment Agency, to define how performance is measured.

Since circular systems are complex, their assessment is difficult. For this reason, different authors (Iakovou, Moussiopoulos, Xanthopoulos, Achillas, & Michailidis, 2009; Kazancoglu, Kazancoglu, & Sagnak, 2018; Ng & Martinez Hernandez, 2016; Olugu & Wong, 2015; Petit et al., 2018; Shen, Olfat, Govindan, Khodaverdi, & Diabat, 2013; Wibowo & Grandhi, 2017; Xu, Zhang, Yeh, & Liu, 2018) adopted also multi-criteria approaches, in particular fuzzy logic, to simplify them.

(Ng & Martinez Hernandez, 2016) proposed a systematic process design and decision-making framework combining multi-criteria analysis and process modelling. Both economic and energy ratios were considered to provide implications on the performance of the selected boundary of system, based on the information on the flows that cross the boundary of the system. Some examples are:

- Economic value ratio, Ec= Economic value of product/Economic value of feed;
- Energy value ratio, En= Energy value of product/Energy value of feed;
- GHG emission = Total GHG emitted/Total energy value of products;
- GHG intensity;

- Net energy demand of a process, EDnet;
- Recoverable energy, ER;

(Shen et al., 2013) used fuzzy multi criteria approach to evaluate green supplier's performance in green supply chain with linguistic preferences. Multi-criteria approaches (expert fuzzy rule-based system for evaluation) were adopted by (Olugu & Wong, 2015) to build a closed-loop supply chain performance measurement framework, considering both forward and reverse chain performance evaluation. Specific reverse chain measures and metrics were detected: Recycling efficiency (RE), Recycling cost (RC), Management commitment (MC), Material features (MF), Customer involvement (CI), Supplier commitment (SC).
(Wibowo & Grandhi, 2017) used multi-criteria decision-making approach for evaluating the performance of recoverable end-of-life products in the reverse supply chain. Four criteria were identified for evaluating the performance of recoverable end-of-life products in an organization, including Technical, Commercial, Environmental and Societal. Finally, an efficient algorithm was developed for producing a performance index for every recoverable end-of-life product alternative across all evaluation criteria.
(Xu et al., 2018) applied to WEEE recycling the capacity-based Multi-Criteria Decision Making (MCDM) approach, by integrating the triple-bottom-line (TBL) principle of sustainability and the model of benefits, opportunities, costs, and risks (BOCR).
(Iakovou et al., 2009) created the "Multicriteria Matrix" methodological framework for end-of-life management of electronic products, ranking the components of a product according to the 5 criteria: residual/market value of components, environmental burden, weight, quantity of the component in the product, ease of disassembly.
(Kazancoglu et al., 2018) proposed the main criteria and sub-criteria for Green Supply Chain Management (GSCM) Performance Assessment: environmental, economic/financial, operational, logistics, organizational, marketing.

Other authors focused their attention on the design phase to enable circularity (Akinade et al., 2017; Favi, Germani, Luzi, & Mandolini, 2017; Grimaud et al., 2017; Issa, Pigosso, Mcaloone, & Rozenfeld, 2015; Lee, Lu, & Song, 2014; Oliveira, França, & Rangel, 2018; Santini et al., 2015), using Design for X (DfX) approaches and guidelines.
(Oliveira et al., 2018) proposed strategic guidelines for the circular economy. They state that there is some research being carried out on the development of CE indicators, but only at an unripe stage. Thus, the guidelines provided by them may contribute as guidance for the formulation of generic performance parameters for circularity.
(Akinade et al., 2017) proposed 43 Design for Disassembly (DfD) Critical Success Factors (CSF) for effective material recovery in the construction industry. Specifically, they defined 5 DfD factor groups: (a) stringent legislation and policy, (b) design process and competency for deconstruction, (c) design for material recovery, (d) design for material reuse, and (5) design for building flexibility.
(Santini et al., 2015) proposed a disassembly and composition analysis supported by Design for Recycling software for End-of-Life Vehicles (ELVs). In their analysis the main indexes were the material flow, the recyclability rate, the recoverability rate and end-of-life costs.
(Lee et al., 2014) proposed an innovative approach using an End-of-Life Index based on Design for End-of-Life approach: it enables designers to make informed decisions on design alternatives for optimal End-of-life performance using information from EoL stage.
(Issa et al., 2015), starting from the results of the literature review, selected and systematized the environmental performance indicators (EPI) and provided the support guide. They classified EPIs based on classes and sub-classes of the phases of the life cycle (Pre-manufacturing, Manufacturing and design, Distribution and Packaging, Use and maintenance, End-of-Life, General Activities), of the environmental aspects (Material, Energy, Solid waste, Waste water, Gaseous emissions, Energy loss) and of the type of measure (absolute and relative). Some examples of EPIs are: Number of hazardous materials, Total energy consumption, Reusable parts, Packaging

mass fraction, Polluted liquid waste volume, Useful lifetime, Fossil fuel consumption in transportation, Product degree of utilization, Total air emissions, Rate of defective products, Number of components, Product Density. The results of the analysis highlighted a tendency to develop indicators to measure products' end-of-life performance and material consumed and discarded in processes. Furthermore, a step-by-step approach is provided to generate and customize new EPIs.

(Favi et al., 2017) used DfX approaches (Design for Disassembly (DfD), Design for EoL) and EoL management to provide new metrics (EoL indices) for product EoL assessment and management. These indices are were considered fundamental metrics for the correct EoL management of industrial products from a circular economy perspective. The four new indices evaluate the feasibility of each considered EoL scenario (reuse, remanufacture, recycling and incineration) in the Reverse Supply Chain, to optimise the product EoL management in the early design process.

Other authors decided to measure the flows of variables in the systems assessed. In order to do this, some of them (Expósito & Velasco, 2018; Mardani, Zavadskas, Streimikiene, Jusoh, & Khoshnoudi, 2017; Motevali Haghighi, Torabi, & Ghasemi, 2016; Pagotto & Halog, 2016; Park et al., 2016) used methods coming from the input-output model (Leontief, 1986), as Data Envelopment Analysis (DEA), others (Franklin-Johnson, Figge, & Canning, 2016; Grimaud et al., 2017; Pauliuk, 2018; Voskamp et al., 2017) recurred to Material Flow Analysis (MFA) and Material Flow Cost Accounting (MFCA) approaches.

(Mardani et al., 2017) proposed DEA as an evaluative tool for future analysis on energy efficiency issues, measuring the efficiency of the different Decision-Making Units (DMU).

(Expósito & Velasco, 2018) proposed a novel alternative radial DEA model (with multiple outputs: desirable and undesirable), applying it to the municipal solid waste recycling market.

(Pagotto & Halog, 2016) combined DEA input-output-oriented approaches and MFA to propose an approach to evaluate the eco-efficiency performance. The research utilized the following indicators/measures:

- Undesirable outputs
    - Scope 1 GHG emissions,
    - Scope 2 GHG emissions,
    - Scope 3 GHG emissions,
- Inputs
    - Primary energy (direct),
    - Water use (direct),
    - Production costs,
- Desirable output
    - Value added to the economy.

(Motevali Haghighi et al., 2016) built a hybrid Balanced Score Card (BSC) - DEA framework for performance evaluation in sustainable supply chains. They detected important Sustainable Supply Chain Management (SSCM) indicators for recycling industry, dividing them in economic, environmental and social:

- Economic:
  1. Flexibility, Production flexibility,
  2. Delivery cost,
  3. Investment in sustainability design,
  4. Time delivery,
  5. Supplier rejection rate,
  6. Service quality,
- Environmental:
  7. Amount of Pollution,

    8. ISO 14001 certification,
    9. Hazardous materials,
    10. Number of green products,
- Social:
    11. Customers' satisfaction,
    12. Health and Safety Staff.

Among the authors using MFA, (Franklin-Johnson et al., 2016) proposed resource duration as a new indicator for environmental assessment performance linked to Circular Economy, combining Non-monetary approach (longevity based method) and MFA. This new performance metric, the longevity indicator, is composed of three generic components: initial lifetime, earned refurbished lifetime and earned recycled lifetime. It seeks to show the length of time for which a material is retained in a product system: retention is a means to maximise resource exploitation in the same product system through product use and reuse, as well as materials recycling. As an indicator, longevity might therefore be considered to adopt a non-monetary, value-based approach. An alternative that keeps a resource x-times longer in the system than another alternative, is also x-times more value-creating from the perspective of longevity. This value is expressed in the unit of time and thus is a nonmonetary unit. Three temporal calculations (to establish lifetime lengths between two events) and two directional calculations (to establish the flow of the product and/or materials) enable longevity to be determined. A minimum cycle exists, but an infinite number of cycles can be added by continuing to model directional events.
(Voskamp et al., 2017) applied some modification to the MFA Eurostat method to conduct a comprehensive assessment of urban metabolism. Based on concepts as direct material input (DMI) and domestic material consumption (DMC), they measured DMI/GDP (t/million euro), DMI/capita (t), DMC/GDP (t/million euro), DMC/capita (t), DMC/capita (t), to monitor the system.
Cagno, Micheli and Trucco, of Politecnico di Milano, have proposed an interesting method for the quantification of environmental costs that allows to analyse the flow of products, by-products and waste generated by a production plant, or simply by a section of it, with the aim of proposing a series of possible actions and making better decisions to move towards a higher level of eco-efficiency, and therefore of sustainability (Cagno, Micheli, & Trucco, 2012). Their model starts from a generic environmental cost assessment ("Activity-Based Environmental Costing", ABEC), but unlike this, it considers as cost targets not only the expected products, but also the by-products and waste, just as in ISO 14051 standards, which refer to the quantification of the costs of material flows. The work of Cagno, Micheli and Trucco also starts from a careful and detailed analysis of all the flows involved in a production process, but it aims to the waste minimization, and therefore the maximization of productivity based on cost objective functions.

Instead, some of the works were aimed at measuring only one of the variables, in particular energy, using concepts as emergy and exergy (Huysman et al., 2017; Jamali-Zghal et al., 2015; Pan et al., 2016). Specifically, (Pan et al., 2016) dealt with emergy, defined as the sum of all inputs of available energy directly or indirectly required by a process to provide a given product or flow in terms of energy. They considered several indicators in their emergy method to evaluate recycling and reuse benefit of industrial parks: Emergy Yield Rate (EYR), Unit Emergy Value of Economic output (UEVE), Improved Environmental Loading Ratio (IELR), Recycling and Reuse Benefit Ratio (RRBR), Improved Emergy Sustainable Index (IESI).
Based instead on the concept of exergy of a natural resource, defined as the minimum energy required to produce it with a specific structure and concentration from common materials in the reference environment, (Huysman et al., 2017) introduced the ‘circular economy performance indicator’ (CPI), as the ratio of the actual obtained environmental benefit (i.e. of the currently applied waste treatment option) over the ideal environmental benefit according to quality. These environmental benefits are expressed in terms of natural resource consumption, which can be

calculated by Life Cycle Assessment, for example by using the Cumulative Exergy Extraction from the Natural Environment (CEENE) method to support LCIA.
Also (Jamali-Zghal et al., 2015) combined LCA and emergy approaches (emergy evaluation combined with exergetic life cycle assessment (ELCA)) proposing three sustainability ratios: the resource efficiency ratio (which is the ratio of the specific emergy used in the recycling process to the specific emergy of the primary material), the quality ratio (which is the ratio between the specific exergy of the recycled material and the specific exergy of the primary material), and the eco-design ratio (which is the ratio of the specific emergy used in the manufacturing process and the emergy of the primary material).

Other works used simulation approaches, as Discrete Event Simulation (DES) and process simulation, combining it with LCA approaches (Gbededo et al., 2018; van Schalkwyk et al., 2018).
For example, (Gbededo et al., 2018) applied discrete event simulation (DES) and holistic Life cycle sustainability assessment (LCSA) to Sustainable Product Development (SPD) and Sustainable Performance Assessment (SPA) contexts. They used the method of Productivity Factor (PF) and weighted Social Impact Coefficient (SIC) as the social inputs to propose a simulation-based sustainability impact analysis. SIC represents an aggregated weighted value of the social impact indices (positive and negative) of an organisation and from the socio-economic development perspective determines the labour factor productivity, the influence of social impacts on productivity.
Other approaches have also been used, but only by few authors.
(Awasthi et al., 2018) used regression models to investigate and model the relation between e-waste quantities and economic increase.
(Sénéchal, 2017) used the eco-value analysis matrix to build a framework and a related dashboard for performance measurement in Sustainable Condition-Based Maintenance (SCBM).

Some assessments made in the construction industry used industry-specific methods, as the BIM-based Whole-life Performance Estimator (BWPE) to build a salvage performance model of building materials (Akanbi et al., 2018), a real estate appraisal combined to LCA (Fregonara et al., 2017), AHP as a basis for a framework for sustainability assessment of modular buildings (Kamali, Hewage, & Milani, 2018).
In particular, (Fregonara et al., 2017) developed a methodology for supporting decision making in design activities based on an economic environmental indicator (composed of Total Embodied Energy, Embodied Carbon (EC), Level of Disassembly (LD), Recycled Materials Index (RM)).
(Kamali et al., 2018) detected different areas that can significantly contribute to the life cycle sustainability of buildings, such as energy, material, cost, and so forth. To evaluate the sustainability of a building, each area has been broken down into several assessment criteria: environmental, economic and social Sustainability Performance Criteria (SPC).

(Li, 2011) used the AHP method to conduct a comprehensive evaluation on circular economic performance of eco-industrial parks. He divided the indexes into five dimensions, including element, environment, economy, social and management.

(Yang, Chen, & Gao, 2011; Yang, Gao, & Chen, 2011) used factor analysis to build an evaluation index system of circular economy (macro) composed of index of energy consumption, of resource recycling and reuse, of resource and environment protection, of economy and social development.

A sensitivity analysis based on different dismantling scenarios has been performed by (Delogu, Del, Berzi, Pierini, & Bonaffini, 2017) to calculate the recyclability and recoverability rate of vehicles, based on the guideline proposed by UNIFE ‘‘Recyclability and Recoverability Calculation Method - Railway Rolling Stock”.

(Berzi, Delogu, Pierini, & Romoli, 2016) used ISO 22628 and UNIFE assessments, adapted from railway sector, to propose a method for evaluation of the end-of-life performance.

(Su, Heshmati, Geng, & Yu, 2013), proposed a set of indicators for the evaluation of the Circular Economy. They assume that a successful implementation for the Circular Economy includes policies that require efforts on three different levels: micro, meso and macro and categorize the practices supporting the Circular Economy in four areas (production, consumption, waste management and other supports). Having in mind this approach, the following set of indicators they proposed for the evaluation of a circular system is shown in Figure 6.

