Chapter 3

Circular Economy Performance Assessment

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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. This chapter focuses on the definition of a novel Circular Economy Performance Assessment (CEPA) methodology to be adopted within the FENIX project. This implementation activity has been done into two steps. From one side, a state-of-the-art analysis of existing CE methodologies and related KPIs has been executed and the most common circularity assessment methods (and KPIs) have been identified. Subsequently, a totally new CEPA methodology has been developed starting from the findings coming from the literature. This methodology, together with classic LCA and LCC methods, will be exploited for the quantitative assessment of CBMs.

3.1 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 summarize the findings coming from an extensive literature review reported in [4], there is a strong orientation of CEPA methodologies on the environmental aspect of the Triple Bottom Line (TBL) of sustainability. Indeed, all the contributions involve the environmental perspective, either alone (37.7%) or combined with the economic one (17%) or embedded in the

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Fig. 3.1 Positioning framework

entire triple perspective (45.3%). This environmental perspective was also differentiated among energy, materials and pollution, or a combination of them. Once again, the focus was on one element (i.e. materials and pollution). 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 [5].

Starting from these categorizations, POLIMI’s team created a framework to position existing methodologies in order to map the existing gaps in literature (see Fig. 3.1). The framework is constituted by three axes: (i) Product Lifecycle Stages, for mapping lifecycle phases considered; (ii) Variables, for mapping the type of variables considered and measured; and (iii) Field of analysis, for mapping the perspective used to analyse variables.

What emerges from the mapping process is the relatively low amount of industries considering benefits related with biological models and resource flows as a source of inspiration for new measures able to reduce environmental impacts and, in parallel, generate economic savings. To this aim, it is necessary to work both at system and single product level (i.e. company level or entire product lifecycle level) at the same time, going into detail at single production phase and single resource flow. For this reason, a quantitative (product-oriented) assessment model has been proposed to calculate the circularity performance.

3.2 The Circular Economy Performance Assessment Methodology

The Circular Economy Performance Assessment (CEPA) methodology proposed by POLIMI is composed by three different sub-methodologies. Each of them is related to three different fields of analysis: (i) a Circularity Product Assessment (CPA), (ii) a Circularity Cost Assessment (CCA) and (iii) a Circularity Environmental Assessment (CEA). The first sub-methodology is presented in this chapter, while the other ones are just mentioned in a qualitative manner.

Firstly, CPA allows to both calculate the circular share of resource flows used during the product life cycle and obtain an exhaustive index (KPI) about the circular percentage share of the product compared to total resources used (Circularity Product Indicator, CPI). Given its dependency on the resources type exploited for the creation of a generic product, this methodology can be exploited to compare different scenarios and assess the most virtuous ones in terms of resource flows maximization. Secondly, CCA allows to analyse and quantify the economic benefits related to CE, always referring to a well-defined product. It can be exploited to both calculate the cost savings generated by the triggering of materials and other resources circularity and evaluate the economic savings related to energy circularity. Finally, CEA allows to evaluate the environmental benefits resulting from the use of a CBM. Here the focus is quantifying 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 characterizing each circular resource flow, in order to be able to calculate the difference with the environmental impacts of the corresponding linear system.

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 economic and environmental benefits related with CE. They can be used in different application fields:

- Creation of certification standards related to resource flows circularity
- Decision-support of new products (e.g. defining Design for CE guidelines)
- Circular scenarios comparison (e.g. based on circularity levels and benefits) of both new and existing products
- Internal reporting and benchmarking.

In general terms, the main principle on which the CEPA methodology developed by POLIMI is based on is the Material Flow Analysis (MFA). MFA is a systematic assessment of stocks and flows of materials within a system defined in space and time. Because of the physical law of conservation of matter, the results of an 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 [1, 2].

3.3 Circularity Product Assessment (CPA) Methodology

The objective of CPA is quantifying the circularity level of each resource involved within a product lifecycle. Given 100% as the input quantity of a given resource “*k*” in a generic product lifecycle phase “*p*”, *X*% of this input will end up in the output of that activity, *Y*% will be discarded and—in case of circularities—*Z*% will be reused either within the same system or in a different one. Therefore, the generic constraint to be considered is:

$$X\% + Y\% + Z\% = 100\% \text{ of resource } k \text{ in phase } p.$$

This calculation process is carried out for all the resources and phases of the analysed system, trying to limit the analysis to the product lifecycle. Unlike the objectives of environmental impact assessment models (e.g. LCA), CPA aims to identify and quantify circularities present in a system. With the term “circularity” we refer to those feedback resource flows (of any kind) falling retroactively in the system (the same or another) (Fig. 3.2).

Fig. 3.2 Flow schematization

3.3.1 CPA Phase 1—Objectives Definition and Settings

CPA methodology is composed by four different phases. Phase 1 identifies the context of analysis. It is very important to understand from the beginning what kind of study must be carried out, as it is associated with both different modelling principles and methodological choices. Regarding the modelling principles to be used, we refer to LCA guidelines [6, 7], given the similarity between phase 1 of the proposed model and that of LCA. The modelling principles are two: (i) the “attributorial” modelling, describing the system in a static way; and (ii) the “consequential” modelling, describing the system as a result of the analysed decisions, then inserting it into a dynamic sphere.

Furthermore, the context of analysis 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 