Dimensions	No.	Indicators
1.Resource output rate	1.1	Output rate of main mineral resources
	1.2	Output rate of land
	1.3	Output rate of energy
	1.4	Output rate of water
2.Resource consumption rate	2.1	Energy consumption per unit of production value
	2.2	Energy consumption per unit of production in the key industrial sector[a]
	2.3	Water consumption per unit of production value
	2.4	Water consumption per unit of production in the key industrial sector
3.Integrated resource utilization	3.1	Utilization rate of industrial solid waste
	3.2	Reuse ratio of industrial water
	3.3	Recycling rate of industrial wastewater
4.Reduction in waste generation	4.1	Decreasing rate of industrial solid-waste generation
	4.2	Decreasing rate of industrial wastewater generation

Dimensions	No.	Indicators
Economic development	1.1	Industrial value added per capita
	1.2	Growth rate of industrial value added
Material reducing and recycling	2.1	Energy consumption per industrial value added
	2.2	Fresh water consumption per unit of industrial value added
	2.3	Industrial wastewater generation per unit of industrial value added
	2.4	Solid waste generation per unit of industrial value added
	2.5	Reuse ratio of industrial water
	2.6	Utilization rate of industrial solid waste
	2.7	Reuse ratio of middle water[a]
Pollution control	3.1	Chemical oxygen demand loading per unit of industrial value added
	3.2	SO_2 emission per unit of industrial value added
	3.3	Disposal rate of dangerous solid waste
	3.4	Centrally provided treatment rate of domestic wastewater
	3.5	Safe treatment rate of domestic rubbish
	3.6	Waste collection system
	3.7	Centrally provided facilities for waste treatment and disposal
	3.8	Environmental management system
Administration and management	4.1	Extent of establishment of the information platform
	4.2	Environmental report release
	4.3	Extent of public satisfaction with local environmental quality
	4.4	Extent of public awareness degree with eco-industrial development

Figure 6: Examples of CE indicators *(Su et al., 2013)*

(Despeisse, Ball, Evans, & Levers, 2012) proposed a study to suggest a more holistic view of the individual production activity in order to provide opportunities for wider improvements. The developed model focuses on materials, energy and resource flows to better understand the interactions between different industrial actors. The work is a basis on which to build quantitative modelling tools for maximizing the efficient and effective use of resources in economic-productive processes.

The Circular Economy philosophy is fully in line with this maximization of productivity of resources with a view to reducing waste and associated emissions; it represents an alternative model to the linear one (in which the economic activities are characterized by unidirectional flows of resources) and therefore constitutes a new economy that supports sustainable development through industrial ecology, life cycle management and cleaner production. This refers to the continuous application of an integrated and preventive environmental strategy to processes, products and services with the aim of increasing their eco-efficiency and reducing the risk for human and the environment (Romero & Molina, 2012). This reduction is possible through the conservation of virgin raw materials, water and energy in production processes, through the elimination of toxic substances, emissions and harmful waste. The same argument applies therefore also when the protagonists are the products and the services, with an improvement of the impact that these have on the entire life cycle.

Romero and Molina (Romero & Molina, 2012) have done an interesting work regarding the creation of "virtual environments for green businesses" ("Green Virtual Enterprise Breeding Environment", GVBE). A GVBE is a long-term strategic alliance between green businesses and institutions that relate to them in order to provide the necessary conditions to efficiently promote the sharing and recycling of resources such as information, materials, water, energy and infrastructure with the 'intention to achieve collaborative sustainable development. For Romero and Molina a GVBE is therefore a model of sustainable industrial development to implement a circular economy on three different levels: micro (through the development of green businesses), meso (with the creation of virtual green enterprises) and macro (with GVBE as an intelligent network for managing skills and resources among green businesses). This systemic alliance aims to combine the "eco-skills" of the leading institutions to develop strategies to support sustainability in its three main components (environmental, economic and social). The basic assumption of their work is that development through sustainability and closed-loop systems can be introduced more efficiently and effectively in industries thanks to a value network and eco-business models starting from small entities ("green companies"), until you get to work on a large scale through collaborative mechanisms. This approach represents the guideline for increasing industrial symbiosis and intra and inter-system collaboration (Romero & Molina, 2012).

2.2. Literature review results: towards a positioning framework

Trying to summarize the findings coming from this extensive literature review, contributions analysed reveal a strong orientation of CEPA methodologies on the environmental aspect of the Triple Bottom Line (TBL) of Sustainability (**Table 3**). Indeed, all the contributions involve the environmental perspective, either alone (37,7%) or combined with the economic one (17%) or embedded in the entire triple perspective (45,3%).

Environmental	Economic	Social	Environmental, Economic	Environmental, Social	Economic, Social	All
21			10			25

Table 3:Circular Economy performance assessment: categorization based on the Sustainability Triple Bottom Line (TBL)

The strong tendency of CEPA methodologies to focus on the environmental point of view led the authors to shift their attention on the variables involved in circular systems considered, by differentiating among energy, material and pollution, or a combination of them. Also in this case, there is a strong focus on only one element, i.e. material. This confirms the importance of such variables in the circularity performance context, since a continuous flow of technical and biological materials through the 'value circle' is considered in CE (The Ellen MacArthur Foundation, 2015). Only 2 out of 53 contributions divert the focus on energy and pollution (3,8%). All the other articles involve material in their evaluation, either alone (28,3%) or combined to energy and pollution (67,9%).

Energy	Material	Pollution	Energy, Material	Energy, Pollution	Material, Pollution	All

1	15	1	3		2	34

Table 4: Circular Economy performance assessment: categorization based on variables (Material, Energy, Pollution)

Starting from these categorizations, the POLIMI's team created a framework to position the existing methodologies in order to understand in which areas the main gaps found in literature are present. This positioning framework is composed by three axes related with the most important dimensions to analyse:

- Product Lifecycle Stages: which lifecycle phases are considered for CE evaluation,
- Variables: which types of variables are considered and measured,
- Field of analysis: the perspective used to analyse variables in the methodologies.

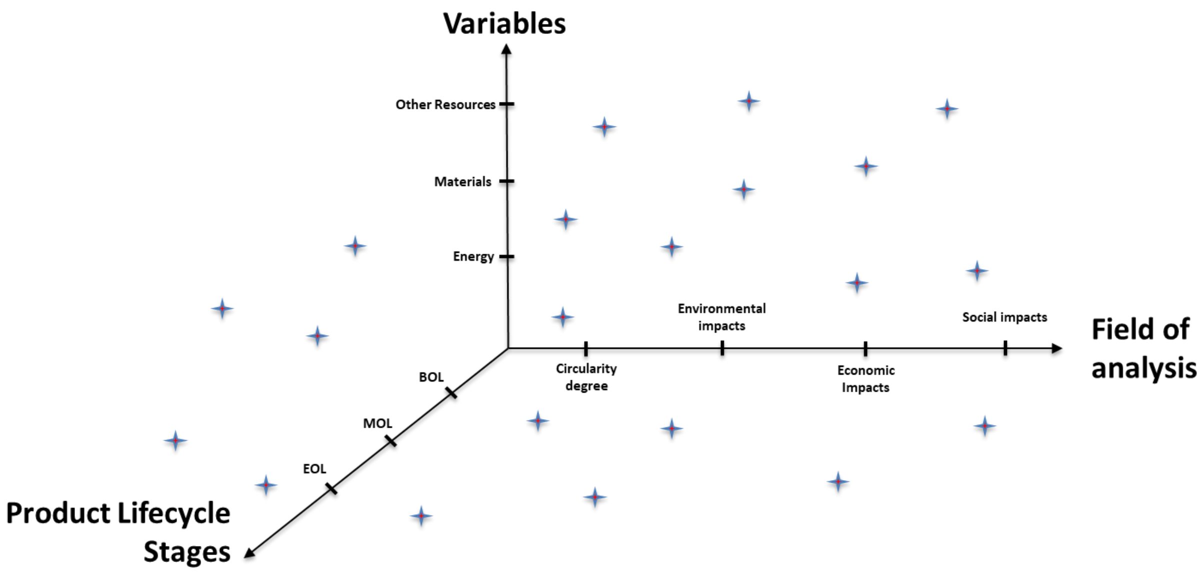


Figure 7: Positioning framework

Nowadays, still too few industries consider their manufacturing systems are inspired by biological models where materials and energies are used not only efficiently, but also effectively (Despeisse et al., 2012). By analysing resource flows, it is possible to identify solutions to reduce environmental impact and, at the same time, generate economic savings. However, CE does not mean only Industrial Symbiosis and systemic optimization. It also means life cycle optimization. Speaking about "self-regenerating economy" it is necessary to work at system level and at single product level at the same time, with the possibility to go into detail and analyse the single production phase and the single resource flow. This way, it is possible to understand where the improvements are. For this reason, a quantitative analysis model has been proposed with the aim to keep the product as the protagonist of the analysis in terms of CE and to calculate the circularity degrees. The literature analysis carried out shows the lack of methodologies regarding the overall evaluation of CE benefit. This overall evaluation and the circularity degree calculation can be determined through the methodology presented below.

3. THE CIRCULAR ECONOMY PERFORMANCE ASSESSMENT METHODOLOGY

The Circular Economy Performance Assessment (CEPA) methodology is composed by three different sub-methodologies that are related to three different fields of analysis: (i) the Circular Product Assessment (CPA), (ii) the Circular Cost Assessment (CCA) and (iii) the Circular Environmental Assessment (CEA). The first sub-methodology is presented in this deliverable, while the second and third methodologies are only mentioned in a qualitative manner. The main principle on which the Circular Economy Assessment is based on is the Material Flow Analysis (MFA). MFA is a systematic assessment of flows and stocks of materials within a system defined in space and time. Because of the physical law of conservation of matter, the results of a MFA can be controlled by a simple material balance comparing inputs, stocks and outputs of a process. This characteristic of MFA makes the method attractive as a decision-support tool in resource management, waste management and environmental management. A MFA delivers a complete and consistent set of information about flows and stocks of a material within a system. Through balancing inputs and outputs, the waste flows and environmental loadings become visible and their sources can be identified. Anthropogenic systems consist of many material flows and stocks. Energy, space, information and socio-economic issues must also be included if the anthroposphere must be managed in a responsible way. MFA is therefore an appropriate tool to investigate flows and stocks of any material-based system. It gives insight into the behaviour of the system, and when combined with other disciplines such as energy-flow analysis, economic analysis, and consumer-oriented analysis, it facilitates the control of an anthropogenic system. The objectives of MFA are the following (Brunner & Rechberger, 2004):

1. Delineate a system of material flows and stocks by well-defined, uniform terms;
2. Reduce the complexity of the system as far as possible while still guaranteeing a basis for sound decision making;
3. Assess the relevant flows and stocks in quantitative terms, thereby applying the balance principle and revealing sensitivities and uncertainties;
4. Present results about flows and stocks of a system in a reproducible, understandable and transparent way;
5. Use the results as a basis for managing resources, the environment and wastes.

In particular, this last point allows to:

a. Early recognition of potentially harmful or beneficial accumulations and depletions of stocks, as well as for timely prediction of future environmental loadings.
b. Setting of priorities regarding measures for environmental protection, resource conservation and waste management.
c. Design of goods, processes and systems that promote environmental protection, resource conservation and waste management (green design, eco-design, design for recycling, design for disposal, etc.).

- ***Circularity Product Assessment (CPA)***

Through CPA it is possible to calculate the circular share of resource flows used during the product life cycle, in order to obtain an exhaustive final index (KPI) about the circular percentage share of the product compared to total resources used (Circularity Product Indicator, CPI). This methodology has its strength in the product system Eco-Effectiveness evaluation through CPI calculation. Given that this methodology depends from technological peculiarities and resources type exploited for the creation of a generic product, it is a tool for the comparison of different productive realities and for the analysis of the most virtuous ones in terms of resource flows maximization. This aspect is useful to compare the three CBMs detected in Deliverable 1.1: 1) product-oriented, 2) result-oriented and 3) use-oriented PSSs.

- ***Circularity Cost Assessment (CCA)***

Starting from the system circularity calculation and KPIs system carried out in the first methodology, through CCA is possible to analyse and quantify the economic benefits related to CE, always referring to a well-defined product system. Its application is used to calculate the cost savings generated by the triggering of materials and other resources circularity and to evaluate the economic savings related to energy circularity.

- ***Circularity Environmental Assessment (CEA)***

Finally, with CEA it is possible to evaluate the environmental benefits resulting from the use of a circular business model. The objective is therefore to quantify the emissions and other forms of pollution avoided by triggering the resources flows circularity present throughout the entire life cycle. This methodology consists in the association of a "weight" to all the environmental impacts that characterizes each circular resource flow, in order to be able to calculate the difference with the environmental impacts of the corresponding linear system. This analysis can be carried out through the Life Cycle Assessment methodology (see D2.1 for details).

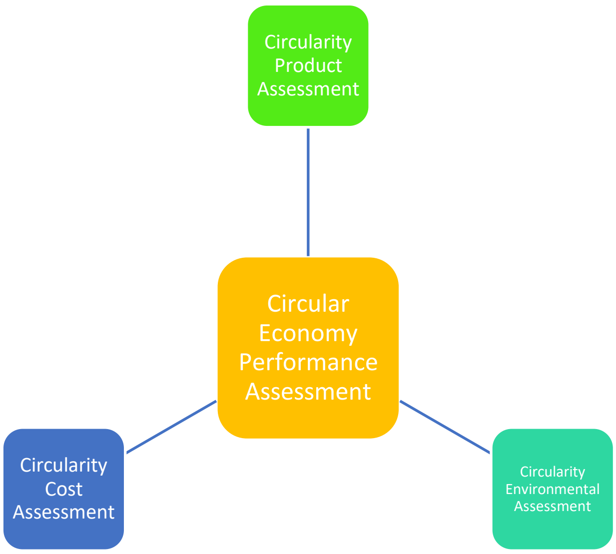


Figure 8: Circular Economy Performance Assessment methodology

Outputs of the CEPA methodology consist in a set of specific KPIs regarding resources circularity degree present within the product life cycle and the quantification of those that are the economic and environmental benefits of the CE. They can be used in different application fields:

- Creation of a product certification system related to the circularity of resource flows;
- Design of new products considering the circularity as a decision criterion (Design for Circular Economy);
- Comparison of different versions of the product ("what if" analysis) based on their degree of circularity and the benefits they can bring; this applies both to new products and to developments and improvements linked to existing products;
- Internal reporting and benchmarking. Companies would be able to compare different products based on their circularity and on benefits they can achieve.

4. CIRCULARITY PRODUCT ASSESSMENT (CPA) METHODOLOGY

The objective of CPA is to quantify the circularity of each type of resource within the product life cycle. Executing mass and energy balances, made 100% the input quantity of a given resource k in a generic phase p of the product system under analysis, a percentage of this input will end up in the output of that activity (X%), a percentage will be discarded (Y%), and – if there are any circularities – another percentage (Z%) will be reused "somehow" within the same system or in a different system. Therefore, the generic constraint to be considered will be always of the type:

X% + Y% + Z% = 100% of resource k in phase p

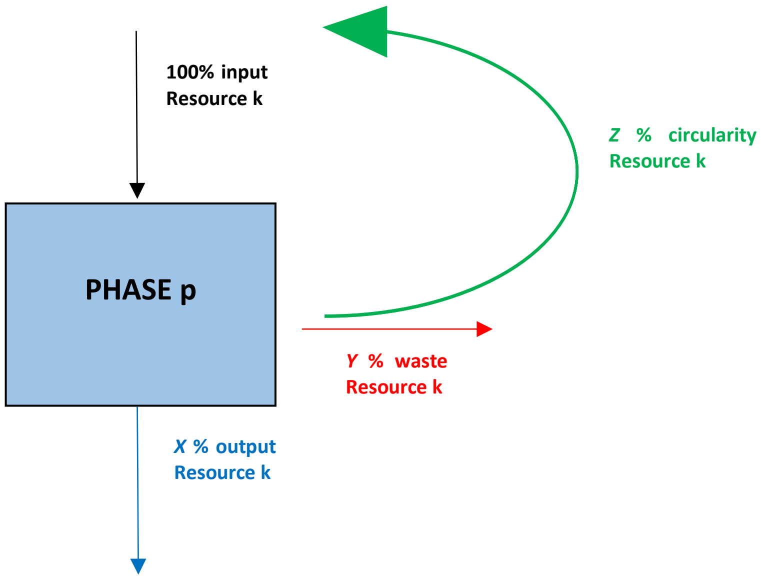


Figure 9: Flow schematization

This type of quantification is carried out for all the resources, and for all the phases, of the analyzed system, trying to limit the analysis to the product lifecycle.
Unlike the objectives of the environmental impact assessment models (e.g. LCA), in which the aim is to evaluate and quantify the environmental impacts related to the quantities used by all the k resources present in the system, CPA aims to identify and quantify the circularities present in the system so calculating how much the economic-productive process is circular. With the term "circularity" we refer to those resource flows (of any kind) that fall retroactively in the system (the same or another) to be reused. The circularity of resources and their low environmental impact can be considered two fundamental pillars of sustainable manufacturing system. However, these two principles do not necessarily coexist. For example, a process could be at the same time highly circular and have a high environmental impact (e.g. in presence of small percentages of toxic resources that are not recovered). Contrarily, a process could be at the same time linear and have a very low environmental impact. Given all of these points, together with the evaluation of circular flows, it is necessary to assess also the environmental impacts associated with them. However,

this is the objective of the CEA methodology, while here we focus on their relative quantification with respect to the total resources consumed.

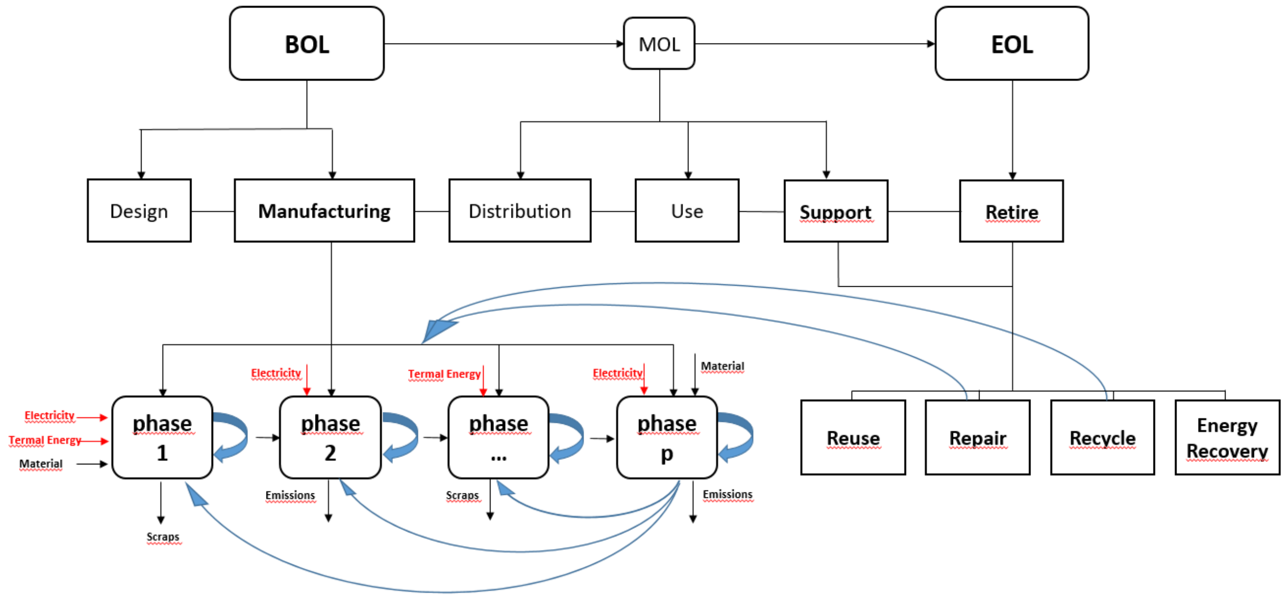


Figure 10: Product lifecycle flows schematization

4.1. CPA Phase 1: Objectives definition and settings

Within this phase the analysis context is identified. It is very important to understand from the beginning what kind of study has to be carried out as it is associated with different modelling principles and different methodological choices. Regarding the modelling principles choice that can be used, we refer to the Life Cycle Assessment guidelines (The International Standards Organisation, 2006), given the different similarities between the first phase of our model and the first phase of LCA. The main modelling principles are two:

- the "attributional" modelling, describing the system in a static way;
- the "consequential" modelling, describing the system as it is expected as a result of the analysed decisions, then inserting it into a dynamic sphere.

Furthermore, the study context may vary depending on whether the analysis is undertaken to support (or not) any decision and basing on the types of process changes in the analysed systems.

<table>
<tr><td rowspan="4">Decision support?</td><td rowspan="2"></td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Yes</td><td>Situation A
"Micro-level decision support"</td><td>Situation B
"Meso/macro-level decision support"</td></tr>
<tr><td>No</td><td colspan="2">Situation C
"Accounting"
(with C1: including interactions with other systems, C2: excluding interactions with other systems)</td></tr>
</table>

Table 5: Modelling principles

According to the above schematization, the situations A and C are **attributional** types, while the situation B is **consequential** type, since it foresees significant system changes to support decisions on a medium/large scale.

4.1.1. System to study

<u>System boundaries</u>

According to the first law of thermodynamics (the law of the mass conservation), total inputs must be equal to total outputs plus net accumulation of materials in the system. This material balance principle holds true for the economy as well as for any subsystem (e.g. an economic sector, a company, a plant). For a consistent compilation of an economy-wide material flow account, it is necessary to define exactly where the boundary between the economic and the environmental system is (Hinterberger, Giljum, & Hammer, 2003). Subsequently, process phases included in the analysis are decided, depending on the purpose of the study. The choice to not consider certain processes, activities, inputs or outputs must be clearly explained, as well as the reasons and implications must be clarified. Furthermore, the system must be described with enough detail and clarity. The term "system" indicates the part of the lifecycle enclosed within the chosen boundaries and the different activities or sub-activities contained in the system will be indexed with "p". Some examples of different boundaries can be: "from gate to gate", "from cradle to gate", "from gate to grave", "from cradle to grave", "from cradle to cradle". The latter case is the most suitable for the analysis of system circularity, since it allows the analysis of long-range circularities as well.

<u>Functional unit and reference flow</u>

A system can have more than one function. The functional unit represents the "quantified performance of the system to be used as a reference unit" (The International Standards Organisation, 2006). It is an index of the system performances and it is the reference unit of measure to which the input and output elements of the studied system can be linked on. It is very important that the comparison between different systems is carried out basing on the same function, quantified by the same functional unit. Instead, the reference flow represents the quantity of product necessary to satisfy the chosen functional unit (sometimes functional unit and reference flow coincide, i.e. the functional unit is already expressed as quantity of product).

<u>Data characteristics</u>

To determine the reliability of results, it is necessary to define the temporal coverage, the geographical coverage, the technological coverage, the precision, the completeness, the representativeness, the consistency, the reproducibility, the sources, the uncertainties about information and the degree of error. In general, it is possible to classify data according to their solidity in: first level (experimental data), second level (from literature) and third level data (estimates and average data).

Allocation and multi-process cases resolution

Given the model objective, it is necessary to allocate the material circularities of a system correctly. With the term "secondary material", we refer to materials produced by recycling phases, while the term "primary material" refers to materials produced from virgin resources. Therefore, secondary materials can be used to replace primary materials. This way, it is important to consider that every recycling activity influences the environment through the consumption of resources, the release of emissions and waste. However, recycling activities make possible to replace the production and management of primary materials. Hence, the procedure for the allocation of flows are a key factor for the analysis of benefits related to circularity and material recycling. Referring to (The International Standards Organisation, 2006), it is possible to distinguish between the "closed-loop " allocation procedure and the "open-loop" allocation procedure.

- The "closed-loop" allocation is applied to closed-cycle product systems and open-cycle product systems in which no alterations in the properties of the recycled material occur. In these two cases there is no need to allocate flows because the use of secondary materials replaces that of primary (virgin) materials. In the first case, the recycled material is recovered in the final phase of the product system and is reused again in the same product system, while in the second case the material has the same properties as the primary material, but it is reused in a different product system. In this last reality the greenhouse gases emissions related to the final disposal of the product, including the recycling processes, are allocated to the product that supplies the recycled material, but this recycled material that "leaves" the product system, obtains a "recycling credit" corresponding to the emissions of the relevant primary material. This means that for a certain material, a 1:1 substitution ratio can be used (concept resumed in the continuation of the work) since a reference unit (e.g. in bulk terms) of secondary material can replace a reference unit of primary material. This implies that it is possible to use 100% recycled material instead of virgin material (this is the case of aluminium and its alloys, which have the ability to maintain their properties during recycling). Below, a scheme for the aluminium packaging recycling (with fictitious numbers) is proposed, as described in the guidelines of (The International Standards Organisation, 2012).

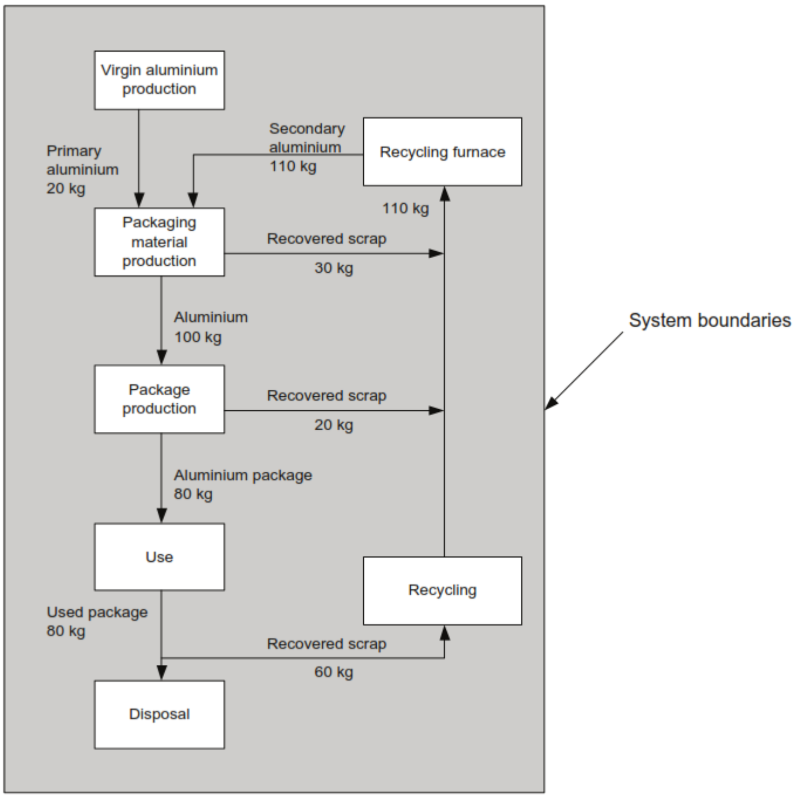


Figure 11: "closed-loop" aluminium recycling ("General Guide for Life Cycle Assessment", 2010)

- The "open-loop" allocation is applied to open-cycle product systems, in which the materials are recycled into other product systems, undergoing changes in the properties of the material (e.g. chemical and structural composition). After making the system expansion, if possible, to not allocate the same resource flows on different product systems, the allocation procedure should consider: physical properties, economic value and number of subsequent uses of the recycled material (The International Standards Organisation, 2012). The "shared process units" for open-cycle product systems refer to the extraction and processing of raw materials and end-of-life operations of the product. Also in this case, the allocation can be avoided thanks to the process subdivision. One possibility is to separate the emissions of the disposal/recycling phases into a component that will be added to the product system that creates recycled material and a component that it will add to the system in which the recycled material is introduced. Given that the first criterion to be used for the classification of materials (i.e. the one based on physical properties) is extremely contingent and different for each specific case, the second parameter to be used according to (The International Standards Organisation, 2012) is the one based on economic value. It provides an allocation factor A, calculated as the ratio between the market price of the recycled material and the market price of the primary material, typically on a long-term average (e.g. five years). The number of subsequent uses of the recycled material can be used as a third possibility if they can be determined and justified and in the hypothesis of not being able to use the first two classification methods. According to the standard, if none of these three criteria were applicable, it is possible to use an arbitrary allocation factor of

0.5 (since A is an economic parameter, it will also be linked to the costs of recycling processes, and consequently to yields of the latter).

The substitution ratio represents a good approximation, both for the evolution of the physical properties of the material to be recycled and of the number of uses to which it is subject. For example, it is possible to calculate the paper replacement ratio, a material that cannot be recycled endlessly and for which it is therefore not possible to use a 1:1 substitution ratio (Rigamonti, Grosso, & Sunseri, 2009). Unlike aluminium, glass and iron, paper can be recycled only a limited number of times (e.g. five times) (Comieco 2008). This means that virgin pulp can be used in its whole life to produce only five secondary pastes (always referring to a unitary quantity of reference). This way, all the consumption of materials and energies that occur in the production of virgin pulp must be divided between six units (and not between infinite units, as for aluminium). Consequently, in the production of 1 kg of secondary pulp, we need to add 1/6 of the consumption of material and energy relative to the production of 1 kg of virgin pulp, together with the consumption of material and energy from recycling activities. With this assumption, 1 kg of secondary pulp plus 0.167 kg (1/6) of virgin pulp, will succeed in substituting a kg of virgin pulp or, in other words, 1 kg of secondary pulp will replace 0.833 (1-0.167) kg of virgin pulp and therefore the paper replacement ratio is 1:0.833. This value, calculated from the possible number of recycles, as suggested in the ISO/TR 14049 standard, reflects the differences in mechanical properties and colour between virgin pulp and recycled pulp and therefore allows to take into account the material quality losses due to recycling. Like in the "closed-loop" procedure, also for the "open-loop" procedure we propose two schemes of the recycling process of aluminium packaging (always referring to (The International Standards Organisation, 2012)).

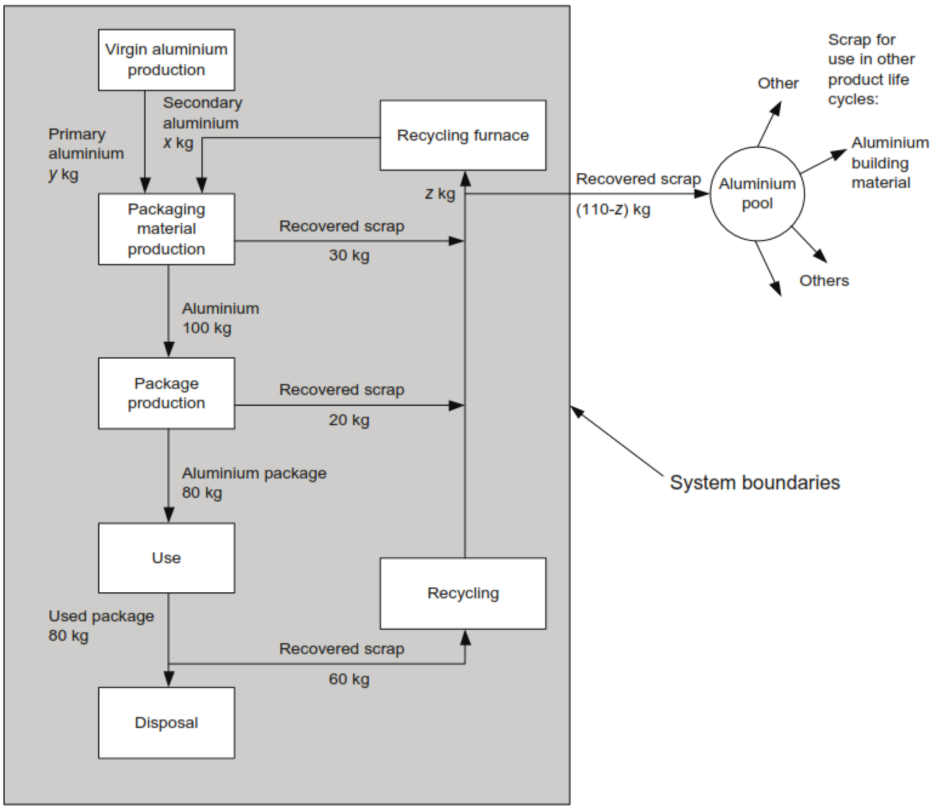


Figure 12: "open-loop" aluminium recycling (without system expansion) ("General Guide for Life Cycle Assessment", 2010)

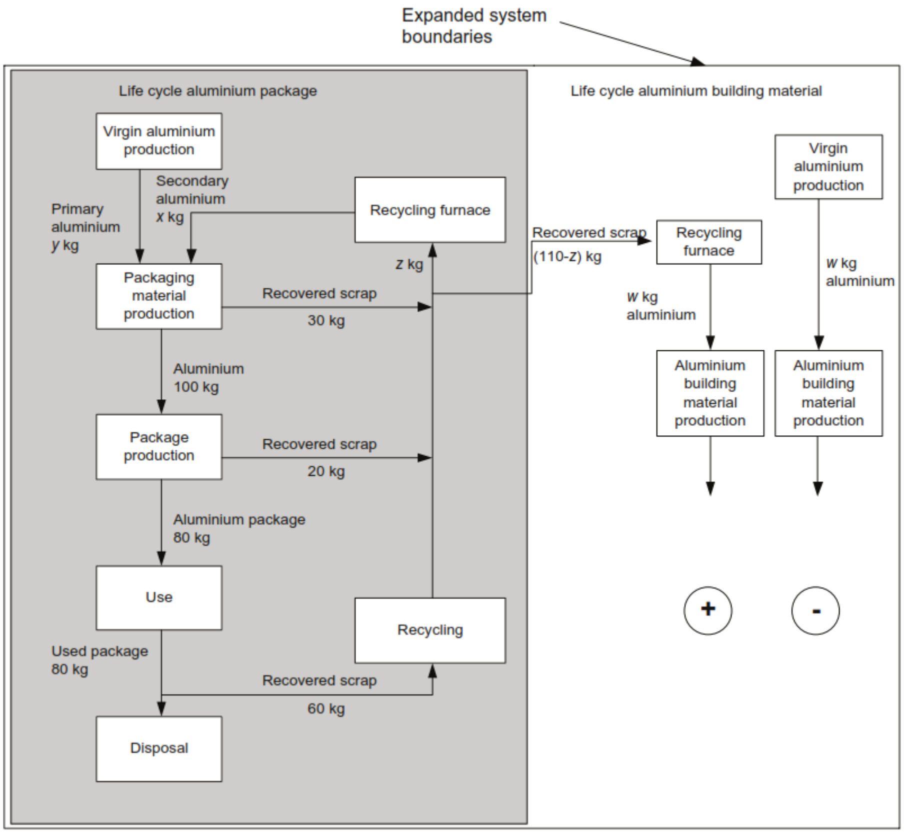


Figure 13: "open-loop" aluminium recycling (with system expansion) ("General Guide for Life Cycle Assessment", 2010)

<u>Hypothesis and limitations</u>

For every system we want to study, it is always right to make, if necessary, adequate limitations and hypotheses according to the specific situation and the constraints of the case.

4.2. CPA Phase 2: Inventory analysis and resource flow decomposition

The second CPA phase includes the compilation and quantification of the inputs and outputs of each phase for a product/functional unit during its lifecycle. Data must be collected for each process unit included in the system boundaries and must be referred to the functional unit.

4.2.1. Lifecycle phases description

In the first phase of the methodology the boundaries of the system were defined. Within these boundaries, the individual phases of the life cycle must be delineated into detail. For this reason, it is necessary in a first instance a detailed description of the individual phases of the lifecycle to be analysed. Coherently with system boundaries selected, the phases analysed will be p (ranging from 1 to P), stating that:

- For the EoL phase we will have p = eol, in order to separate conceptually and at the nomenclature level the phase of disposal of the product at the end of its life.
- If there are maintenance or repair activities of the product after the use phase, they will be indexed f and will go from p = f1 to p = ff.

If the product, or a part of it, is repaired or remanufactured (because it is convenient at the economic level and for the resources used), we can talk about maintenance circularity. According to the cardinal principles of Circular Economy, the repair of a product triggers a retroactive flow in the technical sphere of the system. This allows a saving of resources used compared to the case in which a new product was created and in addition allows the extension of the life cycle of the product itself through the lengthening of the use phase. For this reason, the circularity is quantified in the model as the ratio between the resources saved and the resources used in the case of a new production. Since not all types of products have the possibility of being repaired (e.g. fast-moving consumer goods), and because even for those for which there is the possibility there is always a uncertainty degree that this is actually carried out, it was decided to treat the maintenance phases through a binary variable that is activated only if it is actually carried out. Then, another uncertainty degree to consider is related to the lengthening of the use phase of a post-repair product. A coefficient has been introduced that expresses the temporal benefit of the extension of the life cycle due to the maintenance sphere, compared to the average life span of the product itself.

- f [0, 1, …, F] = number of repair

- A = binary variable whose value is:
- 1 if f>0 (at least one repair for the product)
- 0 if f=0 (no repair for the product)

- $z_f = \frac{(f+1)-th\ useful\ life}{average\ useful\ life}$ = coefficient expressing the temporal benefit in terms of product life cycle extension thanks to maintenance and repairs. f is the number of times the product is repaired. Consequently, with the term "(f + 1)-th useful life" we mean the useful life span after the f-th maintenance, so "[(f + 1)-th useful life] / (average useful life))]" indicates the product life cycle extension after the f-th maintenance (with respect to its average duration). The duration can be expressed in different units of measure depending on the type of product being studied (days, months, years, ...).

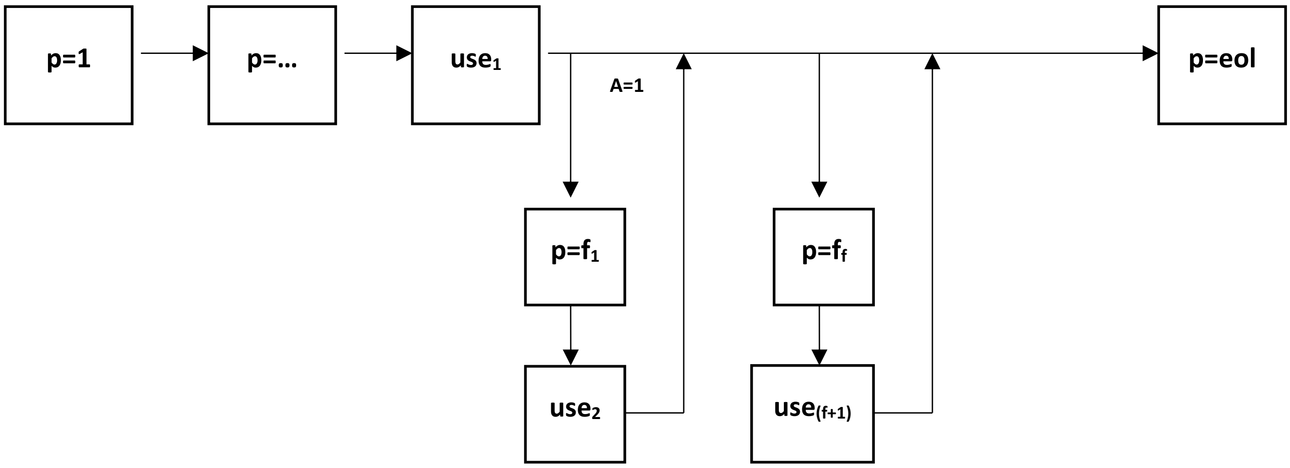


Figure 14: Maintenance phases flow schematization

4.2.2. Inventory analysis and Input-Output analysis

After having described all system phases, the methodology moves on to the inventory phase of all the resources used to create the product:

- Energy flows (electricity and thermal energy);
- Material flows: they concern the different materials that make up the product;
- Other resources flows used for product formation: they relate to the resources that do not constitute the materials that make up the product, but which are however necessary for the formation of the same (for example water, cooling fluids, chemical additives, consumables, etc.).

These three types of flows will then be quantified and allocated in the respective phases so that they can be used in the subsequent calculation steps in the model. Below, the acronyms, indexes and subscripts used to identify the variables present in the model are described into detail.

p (phase) : system phase

f : maintenance phase

m (material) : materials that make up the product

r (resource) : resources that make up the product

in : input flow

out : output flow

C (circular) : circular flow

SS (same system) : system under analysis

OS (other system) : other systems that are out of the boundaries

eol : End – of – Life

W (weight) : resource weight

E (energy) : energy flow

EE : electric energy

TE : thermal energy

MF : material flow

RF : resource flow

LHV : lower heating value

en_rec : energy recovery

V: virgin resource

N_V : not virgin resource

maint : maintenance phase resource flow

WIP : work in process

FP : final product

MFC : material flow circularity

RFC : resource flow circularity

CI : circularity indicator

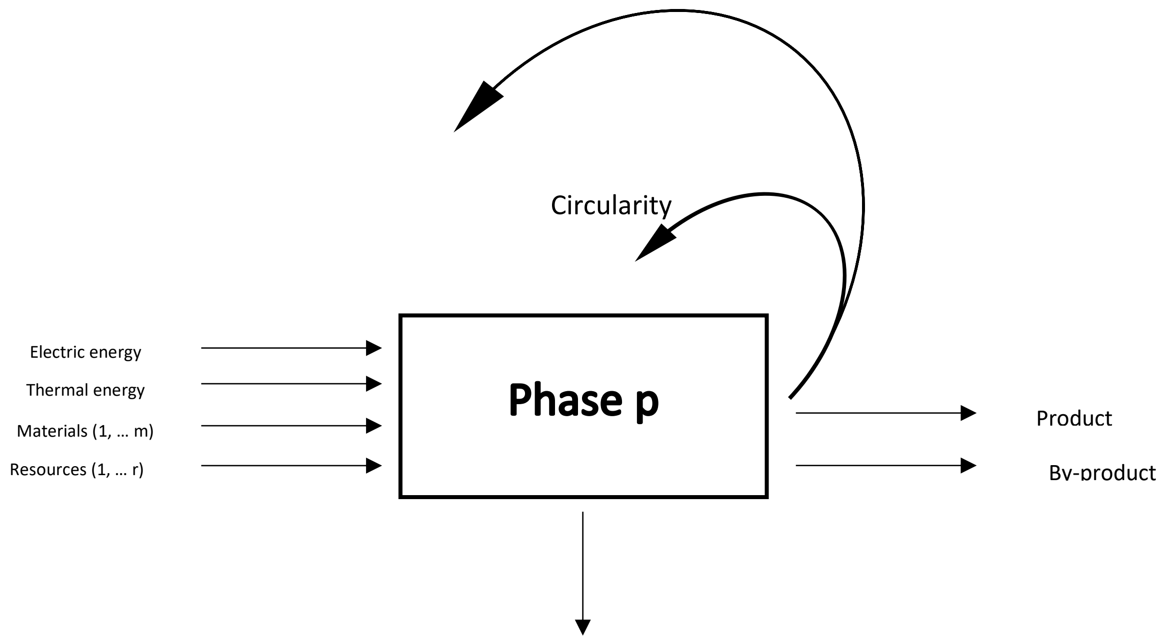


Figure 15: Single phase flows schematization

4.2.3. Circular flow decomposition and calculation

In this CPA phase, for each system phase, all the resource flows (energy, materials and complementary resources) used within product lifecycle are analysed in such a way to be able to calculate the different types of circularity. "Quantifying circularity" means determining the share of the resource flows that can be considered circular with respect to the total resources used. This way, by keeping in mind the mass and energy balances for each phase, it is possible to obtain a set of indexes on a percentage scale that are exhaustive of the real degree of circularity of each resource within the system phases. However, by establishing precise boundaries for the system does not necessarily imply the study of a closed system. In fact, among the different types of material flows and resources considered there are also those coming from other systems. So, also the possible interactions of lifecycles of other products must be taken into account. This logic creates a bridge between the concept of Product Life Cycle and Industrial Symbiosis. In particular, the following types of circularity will be analysed:

- Electric or thermal flows from renewable energy sources;
- Thermal energy flows from thermal recovery;
- Electric or thermal flows from energy recovery of materials and other discarded resources;
- Materials flows or other non-virgin resources in input from other systems;
- Materials flows or other non-virgin resources in input from the same system under analysis (short-range if coming from the same phase p, long-range if coming from another phase p, or from the end-of-life phase);
- Material flows or other non-virgin output resources intended for re-use in the same system or in other systems;
- Resource flows saved as a result of maintenance and repair activities.

- Energy flows

The use of energy produced from renewable sources is one of the cardinal principles underlying the CE philosophy. Given their finite nature, the use of energy deriving from fossil fuels (whether produced autonomously or purchased from the electricity grid) is, by definition, a linear process. With the term "renewable" the literature considers forms of energy that are regenerated in a short time if compared to the times of human history, in the sense that they regenerate at least at the same speed with which they are consumed, or they are not exhaustible in the scale of the "geological eras" times. They are "clean" because they have the peculiarity of not introducing polluting or climate-altering substances into the atmosphere and their use does not affect the same natural resources for future generations because they allow the use of sustainable methods for their exploitation. These energies applied to production processes for the creation of goods implies retroactive circular flows within the biological sphere of economic systems.

A second type of circular energy flow, valid only in the thermal case, concerns energy recovery. The possibility of reusing a discarded amount of heat to generate new energy (electrical or thermal) doesn't imply the introduction of "new" energy flows.

For each product lifecycle phase (p) it is necessary to quantify the following variables related to the energy resources flows:

- $\mathbf{EE}_{p}$ = Kwh of Electric Energy consumed in the phase p
- $\mathbf{TE}_{p}$ = Kwh of Thermal Energy consumed in the phase p

Also the energy consumption related to recycling or recovery activities related to the phase p are included. If, for example, a treatment is needed to make a material re-usable in the phase p, the energy consumed for that treatment can be allocated to the phase p, to another phase or even to another system.

- $\mathbf{EE\_R}_{p}$: electric kwh from renewable sources consumed in the phase p
- $\mathbf{TE\_R}_{p}$: thermal kwh from renewable source or from thermal recovery consumed in phase p
- $\mathbf{E\_maint}_{f}$: kWh of electrical and thermal energy consumed for the product f-th maintenance or for a part of it (including those used for the creation of any spare parts)

- Material flows

Like evidenced for energy, for each product lifecycle phase (p) and for each material (m) it is necessary to quantify the following variables related to the material resource flows:

- $\mathbf{MF\_TOT\_in}_{m,\ p}$: Mass of m-th material, of any type (circular flows, virgin flows, by-products, semi-finished products, etc.), in input in the phase p.
- $\mathbf{MF\_WIP\_in}_{m,\ p}$: Mass of m-th material entering in the phase p representing a semi-finished product or a by-product and constituting an input already partially processed; it is therefore the mass of the m-th material used for the creation of the product in the phase p.
- $\mathbf{MF\_in}_{m,\ p}$: Mass of m-th material in input for the first time in the phase p (thus excluding the semi-finished and incoming by-products since for them the material has already been counted in the previous phases or does not exist). For the first time means for the first time for this product and for this phase. It does not refer to the concept of circularity; a clarification is necessary to exclude the semi-finished products and the incoming by-

products (WIP) because for them the material has already been counted in the previous phases or does not exist.

- **MF_V_in $_{m, p}$**: Mass of virgin m-th material in input in the phase p.
- **MF_NV_in $_{m, p}$**: Mass of non-virgin m-th material in input in the phase p.
- **MF_WIP_out $_{m, p}$**: Mass of material m-th leaving the phase p representing a semi-finished product or a sub-product and constituting an input, already partially processed, for one or more successive phases; it is therefore the mass of the m-th material used for the creation of the product in the phase p.
- **MF_out $_{m, p}$**: Mass of m-th material discarded by the phase p (which therefore does not constitute an output that ends up in the product or in a semi-finished product). This can therefore be a waste or a circularity.
- **MF_W_out $_{m, p}$**: Mass of m-th material discarded in the phase p (which therefore does not constitute an output that ends up in the product or in a semi-finished product) and not reusable within the phase p, in other phases or in other systems. It is what is discarded, which is a waste (and therefore no type of circularity).
- **MF_W_out $_{m, eol}$**: Mass of m-th material discarded in the EOL (hence after the product use phase) and not reusable within any phase of the system or in other systems. It is what is actually discarded from the disposal of the product and cannot be recovered, which is a waste
- **MF_FP $_{m}$**: Mass of m-th material contained in the finished product. Note that this quantity can be interpreted as the input of the EoL phase.
- **MF_maint_in $_{m, f}$**: Mass of m-th material in input in the maintenance phase f. It is the mass used for the creation of the spare part or used for the direct repair of the product.

Absorbed circularity

The term "absorbed circularity" focuses on the quantification of retroactive flows on the inputs present in each phase. In other words, the circular part of the resource streams is quantified made 100% the input of that resource at that phase. Hence the adjective "absorbed", since it refers to the use of non-virgin material entering the phase. These circularities can have multiple origins:

- **MFC_in $^{short}_{m, p}$ (short-range material circularity)**: Mass of m-th material discarded in the phase p and reusable within the phase p (then recovered or recycled within the same phase).
- **MFC_in $^{long}_{m, p}$ (long-range material circularity)**: Mass of m-th material discarded in one or more phases downstream of phase p (p + 1, p + 2, ...), and reusable within the phase p.
- **MFC_in $^{eol}_{m, p}$ (material circularity from EOL)**: Mass of m-th material recovered or recycled from the product EOL and reusable within the phase p.
- **MFC_in $^{OS}_{m, p}$ (material circularity from other systems)**: Mass of m-th material recovered or recycled from other systems and reusable within phase p.

Generated circularity

The term "generated circularity" instead, focuses on the quantification of retroactive flows on the outputs present in each phase. In other words, the circular part of the resource streams is quantified made 100% the output of that resource at that phase. Hence the adjective "generated", since it refers to the ability to make available non-virgin material that can be reused in many ways:

- **MFC_out** $^{OS}_{m,\ p}$: Mass of m-th material discarded from phase p and usable in other systems
- **MFC_out** $^{SS}_{m,\ p}$: Mass of m-th material discarded from phase p and reused in the system (in the phase p or in other phases)
- **MFC_out** $^{en\_rec}_{m,\ p}$: Mass of m-th material discarded by the phase p and sent to energy recovery
- **MFC_out** $^{SS}_{m,\ eol}$: Mass of m-th material discarded from the EOL and reused in the system, so after the product use phase (in phase p or in other phases)
- **MFC_out** $^{OS}_{m,\ eol}$: Mass of m-th material discarded from the EOL and reused in other systems (i.e. after the product use phase)
- **MFC_out** $^{en\_rec}_{m,\ eol}$: Mass of m-th material discarded from the EOL phase and sent to energy recovery

The constraints are dictated by the mass balance at the phase and system level:

$$\mathbf{MF\_TOT\_in}_{m,\,p} = \mathbf{MF\_out}_{m,\,p} + \mathbf{MF\_WIP\_out}_{m,\,p}$$

$$\mathbf{MF\_in}_{m} = \sum\nolimits^{P}_{p=1} \mathbf{MF\_in}_{m,\,p}$$

$$\mathbf{MF\_V\_in}_{m} = \sum\nolimits^{P}_{p=1} \mathbf{MF\_V\_in}_{m,\,p}$$

$$\mathbf{MF\_NV\_in}_{m} = \sum\nolimits^{P}_{p=1} \mathbf{MF\_NV\_in}_{m,\,p}$$

$$\mathbf{MF\_out}_{m} = \sum\nolimits^{P}_{p=1} \mathbf{MF\_out}_{m,\,p}$$

$$\mathbf{MF\_TOT\_in}_{m,\,p} = \mathbf{MF\_WIP\_in}_{m,p} + \mathbf{MF\_V\_in}_{m,p} + \mathbf{MFC\_in}^{short}_{m,p} + \mathbf{MFC\_in}^{long}_{m,p} + \mathbf{MFC\_in}^{eol}_{m,p} + \mathbf{MFC\_in}^{OS}_{m,p}$$

$$\mathbf{MFC\_in}^{eol}_{m} = \sum\nolimits^{P}_{p=1} \mathbf{MFC\_in}^{eol}_{m,\,p}$$

$$\mathbf{MFC\_out}_{m,\,p} = \mathbf{MFC\_out}^{OS}_{m,\,p} + \mathbf{MFC\_out}^{SS}_{m,\,p} + \mathbf{MFC\_out}^{en\_rec}_{m,\,p} + \mathbf{MF\_W\_out}_{m,\,p}$$

$$\mathbf{MFC\_out}_{m,\,eol} = \mathbf{MFC\_out}^{OS}_{m,\,eol} + \mathbf{MFC\_out}^{SS}_{m,\,eol} + \mathbf{MFC\_out}^{en\_rec}_{m,\,eol} + \mathbf{MF\_W\_out}_{m,\,eol}$$

[MFC_out $_{m,\ eol}$**: mass of m-th material discarded from the EOL and reused in the system or outside it]**

❖ Other resource flows

As for materials and energies, for each product life cycle phase (p) and for each other resources (r) it is necessary to quantify the following variables related to the other resources flows. The term "other resources" refers to all the complementary resources that are used in the creation of the product, but which do not constitute materials that end up in the finished good (for example the sand used in a sandblasting process for a metallic product or water used for the machine cooling circuit).

- **RF_TOT_in** $_{r,\ p}$: Mass or volume of r-th resource, of any nature (circular flows, virgin flows, semi-finished, etc.), in input in phase p
- **RF_WIP_in** $_{r,\ p}$: Mass or volume of r-th resource entering in the phase p representing a semi-finished product or a sub-product and constituting an input already partially processed; it is therefore the mass of the r-th resource used for the creation of the product in the phase p
- **RF_in** $_{r,\ p}$: Mass or volume of r-th resource in input for the first time* in the phase p. For the first time means for the first time for this product and for this phase. It does not refer to the concept of circularity; is a clarification necessary to exclude the other resources used for

semi-finished products and for the incoming by-products (WIP) because for them these resources have already been counted in the previous phases or does not exist.

- **RF_V_in** $_{r, p}$: Mass or volume of r-th virgin resource in input in the phase p
- **RF_NV_in** $_{r, p}$: Mass or volume of r-th non-virgin resource in input in the phase p
- **RF_WIP_out** $_{r, p}$: Mass or volume of r-th resource leaving the phase p used for the creation of a semi-finished product or a sub-product that constitutes an input for one or more successive phases; it is therefore the mass or volume of r-th resource used ("consumed") for the creation of the product in the phase p
- **RF_out** $_{r, p}$: Mass or volume of r-th resource rejected by the phase p
- **RF_W_out** $_{r, p}$: Mass or volume of r-th resource rejected in phase p and not reusable within phase p, in other phases or in other systems. It is what constitutes a waste (and therefore no type of circularity)
- **RF_FP** $_{r}$: Mass or volume of r-th resource contained (or "consumed") in the finished product. Being "other resources", then used for the formation of the product, but not really present in the finished product, this variable indicates the quantities consumed for the realization of the finished product. It is as if it represented the total of the r-th resource used for the functional unit, even if not physically present. In other words, it is the sum of all the phases of the differences between the inputs and the outputs of the r-th resource
- **RF_maint_in** $_{r, f}$: Mass or volume of resource r-th in input in the maintenance phase f. It is the mass or volume used for the creation of the spare part or used for direct repair

<u>Absorbed circularity</u>

- **RFC_in** $^{short}{}_{r, p}$ (short-range resources circularity): Mass or volume of r-th resource rejected in the phase p and reusable within the phase p (then recovered or recycled within the same phase)
- **RFC_in** $^{long}{}_{r, p}$ (long-range resource circularity): Mass or volume of r-th resource rejected in one or more phases downstream of phase p (p + 1, p + 2, ...), and reusable within the phase p
- **RFC_in** $^{eol}{}_{r, p}$ (resources circularity from the EOL): Mass or volume of r-th resource recovered or recycled from the product EOL and reusable within the phase p
- **RFC_in** $^{OS}{}_{r, p}$ (circularity of resources from other systems): Mass or volume of r-th resource recovered or recycled from other systems and reusable within phase p

<u>Generated circularity</u>

- **RFC_out** $^{OS}{}_{r, p}$: Mass of r-th resource rejected by the phase p and reused in other systems
- **RFC_out** $^{SS}{}_{r, p}$: Mass of r-th resource rejected by the phase p and reused in the system (in phase p or in other phases)
- **RFC_out** $^{en\_rec}{}_{r, p}$: Mass of r-th resource rejected by the phase p and send to energy recovery
- **RFC_out** $^{OS}{}_{r, eol}$: Mass of r-th resource rejected by EOL and reused in other systems (hence after the product use phase)
- **RFC_out** $^{SS}{}_{r, eol}$: Mass of r-th resource rejected by the EOL and reused in the system, then after the use phase of the product (in phase p or in other phases)
- **RFC_out** $^{en\_rec}{}_{r, eol}$: Mass of r-th resource rejected by EOL and sent to energy recovery (therefore after the use phase of the product)

The constraints are dictated by the mass balance at the phase and system level:

$RF\_in_{r} = \sum^{P}_{p=1} RF\_in_{r,p}$

$RF\_V\_in_{r} = \sum^{P}_{p=1} RF\_V\_in_{r,p}$

$RF\_NV\_in_{r} = \sum^{P}_{p=1} RF\_NV\_in_{r,p}$

$RF\_out_{r} = \sum^{P}_{p=1} RF\_out_{r,p}$

$RF\_TOT\_in_{r,p} = RF\_WIP\_in_{r,p} + RF\_V\_in_{r,p} + RFC\_in^{short}_{r,p} + RFC\_in^{long}_{r,p} + RFC\_in^{eol}_{r,p} + RFC\_in^{OS}_{r,p}$

$RF\_in_{r,p} = RF\_V\_in_{r,p} + RF\_NV\_in_{r,p}$

$RF\_in_{r,p} = RF\_V\_in_{r,p} + RFC\_in^{short}_{r,p} + RFC\_in^{long}_{r,p} + RFC\_in^{OS}_{r,p}$

$RFC\_out_{r,p} = RFC\_out^{OS}_{r,p} + RFC\_out^{SS}_{r,p} + RFC\_out^{en\_rec}_{r,p} + RF\_W\_out_{r,p}$

$RFC\_out_{r,eol} = RFC\_out^{OS}_{r,eol} + RFC\_out^{SS}_{r,eol} + RFC\_out^{en\_rec}_{r,eol} + RF\_W\_out_{r,eol}$

[$RFC\_out_{r,eol}$: mass of r-th resource discarded by EOL and reused in the system or outside it]

4.3. CPA Phase 3: Weights and indexes calculation

Here the weights and indexes used in CPA are calculated. They have been created to analyse the resources present in the life cycle based on their characteristics. In particular, the attention has been focused on the "physical" weight of materials and other resources and on the weight of each phase in terms of resources used (energy, materials and other resources). Subsequently, the recyclability characteristics of the materials have been taken into consideration, with the aim to calculate with more detail their potential reuse. For these reasons, the following weights and indices are proposed:

- **W^{E}_{p}**: energy weight in the phase p
- **$W^{M,P}_{m,p}$**: weight of the m-th material in the phase p
- **$W^{R,P}_{r,p}$**: weight of the r-th resource in the phase p
- **W^{M}_{m}**: relative weight of the m-th material
- **W^{R}_{r}**: relative weight of the r-th resource
- **IRC_{m}**: composed recyclability index of the m-th material

4.3.1. Establishing weights on resources present in the system

W^{E}_{p}: Weight (percentage) of energy consumed in the phase p on the total energy of the system

$$W^{E}_{p} = \frac{EE_p + TE_p}{E\_system}$$

If A=1, then there is at least one maintenance phase and remember that for the maintenance phases $p=f_1$, $p=f_2$, $p= f_f$. The energy weight of the generic maintenance phase f will therefore become:

$$W^{E}{}_{f_f} = \frac{E\_maint_f}{E\_system}$$

EE_p = Kwh of Electricity consumed in the phase p

TE_p = Kwh of Thermal Energy consumed in the phase p

$EE = \Sigma^{P}{}_{p=1}$ (EE p) = Kwh of Electricity consumed in the life cycle, including consumption of all recycling activities necessary to recover and make reusable resources already used (materials and others)

$TE = \Sigma^{P}{}_{p=1}$ (TE p) = Kwh of Thermal Energy consumed in the lifecycle, including the consumption of all recycling activities necessary to recover and make reusable resources already used (materials and others)

Total energy within the lifecycle:

$$E\_system = EE + TE + (A * \sum_{f=1}^{F} E\_maint_f)$$

$W^{E}{}_{p}$ represents the "energy weight of the phase p", i.e. the amount of energy consumed in the phase p respect to the total energy consumed within the system boundaries. The total energy balance (denominator of the formula) is therefore obtained by adding together any type of energy consumption present in the product lifecycle and it refers to its functional unit. In addition to the consumption necessary for the product creation, the consumption related to all the recovery activities of the resources that can be reused in the system are added. This amount of energy consumed is subtracted from the amount of energy generated if the product or part of it is destined to energy recovery: for example, if the product ends up as an incinerator or in other types of plants for generation of electricity or heat. This share is subtracted because it is as if the product (or a part of it, or its waste) that goes to energy recovery "return" a part of energy that has been consumed to produce it, thus creating an energetic circularity.

$W^{M,P}{}_{m,p}$: Weight (percentage) of the m-th input material in the phase p on the total m-th material used in the system

$$W^{M,P}{}_{m,p} = \frac{MF\_in_{m,p}}{MF\_in_m + (A * \sum^{F}{}_{f=1} MF\_maint\_in_{m,f})}$$

If A=1, then there is at least one maintenance phase and remember that for the maintenance phases p = f_1, p = f_2, p = f_f. The weight $W^{M,P}{}_{m,p}$ of the generic maintenance phase f will therefore become:

$$W^{M,F}{}_{m,f_f} = \frac{MF\_maint\_in_{m,f}}{MF\_in_m + (A * \sum^{F}{}_{f=1} MF\_maint\_in_{m,f})}$$

$W^{R,P}{}_{r,p}$: Weight (percentage) of the r-th resource in input in the phase p on the total of the r-th resource used in the system

$$W^{R,P}{}_{r,p} = \frac{RF\_in_{r,p}}{RF\_in_{r} + (A * \sum^{F}{}_{f=1} RF\_maint\_in_{r,f})}$$

If A=1, then there is at least one maintenance phase and remember that for the maintenance phases p = f_1, p = f_2, p = f_f. The weight $W^{R,P}{}_{r,p}$ of the generic maintenance phase f will therefore become:

$$W^{R,F}{}_{r,f_f} = \frac{RF\_maint\_in_{r,f}}{RF\_in_{r} + (A * \sum^{F}{}_{f=1} RF\_maint\_in_{r,f})}$$

4.3.2. Establishing the relative weight for each material

$W^{M}{}_{m}$: Weight (percentage) of the materials used in input on the total of the input materials used to create the product

$$W^{M}{}_{m} = \frac{MF\_in_{m} + (A * \sum^{F}{}_{f=1} MF\_maint\_in_{m,f})}{\sum^{M}{}_{m=1}(MF\_in_{m}) + (A * \sum^{F}{}_{f=1} \sum^{M}{}_{m=1} MF\_maint\_in_{m,f})}$$

MF_in_{m}: Mass of m-th material in input within the production process

[m: from 1 to M -> materials]

$W^{M}{}_{m}$ represents the "weight of the m-th material" compared to the total materials used for the product. This is the first weight used for the evaluation of the materials circularity used for the creation of the product and represents a "physical" index because it has been conceived as a ratio between masses. Since from this point of view each material is different, it is indeed necessary to give a "physical importance" to the different subjects that make up a particular asset. Each material will then be associated with a "critical weight" linked to the possibility that it will be used several times. In the Circularity Product Assessment these two types of weighing of materials are used because they are considered essential for the "relative" evaluation of the circularity of the materials with respect to the total of the materials used. In the third methodology of Circular Economy Assessment (Circularity Environmental Assessment), in which the focus shifts to the sphere of environmental impacts avoided due to the presence of circularity, the "environmental weight" of each material will be taken into consideration.

4.3.3. Establishing the relative weight for other resources

$W^{R}{}_{r}$: Weight (percentage) of input resources used on the total input resources used for the product

$$W^{R}{}_{r} = \frac{RF\_in_{r} + (A * \sum^{F}{}_{f=1} RF\_maint\_in_{r,f})}{\sum^{R}{}_{r=1}(RF\_in_{r}) + (A * \sum^{F}{}_{f=1} \sum^{M}{}_{m=1} RF\_maint\_in_{r,f})}$$

RF_in $_r$: Mass (or volume) of r-th resource in input within the production process

[r: from 1 to R -> other resources]

Similarly, **W^R_r** represents the "weight of the r-th resource" compared to the total of the other resources used for the creation of the product.

The constraints are dictated by the mass and energy balances present in the analysed system:

$\sum^{P}_{p=1} = W^{E}_{p} = 1$

$\sum^{P}_{p=1} = W^{M,P}_{m,p} = 1$

$\sum^{P}_{p=1} = W^{R,P}_{r,p} = 1$

$\sum^{M}_{m=1} = W^{M}_{m} = 1$

$\sum^{R}_{r=1} = W^{R}_{r} = 1$

4.3.4. Establish the composed recyclability index

In order to calculate the material recyclability, a methodology is proposed below with the aim of giving importance both to the technical characteristics of the material (and how these change through recycling activities) and to the economic value of the material itself. The substitution ratio represents a good approximation of the physical property evolution of the recycled material and of the number of uses. As evidenced by the example of paper, to keep account of the eventual qualitative material decline due to the use and the to the recycling activities, the "substitution" of the primary product can take place in a ratio lower than 1. Below, some examples of substitution ratios found in literature are reported (Rigamonti et al., 2009).

Material	Substitution ratio	Hypothesis
Steel	1:1	Same quality primary and secondary steel
Aluminium	1:1	Same quality primary and secondary aluminium (EAA, 2007)
Glass	1:1	Characteristics of the container made by recycled glass equal to those of the container produced from virgin raw materials. Within glass recycling, 83.5% of glass scrap and 16.5% of virgin raw materials are used.
Panel wood	1:1 – 1:0.6	SR<1 calculated on the basis of the different mechanical resistance performances of the primary and secondary products
Paper pulp	1:1 – 1:0.83	SR<1 calculated on the basis of the number of possible recycles (ISO 14044), assumed equal to 5
Plastic - PET	1:1 – 1:0.81	SR<1 calculated on the basis of the recycled polymer economic value compared to that of virgin polymer
Plastic - HDPE	1:1 – 1:0.81	SR<1 calculated on the basis of the recycled polymer economic value compared to that of virgin polymer
Plastic – Polyolefin mix	1:1	Profiled bar and wooden planks with the same mechanical characteristics

Table 6: Substitution ratio examples

If it's not possible to have the substitution ratio, let's see briefly how to calculate it for a generic m-th material. Consider a unit quantity of m-th material and let k be the number of times it can be recycled. This means that m can be used one time from virgin material and k times from recycled material (for a total of [k + 1] times). In this way, all consumption of materials and energies that take place in the production of virgin matter must be divided between [k+1] units.

To produce a secondary unit quantity of the m-th material, we have to add (1/[k+1]) of the consumption of material and energy relative to the production of a virgin unit quantity together with the consumption of material and energy of the recycling activities.

Therefore, a unit of secondary material plus (1/[k+1]) of virgin units can replace a unit of virgin material, or in other words, a secondary unit can substitute (1-(1/[k+1])) of virgin unit. The substitution ratio of the m-th material will therefore be of 1:(1-(1/[k+1])).

The second fundamental aspect to be considered for the evaluation of materials recyclability (The International Standards Organisation, 2006) concerns their economic value. In particular, the cost differences that exist between a virgin material and the same recycled material. Among the various studies found in the literature, one of the most interesting work is relating to the recyclability index R proposed by (Villalba, Segarra, Fernández, Chimenos, & Espiell, 2002). This is quite similar to the A index previously cited and proposed within the ISO standards. An economic index like this is a direct consequence of the economic feasibility linked to the recycling of the material (a recycled material with high quality will be paid at a price close to same virgin material, unless the costs of recycling processes are not greater than the costs of processing virgin material: in this case the recycled material would not even be purchased or in any case the recycling activities would not be undertaken). It is therefore also representative of extremely important variables such as the complexity and costs of the recycling process, the costs of collection and selection of the discarded material and other macro-economic factors related to the global market (different for each specific sector). Now let's see how R is calculated. For each material analysed, the following values are considered:

- **Vm**: minimum material value (€/kg). This is the minimum value of the material before it is processed or formed for a specific use (for example metals in ingots or granules polymers).

- **Vr**: residual value of the material (€/kg). This is the value that the material has after its primary use and before it is recycled for its second use. Represents the price at which the material to be recycled is purchased.

- **Vp**: post-recycling value of the material (€ / kg). This is the value that the material has after it has been recycled and is ready for its second use, before it is processed or formed for a specific use. If a material has high recyclability without encountering a high-quality degradation, then Vp will be close to Vm.

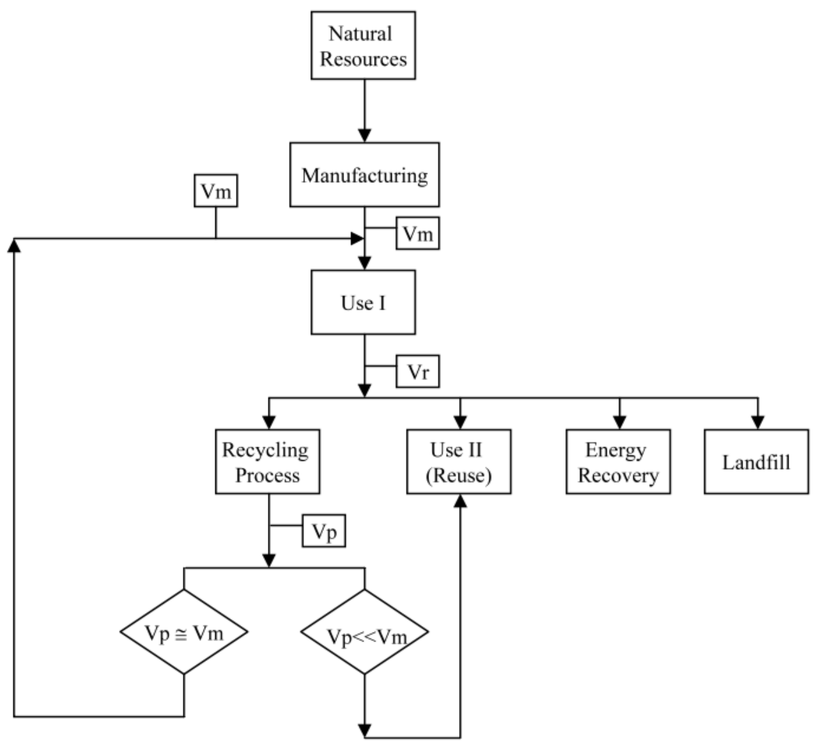


Figure 16: Economic flows values

We can say that:

• The greater the difference between Vm and Vr, the more the material is devalued during use.

• If Vp is approximately equal to Vm, then the recyclability index will be approximately 1.

• If Vp << Vm, then the index will be less than 1 and in many cases the material is reused, sent to landfill or used for energy recovery.

• If Vp >> Vm, then the recycling process is not profitable (and therefore not economically sustainable).

Therefore, the recyclability index R, according to (Villalba et al., 2002), is:

$$\mathbf{R} = \frac{\mathbf{V_p}}{\mathbf{V_m}}$$

For a correct evaluation of the materials economic value, the variables Vm and Vp must consider all the cost items related to the purchase, processing and use of the materials. The production processes, recycling processes, the process yields and their consumption, collection systems and material transport systems and any incentive systems linked to the use of recycled materials in place of the virgin and other items, must therefore be considered related costs, and not just the "market value" of the material. In other words, it is as if Vm represented the "total cost of virgin material" and Vp the "total cost of the recycled material (ready to be reused)", whether these values concern an internal evaluation of the system analysed or external to it.

Starting from the (Villalba et al., 2002) work, we introduce a binary variable β that is true only if there is economic feasibility to use a recycled material. If, for a given material, the economic value (considering all the related cost items) of the recycled product is higher than the economic value of the virgin, there will be no reason that will lead to the purchase or, in general, to the use of the material recycled instead of the virgin one.

It should be noted that the economic benefits associated to resource circularity are the subject of the second evaluation methodology of the Circular Economy Assessment (Circularity Cost Assessment). β represents here only an "economic filter" (which cannot be ignored) concerning the feasibility of using recycled materials.

Therefore β will be worth:

• 1 if Vp ≤ Vm (and therefore R ≤ 1): it is economically feasible to use recycled material.

• 0 if Vp> Vm (and therefore R> 1): it is not economically feasible to use recycled material.

Once calculated the substitution ratio (Rs) and the R index, it is possible to calculate the Composed Recyclability Index, expressed as a product of Rs and of the binary variable β:

IRC = β * Rs

IRC is therefore always between 0 and 1 and in this way, even if only one between β and Rs is null, the composed index is null because it means that for technical or economic reasons it is not possible (or profitable) to use the recycled material. Although the materials have a specific weight through the Composed Recyclability Index, in this first methodology concerning the calculation of circularity, the danger and toxicity degrees of materials and other resources present in the production process have been neglected. This decision is dictated by the objective of the Circularity Product Assessment, i.e. calculate the circularity degree of the resources flows. Everything concerning the dangers of resources is linked to the sphere of environmental impacts and consequently will be treated and considered by the CEA methodology.

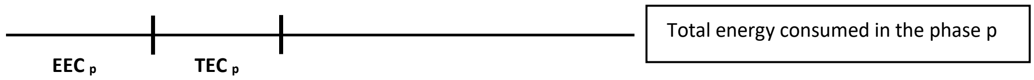
4.4. CPA Phase 4: Circularity indicators calculation

Here, the circularity indexes for the different types of resources are calculated. In particular, the circular shares are weights for each flow present in each system phase grouped into a single index, the Circularity Product Indicator (CPI). In this step the circularity yields are calculated, both for the materials and for the other resources. These values are calculated through the relationship between the "generated" and the "absorbed" circularities by our analysis system. In addition to CPI, these returns have been designed to indicate the virtuosity in terms of CE of the lifecycle with respect to what is outside the boundaries of the analysed system. In other words, determining how much a product is circular may not be enough. It is necessary to understand how many non-virgin (circular) flows are made available to other product systems, compared to those used to create the product itself.

- **Energies**

EEC_p: Percentage share of electricity produced from renewable energy sources used in the phase p, on the total energy consumed in the phase p

$$\mathbf{EEC_p} = \frac{\mathbf{EE\_R_p}}{(\mathbf{EE_p} + \mathbf{TE_p})}$$



For example, if a production plant has an energy plant from renewable sources, EEC $_p$ will be equal to renewable kWh required by a specific production phase, on the total kWh required by the phase itself (renewables and not renewables). Moreover, if electricity was purchased from the grid, it is possible to consider renewable the share of the national energy mix that is produced from renewable sources (for example in Italy in 2016 it was equal to 38.6% of national production).

TEC $_p$: Percentage share of thermal energy, used in the phase p, produced from renewable energy sources or recovered through heat recovery (upstream or downstream of the phase p) on the total energy consumed in the phase p.

$$\mathbf{TEC_p} = \frac{\mathbf{TE\_R_p}}{(\mathbf{EE_p} + \mathbf{TE_p})}$$

ECI $_p$: *Energy Circularity Indicator of the product in the lifecycle phase p:*

$$\mathbf{ECI_p} = \mathbf{W^E}_{\mathbf{p}} * \left(\mathbf{EEC_p} + \mathbf{TEC_p}\right) * \mathbf{100}$$

EC_maint $_f$ *= Energy Maintenance Circularity of the f-th maintenance*

$$\mathbf{EC\_maint_f} = \frac{\mathbf{E\_saved_f}}{\mathbf{E\_system}} = \left\{\mathbf{1} - \left[\frac{\mathbf{E\_maint_f}}{\mathbf{E\_system}}\right]\right\} * \mathbf{100}$$

E_saved $_f$ *= Total kWh saved doing the f-th maintenance, compared to the case in which a new product is created*

$$\mathbf{E\_saved_f} = (\mathbf{E\_system}) - \mathbf{E\_maint_f}$$

ECI: *Energy Circularity Indicator of the product in the lifecycle:*

$$\mathbf{ECI} = \sum_{\mathbf{p=1}}^{\mathbf{P}} (\mathbf{ECI_p}) + \mathbf{A} * \sum_{\mathbf{f=1}}^{\mathbf{F}} (\mathbf{EC\_maint_f} * \mathbf{W^E}_{\mathbf{f_f}} * \mathbf{z_f})$$

However, CE within the energy sphere does not mean only renewable energy. It also means lower consumption in production processes. Energy efficiency in terms of lower consumption within the life cycle is also reflected in the model through the calculation of the circular shares. At mathematical level, in fact, if energy consumption decreases (for example by using recycled materials and avoiding consumption related to the processing of virgin materials), the denominator of EEC_p and TEC_p decreases (i.e. [$EE_p + TE_p$]). This will increase the relative importance of the renewable energy shares (if they exist). A short numerical example to simplify the concept is presented below:

CASE A

- Life cycle consisting of two phases
- 20 kWh consumed in the phase 1 with 10 kWh supplied by a renewable energy plant
- 20 kWh consumed in the phase 2 with 10 kWh supplied by a renewable energy plant

W^E_1 = (20 kwh) / (40kwh) = 50%

W^E_2 = (20 kwh) / (40kwh) = 50%

EE_C_1 = (10 kwh) / (20 kwh) = 50%

EE_C_2 = (10 kwh) / (20 kwh) = 50%

ECI_1 = (50%) * (50%) = 25%; ECI_2 = (50%) * (50%) = 25%

ECI = 50%

CASE B

- Life cycle consisting of two phases
- 50 kWh consumed in phase 1 with 10 kWh supplied by a renewable energy plant
- 50 kWh consumed in phase 2 with 10 kWh supplied by a renewable energy plant

W^E_1 = (50 kwh) / (100kwh) = 50%

W^E_2 = (50 kwh) / (100kwh) = 50%

EE_C_1 = (10 kwh) / (50 kwh) = 20%

EE_C_2 = (10 kwh) / (50 kwh) = 20%

ECI_1 = (50%) * (20%) = 10%; ECI_2 = (50%) * (20%) = 10%

ECI = 20%

- **Materials**

MCI $_{m,p}$ *= Material Circularity Indicator (absorbed circularity) of the m-th material of the product in the lifecycle phase p*

$$\mathbf{MCI_{m,p}} = \frac{(\mathbf{MFC\_in^{short}{}_{m,p}} + \mathbf{MFC\_in^{long}{}_{m,p}} + \mathbf{MFC\_in^{eol}{}_{m,p}} + \mathbf{MFC\_in^{OS}{}_{m,p}})}{\mathbf{MF\_in_{m,p}}}$$

MC_maint $_{m,f}$ = *Material Maintenance Circularity of the m-th material for the f-th maintenance activity*

$$\mathbf{MC\_maint_{m,f}} = \left[\mathbf{1} - \frac{\mathbf{MF\_maint\_in_{m,f}}}{\mathbf{MF\_in_{m}}}\right]$$

This way, the savings coincide with the masses of the m-th material that it's not used to repair the product, but that would be used to build a new one. MF_maint_in $_{m,f}$ represents the mass of m-th material in input in the maintenance phase f. It is the mass used for the creation of the spare part or used for direct repair.

MCI $_{m}$ = *Material Circularity Indicator (absorbed circularity) of the m-th material of the product in the lifecycle*

$$\mathbf{MCI_m} = \sum_{p=1}^{P}[\mathbf{MCI_{m,p}} * \mathbf{W^{M,P}}_{\mathbf{m,p}}] + \mathbf{A} * \sum_{f=1}^{F}[\mathbf{MC\_maint_{m,f}} * \mathbf{W^{M,F}}_{\mathbf{m,f_f}} * \mathbf{z_f}]$$

MCI = *Material Circularity Indicator (absorbed circularity) of the product in the lifecycle*

$$\mathbf{MCI} = \sum_{m=1}^{M}[(\mathbf{MCI_m} * \mathbf{W^{M}}_{\mathbf{m}} * \mathbf{IRC_m}) * \mathbf{100}]$$

- **Other resources**

RCI $_{r,p}$ = *Resource Circularity Indicator (absorbed circularity) of the r-th resource of the product in the lifecycle phase p*

$$\mathbf{RCI_{r,p}} = \frac{(\mathbf{RFC\_in^{short}}_{\mathbf{r,p}} + \mathbf{RFC\_in^{long}}_{\mathbf{r,p}} + \mathbf{RFC\_in^{eol}}_{\mathbf{r,p}} + \mathbf{RFC\_in^{OS}}_{\mathbf{r,p}})}{\mathbf{RF\_in_{r,p}}}$$

RC_maint $_{r,f}$ = *Resource Maintenance Circularity of the r-th resource for the f-th maintenance activity*

$$\mathbf{RC\_maint_{r,f}} = \left[\mathbf{1} - \frac{\mathbf{RF\_maint\_in_{r,f}}}{\mathbf{RF\_in_{r}}}\right]$$

This way, the savings coincide with the masses (or volume) of the r-th resource that it's not used to repair the product, but that would be used to build a new one. RF_maint_in $_{r,f}$ represents the mass (or volume) of r-th resource in input in the maintenance phase f. It is the mass (or volume) used for the creation of the spare part or used for direct repair.

RCI $_r$ *= Resource Circularity Indicator (absorbed circularity) of the r-th resource of the product in the lifecycle*

$$\mathbf{RCI_r = \sum_{p=1}^{P} [RCI_{r,p} * W^{R,P}{}_{r,p}] + A * \sum_{f=1}^{F} [RC\_maint_{r,f} * W^{R,F}{}_{r,f_f} * z_f]}$$

RCI *= Resource Circularity Indicator (absorbed circularity) of the product in the lifecycle*

$$\mathbf{RCI = \sum_{r=1}^{R} [(RCI_r * W^{R}{}_r) * 100]}$$

4.4.1. Creation of the Circularity Product Indicator (CPI)

This calculation step allows to create the CPI on an objective basis and not constrained by weighing systems for the indicators related to energy, materials and other resources (being percentage values, ECI, MCI and RCI cannot be added, since there is the risk that CPI exceeds 100%, or multiplied, since it is enough that one of the 3 is null and void CPI, in both cases CPI would lose its meaning).

The CPI indicator can be between 0 and 1 (percentage value) and must be zero if ECI, MCI and RCI are simultaneously null (no type of circularity in the system) and one in case the value of ECI, MCI and RCI is at the same time one (totally circular system). And at the same time we must consider ECI, MCI and RCI equally important.

Considering the problem from a geometrical point of view, it is possible to consider ECI, MCI and RCI as three independent variables in a three-dimensional space ("equally important "). With this in mind, we can therefore consider the "total circularity of the system" as a sphere centred in the origin of ECI, MCI and RCI axes.

K is therefore defined as the radius of the sphere centred in the origin of the axes ECI, MCI and RCI:

$$\mathbf{K^2 = ECI^2 + MCI^2 + RCI^2}$$

And so:

$$\mathbf{K = \sqrt{ECI^2 + MCI^2 + RCI^2}}$$

If we consider the maximum radius of the sphere (always centred in the origin) in which ECI = 100%, MCI = 100% and RCI = 100%, this will have K = Kmax = $\sqrt{\mathbf{3}}$**.**

And so:

CPI: Circularity Product Indicator

$$\mathbf{CPI} = \frac{\mathbf{K}}{\sqrt{\mathbf{3}}} = \frac{\sqrt{\mathbf{ECI^2 + MCI^2 + RCI^2}}}{\sqrt{\mathbf{3}}} * \mathbf{100}$$

0 ≤ CPI ≤ 1

In this way, the ratio between the calculated sphere and the maximum sphere, will be a number that expresses the value of ECI, MCI and RCI with respect to their maximum value, i.e. a CPI on a percentage scale.

4.4.2. Circularity yield vector creation

The components of this vector try to express a very important type of information for the product system circularity analysis. This is the quantification of the generated circularity (therefore 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). In fact, although we tried to create a circularity indicator (CPI) that is as complete as possible, it fails to take into account how much a system can make available flows of reusable resources, compared to those who have received in input. This is due to the difficulty in allocating circular flows, which in many cases involve different phases of the system or different systems. If we think, for example, the generated circularities by a system for other systems, these flows are not counted in the CPI, since they do not interact within the system, while still represents a very important resource for determining the overall circularity degree. Two products with the same CPI but with different returns, represent two very different situations.

- Creation of the η_{EC} indicator regarding the generated energy circularity performance compared to those absorbed

The energy circularity performance quantifies the generated circular energy flows (i.e. electrical or thermal energy made available for the same system or for other systems) with respect to those absorbed. Unlike the energy circularity in input that are related to the use of renewable sources or the recovery of thermal energy, the evaluation of those in output to the system is based on kwh obtained from the energy recovery of resources discarded by the system. We remember that:

- $\mathbf{MFC\_out^{en\_rec}_{m,\ p}}$: Mass of m-th material discarded by the phase p and sent to energy recovery
- $\mathbf{RFC\_out^{en\_rec}_{r,\ p}}$: Mass of r-th resource rejected by the phase p and send to energy recovery

If (p=eol), then:

$\mathbf{MFC\_out^{en\_rec}_{m,\ p} = MFC\_out^{en\_rec}_{m,\ eol}}$ **e** $\mathbf{RFC\_out^{en\_rec}_{r,\ p} = RFC\_out^{en\_rec}_{r,\ eol}}$ **:** Mass of m-th material (or r-th resource) discarded by the eol phase and sent to energy recovery. This mass is part of the finished product and the phase is the final one of the lifecycle; this is why the distinction is made by the nomenclature, but the logic is the same.

If ($p=f_f$), then:

$\mathbf{MFC\_out^{en\_rec}_{m,\ p} = MFC\_out^{en\_rec}_{m,\ ff}}$ **e** $\mathbf{RFC\_out^{en\_rec}_{r,\ p} = RFC\_out^{en\_rec}_{r,\ ff}}$ **:** Mass of m-th material (or r-th resource) discarded by the maintenance activity f_f and sent to energy recovery.

$\mathbf{LHV_m}$ = Lower heating value of the m-th material that is sent to energy recovery

$\mathbf{LHV_r}$ = Lower heating value of the r-th resource that is sent to energy recovery

η $^{en\_rec}{}_{m}$ = Yield of the energy recovery process where the m-th material is used (e.g. efficiency of the incinerator combustion process)

η $^{en\_rec}{}_{r}$ = Yield of the energy recovery process where the r-th resource is used (for example, yield of the anaerobic digestion plant to which a biodegradable resource is destined)

E_rec ^{M} *= Energy Circularity Generated by discarded materials sent to energy recovery throughout the life cycle*

$$\mathbf{E\_rec}^{\mathbf{M}} = \left\{ \left[\sum_{\mathbf{p=1}}^{\mathbf{P}} \sum_{\mathbf{m=1}}^{\mathbf{M}} \left(\mathbf{MFC\_out}^{\mathbf{en\_rec}}{}_{\mathbf{m,p}} * \mathbf{LHV_m} * \boldsymbol{\eta}^{\mathbf{en\_rec}}{}_{\mathbf{m}} \right) \right] + \left[\sum_{\mathbf{m=1}}^{\mathbf{M}} \left(\mathbf{MFC\_out}^{\mathbf{en\_rec}}{}_{\mathbf{m,eol}} * \mathbf{LHV_m} * \boldsymbol{\eta}^{\mathbf{en\_rec}}{}_{\mathbf{m}} \right) \right] \right\}$$

E_rec_max ^{M} *= Maximum Energy Circularity potentially generable from the discarded materials and sent to energy recovery throughout the life cycle. It is calculated as the conversion with unit yields of all the outputs of each phase p. It is as if all outgoing flows, excluding WIPs, were sent for energy recovery*

$$\mathbf{E\_rec\_max}^{\mathbf{M}} = \left\{ \left[\sum_{\mathbf{p=1}}^{\mathbf{P}} \sum_{\mathbf{m=1}}^{\mathbf{M}} \left(\mathbf{MF\_out}_{\mathbf{m,p}} * \mathbf{LHV_m} \right) \right] + \left[\sum_{\mathbf{m=1}}^{\mathbf{M}} \left(\mathbf{MF\_FP}_{\mathbf{m,eol}} * \mathbf{LHV_m} \right) \right] \right\}$$

E_rec ^{R} *= Energy Circularity Generated by other resources discarded and sent to energy recovery throughout the life cycle*

$$\mathbf{E\_rec}^{\mathbf{R}} = \left\{ \left[\sum_{\mathbf{p=1}}^{\mathbf{P}} \sum_{\mathbf{r=1}}^{\mathbf{R}} \left(\mathbf{RFC\_out}^{\mathbf{en\_rec}}{}_{\mathbf{r,p}} * \mathbf{LHV_r} * \boldsymbol{\eta}^{\mathbf{en\_rec}}{}_{\mathbf{r}} \right) \right] + \left[\sum_{\mathbf{r=1}}^{\mathbf{R}} \left(\mathbf{RFC\_out}^{\mathbf{en\_rec}}{}_{\mathbf{r,eol}} * \mathbf{LHV_r} * \boldsymbol{\eta}^{\mathbf{en\_rec}}{}_{\mathbf{r}} \right) \right] \right\}$$

E_rec_max ^{R} *= Maximum Energy Circularity potentially generable by other resources discarded and sent to energy recovery throughout the life cycle. It is calculated as the conversion with unit yields of all the outputs of each phase p*

$$\mathbf{E\_rec\_max}^{\mathbf{R}} = \left\{ \left[\sum_{p=1}^{P} \sum_{r=1}^{R} \left(\mathbf{RF\_out}_{\mathbf{r,p}} * \mathbf{LHV_r} \right) \right] + \left[\sum_{r=1}^{R} \left(\mathbf{RF\_FP}_{\mathbf{r,eol}} * \mathbf{LHV_r} \right) \right] \right\}$$

ECI_out = *Energy Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle*

$$\mathbf{ECI_{out}} = \frac{(\mathbf{E\_rec}^{\mathbf{M}} + \mathbf{E\_rec}^{\mathbf{R}})}{(\mathbf{E\_rec\_max}^{\mathbf{M}} + \mathbf{E\_rec\_max}^{\mathbf{R}})}$$

If ECI ≠ 0, then it is possible to calculate:

η_{EC} = *Energy Circularity Yield of the system*

$$\eta_{\mathbf{EC}} = \frac{\mathbf{ECI\_out}}{\mathbf{ECI}}$$

- Creation of the η_{MC} indicator regarding the generated material circularity performance compared to those absorbed

For materials that have a possible destiny in other systems, after being used for the creation of the product, we define:

- t m: regards non-virgin materials and represents the number of times the m-th material has been used (therefore the life cycle analyzed for the calculation of the CPI represents the t-th use of the m-th material)

- Tm_max: regards non-virgin materials and represents the maximum number of times the m-th material can be used (this value is equal to the "k + 1" present in the calculation of the substitution ratios)

So it’s possible to assign a "temporal weight" to the m-th material destined for recycling (or re-use) in other systems: **$W^{T}_{m} = (T_{m\_max} - t_{m}) / T_{m\_max}$**

The higher this ratio, the greater the number of potential uses of the m-th material in other product systems or in the same system, as a result of the t-th use that made the system under analysis. For materials flows that go to energy recovery, which go to landfill or that are not recovered in any way as materials, we assume $W^{T}_{m} = 1$. This because these flows do not contribute to the calculation of MCI_out, since there are no further uses for them in the system or in other systems.

$MFC\_out^{OS}_{m,p}$: Mass of m-th material discarded by phase p and used in other systems

MFC_out ^{SS} $_{m, p}$: Mass of m-th material discarded from phase p and reused in the same system (in phase p or in other phases)

MFC_out $^{en\_rec}$ $_{m, p}$: Mass of m-th material discarded from phase p and sent to energy recovery

MFC_out ^{OS} $_{m, eol}$: Mass of m-th material discarded from the EOL and reused in other systems (i.e. after the product use phase)

MFC_out ^{SS} $_{m, eol}$: Mass of m-th material discarded from the EOL and reused in the same system, so after the use phase of the product (in phase p or in other phases)

MFC_out $^{en\_rec}$ $_{m, eol}$: Mass of m-th material discarded by the EOL and sent to energy recovery (hence after the product use phase)

MFC_out $_{m, eol}$: Mass of m-th material discarded from the EOL and reused in the same system or outside it

MC_out ^{OS} $_{m, p}$ *= Generated Circularity of the m-th material of the product in the phase p for other systems*

$$\mathbf{MC\_out^{OS}}_{\mathbf{m,p}} = \frac{\mathbf{MFC\_out^{OS}}_{\mathbf{m,p}}}{\mathbf{MF\_out}_{\mathbf{m,p}}}$$

MC_out ^{SS} $_{m, p}$ *= Generated Circularity of the m-th material of the product in the phase p for the same system*

$$\mathbf{MC\_out^{SS}}_{\mathbf{m,p}} = \frac{\mathbf{MFC\_out^{SS}}_{\mathbf{m,p}}}{\mathbf{MF\_out}_{\mathbf{m,p}}}$$

MC_out ^{OS} $_{m}$ *= Generated Circularity of the m-th material of the product within the life cycle for other systems*

$$\mathbf{MC\_out^{OS}}_{\mathbf{m}} = \sum_{\mathbf{p=1}}^{\mathbf{P}} [\mathbf{MC\_out^{OS}}_{\mathbf{m,p}} * \frac{\mathbf{MF\_out}_{\mathbf{m,p}}}{\mathbf{MF\_out}_{\mathbf{m}}} * \frac{\mathbf{MF\_out}_{\mathbf{m}}}{\mathbf{MF\_out}_{\mathbf{m}} + \mathbf{MF\_FP}_{\mathbf{m}}}] + [\frac{\mathbf{MFC\_out^{OS}}_{\mathbf{m,eol}}}{\mathbf{MF\_FP}_{\mathbf{m}}} * \frac{\mathbf{MF\_FP}_{\mathbf{m}}}{\mathbf{MF\_out}_{\mathbf{m}} + \mathbf{MF\_FP}_{\mathbf{m}}}]$$

And, simplifying, we find:

$$\mathbf{MC\_out^{OS}}_{\mathbf{m}} = \sum_{p=1}^{P} \left[\frac{\mathbf{MFC_{out}}^{\mathbf{OS}}{}_{\mathbf{m,p}}}{\mathbf{MF\_out}_{\mathbf{m}} + \mathbf{MF_{FP}}_{\mathbf{m}}} \right] + [\frac{\mathbf{MFC\_out^{OS}}_{\mathbf{m,eol}}}{\mathbf{MF\_out}_{\mathbf{m}} + \mathbf{MF\_FP}_{\mathbf{m}}}]$$

MC_out $^{SS}{}_{m}$ = *Generated Circularity of the m-th material of the product within the life cycle for the same systems*

$$MC\_out^{SS}{}_{m} = \sum_{p=1}^{P}[MC\_out^{SS}{}_{m,p} * \frac{MF\_out_{m,p}}{MF\_out_{m}} * \frac{MF\_out_{m}}{MF\_out_{m} + MF\_FP_{m}}] + [\frac{MFC\_out^{SS}{}_{m,eol}}{MF\_FP_{m}} * \frac{MF\_FP_{m}}{MF\_out_{m} + MF\_FP_{m}}]$$

And, simplifying, we find:

$$MC\_out^{SS}{}_{m} = \sum_{p=1}^{P}\left[\frac{MFC_{out}{}^{SS}{}_{m,p}}{MF\_out_{m} + MF\_FP_{m}}\right] + [\frac{MFC\_out^{SS}{}_{m,eol}}{MF\_out_{m} + MF\_FP_{m}}]$$

MCI_out ^{OS} = *Material Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle for other systems*

$$MCI\_out^{OS} = \sum_{m=1}^{M}\left(MC\_out^{OS}{}_{m} * W^{M}{}_{m} * IRC_{m}\right) * 100 * W^{T}{}_{m}$$

MCI_out ^{SS} = *Material Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle for the same system*

$$MCI\_out^{SS} = \sum_{m=1}^{M}\left(MC\_out^{SS}{}_{m} * W^{M}{}_{m} * IRC_{m}\right) * 100$$

MCI_out = *Material Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle*

$$MCI\_out = MCI\_out^{OS} + MCI\_out^{SS}$$

If MCI ≠ 0, then it is possible to calculate:

η_{MC} = *Material Circularity Yield of the system*

$$\eta_{MC} = \frac{\text{MCI\_out}}{\text{MCI}}$$

- Creation of the η_{RC} indicator regarding the generated other resources circularity performance compared to those absorbed

Similarly, the calculation of the circularity yield for the other resources is proposed below.

For the other resources that have a possible destiny in other systems, after being used for the creation of the product, we define:

- t_r: regards non-virgin other resources and represents the number of times the r-th resource has been used (therefore the life cycle analysed for the calculation of the CPI represents the t-th use of the r-th resource)

- T_{r_max}: regards non-virgin other resource and represents the maximum number of times the r-th resource can be used (this value is equal to the "k + 1" present in the calculation of the substitution ratios)

So it's possible to assign a "temporal weight" to the r-th resource destined for recycling (or re-use) in other systems: $\mathbf{W^T_r = (T_{r\_max} - t_r) / T_{r\_max}}$

The higher this ratio, the greater the number of potential uses of the r-th resource in other product systems or in the same system, as a result of the t-th use that made the system under analysis. For other resource flows that go to energy recovery, which go to landfill or that are not recovered in any way the product, we assume $W^T_r = 1$. This because these flows do not contribute to the calculation of RCI_out, since there are no further uses for them in the system or in other systems.

$RFC\_out^{OS}_{r,p}$: Mass of r-th resource discarded by phase p and used in other systems

$RFC\_out^{SS}_{r,p}$: Mass of r-th resource discarded from phase p and reused in the same system (in phase p or in other phases)

$RFC\_out^{en\_rec}_{r,p}$: Mass of r-th resource discarded from phase p and sent to energy recovery

$RFC\_out^{OS}_{r,eol}$: Mass of r-th resource discarded from the EOL and reused in other systems (i.e. after the product use phase)

$RFC\_out^{SS}_{r,eol}$: Mass of r-th resource discarded from the EOL and reused in the same system, so after the use phase of the product (in phase p or in other phases)

$RFC\_out^{en\_rec}_{r,eol}$: Mass of r-th resource discarded by the EOL and sent to energy recovery (hence after the product use phase)

$RFC\_out_{r,eol}$: Mass of r-th resource discarded from the EOL and reused in the same system or outside it

$RC\_out^{OS}_{r,p}$ *= Generated Circularity of the r-th resource of the product in the phase p for other systems*

$$\mathbf{RC\_out^{OS}}_{\mathbf{r,p}} = \frac{\mathbf{RFC\_out^{OS}}_{\mathbf{r,p}}}{\mathbf{RF\_out_{r,p}}}$$

RC_out ss r, p *= Generated Circularity of the r-th resource of the product in the phase p for the same system*

$$\mathbf{RC\_out^{SS}}_{\mathbf{r,p}} = \frac{\mathbf{RFC\_out^{SS}}_{\mathbf{r,p}}}{\mathbf{RF\_out_{r,p}}}$$

RC_out os r *= Generated Circularity of the r-th resource of the product within the life cycle for other systems*

$$\mathbf{RC\_out^{OS}}_{\mathbf{r}} = \sum_{\mathbf{p=1}}^{\mathbf{P}} [\mathbf{RC\_out^{OS}}_{\mathbf{r,p}} * \frac{\mathbf{RF\_out_{r,p}}}{\mathbf{RF\_out_r}} * \frac{\mathbf{RF\_out_r}}{\mathbf{RF\_out_r + RF\_FP_r}}] + [\frac{\mathbf{RFC\_out^{OS}}_{\mathbf{r,eol}}}{\mathbf{RF\_FP_r}} * \frac{\mathbf{RF\_FP_m}}{\mathbf{RF\_out_r + RF\_FP_r}}]$$

And, simplifying, we find:

$$\mathbf{RC\_out^{OS}}_{\mathbf{r}} = \sum_{p=1}^{P} \left[\frac{\mathbf{RFC\_out^{OS}}_{\mathbf{r,p}}}{\mathbf{RF\_out_r + MF\_FP_r}}\right] + [\frac{\mathbf{RFC\_out^{OS}}_{\mathbf{r,eol}}}{\mathbf{RF\_out_r + RF\_FP_r}}]$$

RC_out ss r *= Generated Circularity of the r-th resource of the product within the life cycle for the same systems*

$$\mathbf{RC\_out^{SS}}_{\mathbf{r}} = \sum_{\mathbf{p=1}}^{\mathbf{P}} [\mathbf{RC\_out^{SS}}_{\mathbf{r,p}} * \frac{\mathbf{RF\_out_{r,p}}}{\mathbf{RF\_out_r}} * \frac{\mathbf{RF\_out_r}}{\mathbf{RF\_out_r + RF\_FP_r}}] + [\frac{\mathbf{RFC\_out^{SS}}_{\mathbf{r,eol}}}{\mathbf{RF\_FP_r}} * \frac{\mathbf{RF\_FP_r}}{\mathbf{RF\_out_r + RF\_FP_r}}]$$

And, simplifying, we find:

$$\mathbf{RC\_out^{OS}}_{\mathbf{r}} = \sum_{p=1}^{P} \left[\frac{\mathbf{RFC_{out}}^{\mathbf{SS}}{}_{\mathbf{r,p}}}{\mathbf{RF\_out_r + RF\_out_r}}\right] + [\frac{\mathbf{RFC\_out^{SS}}_{\mathbf{r,eol}}}{\mathbf{RF\_out_r + RF\_FP_r}}]$$

RCI_out os = *Resource Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle for other systems*

$$\mathbf{RCI\_out^{OS}} = \sum_{\mathbf{r=1}}^{\mathbf{R}} \left(\mathbf{RC\_out^{OS}}_{\mathbf{r}} * \mathbf{W^{R}}_{\mathbf{r}}\right) * \mathbf{100} * \mathbf{W^{T}}_{\mathbf{r}}$$

RCI_out ^{SS} = *Resource Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle for the same system*

$$\mathbf{RCI\_out^{SS}} = \sum_{\mathbf{r=1}}^{\mathbf{R}} \left(\mathbf{RC\_out^{SS}}_{\mathbf{r}} * \mathbf{W^{R}}_{\mathbf{r}}\right) * \mathbf{100}$$

RCI_out = *Resource Circularity Indicator regarding the circularity generated by the product throughout the entire life cycle*

$$\mathbf{RCI\_out} = \mathbf{RCI\_out^{OS}} + \mathbf{RCI\_out^{SS}}$$

If RCI ≠ 0, then it is possible to calculate:

η_{RC} = *Resource Circularity Yield of the system*

$$\boldsymbol{\eta}_{\mathbf{RC}} = \frac{\mathbf{RCI\_out}}{\mathbf{RCI}}$$

4.4.3. Calculation of the circularity function

The indicators obtained through the application of the methodology can finally be used together to construct a circularity function Φ, so that the state of the system is evaluated both considering the circularity quantity in input (CPI) and considering the capacity of generate circularity in output (yield vector).

- Calculate the yield vector length:

$$\boldsymbol{\eta}_{\mathbf{C}} = \sqrt{\boldsymbol{\eta}_{\mathbf{EC}}{}^{2} + \boldsymbol{\eta}_{\mathbf{MC}}{}^{2} + \boldsymbol{\eta}_{\mathbf{RC}}{}^{2}}$$

- Calculate the circularity function utilizing CPI and η_C as variables:

$$\boldsymbol{\Phi} = \{[\boldsymbol{\pi} * \mathbf{CPI^{2}}] * (\mathbf{1} + \boldsymbol{\eta}_{\mathbf{C}})\}$$

The CPI has been calculated as the ratio of the radius of the sphere that has the variables ECI, MCI and RCI and the radius of the sphere that has the three maximum indicators. Let's consider now this (the CPI) as the radius of the base circumference of the cylinder whose height is (1 + η_C). In this way the circularity function is equal to the volume of this cylinder. The degree of circularity of the system is given by the CPI, but the higher the yield, the more the circularity function will grow (the increase of 1 to the yield is necessary to protect itself from the case in which it was zero or less than 0, so not to lower the CPI value).

1) If the CPI = 0, then the η_C does not exist (since it is not possible to calculate it because the denominators of the three yields are simultaneously null and therefore the existence conditions fall). So, if both CPI and η_C are null, then there will no circular flows in the analysed system and therefore:

$$\mathbf{\Phi = 0}$$

2) If CPI ≠ 0 and η_C = 0, the circularity function will be equal to the base area of the cylinder and will be proportional only to the CPI:

$$\mathbf{\Phi} = \{[\boldsymbol{\pi} * \mathbf{CPI^2}]\}$$

3) If CPI ≠ 0 and η_C ≠ 0, the circularity function will be equal to the cylinder volume and it will be increasing more CPI and η_C increase:

$$\mathbf{\Phi} = \{[\boldsymbol{\pi} * \mathbf{CPI^2}] * (\mathbf{1} + \boldsymbol{\eta}_\mathbf{C})\}$$

Furthermore, in this way the CPI has a higher weight compared to the yield, coherently with the importance that has been given to the two indicators.

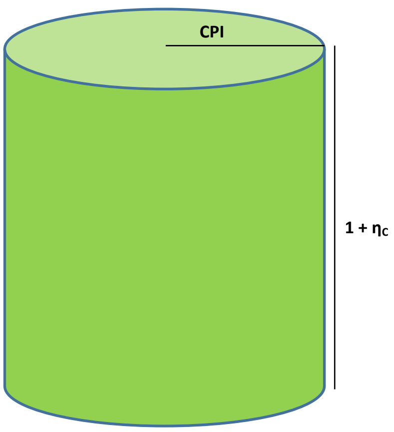


Figure 17: Circularity function representation

5. CONCLUSIONS

Starting from the literature review carried out, it's clear that the strong tendency of CEPA methodologies to focus on the environmental point of view led the authors to shift their attention on the variables involved in circular systems considered, by differentiating among energy, material and pollution, or a combination of them. Also in this case, there is a strong focus on only one element, i.e. material. This confirms the importance of such variables in the circularity performance context, since a continuous flow of technical and biological materials through the 'value circle' is considered in CE (The Ellen MacArthur Foundation, 2015). Only 2 out of 53 contributions divert the focus on energy and pollution (3,8%). All the other articles involve material in their evaluation, either alone (28,3%) or combined to energy and pollution (67,9%).

With this in mind, the variables that deserve more attention in the system analysis when circularity has to be evaluated have been defined. In this deliverable a quantitative analysis model has been proposed with the aim to keep the product as the protagonist of the analysis in terms of Circular Economy and to calculate the circularity degrees.

The Circular Economy Performance Assessment (CEPA) Methodology is composed by three different sub-methodologies that are related to three different field of analysis: (i) the Circular Product Assessment (CPA), (ii) the Circular Cost Assessment (CCA) and (iii) the Circular Environmental Assessment (CEA). The first methodology, particularly focusing on the circularity degree, has been presented in detail in this deliverable, while the second and third methodologies, dealing respectively with economic and environmental aspects, have been only mentioned in a qualitative manner in section 3, because of reasons of length. Based on this, we have to highlight that a further effort needs still to be done to be able to study also the social impact of the analysed systems.

In particular, through the CPA methodology it's possible to calculate the circular shares of resource flows used during the product life cycle, in order to obtain an exhaustive final indicator (KPI) regarding the circular percentage share of the product compared to the total resources used (Circularity Product Indicator, CPI). This methodology has its strength in the product system Eco-Effectiveness evaluation through CPI calculation. Since it's a methodology released from technological peculiarities and resources type used for the creation of a generic product, it's a tool for the comparison of different productive realities and for analyse which are the most virtuous in terms of Circular Economy among them and consequently for the resource flows maximization. This aspect is useful to compare the three different Circular Business Models detected in D1.1: 1) recycling, 2) result-oriented PSSs and 3) use-oriented PSSs.

So, the methodology output consists in a set of specific KPIs regarding resources circularity degree present within the product life cycle and the quantification of those that are the economic and environmental benefits of the Circular Economy. It can be used in different fields of application:

- It can represent an objective basis for the creation of a product certification system related to the circularity of resource flows;
- Design of new products considering the circularity as a decision criterion (Design for Circular Economy);
- The methodology indicators allow the comparison between different versions of the product ("what if" analysis) based on their degree of circularity and the benefits they can bring; this applies both to new products and to developments and improvements linked to existing products;
- Internal reporting and benchmarking. Companies would be able to compare different products based on their circularity and on the benefit they can achieve.

Wrapping up, this methodology can support the analysis of a certain system on different levels:

- being applicable to different dimensions of the system (micro, meso and macro),

- focusing on different phases of its lifecycle (BoI, MoL, EoL or entire lifecycle),
- considering at the same time single or multiple variables belonging to it,
- taking either an economic, environmental or resource efficiency perspective.

This flexibility represents of course the main strength of the methodology proposed, also helping users in balancing the effort needed to adopt it, that has not to be neglected, and the degree of focus of the analysis.

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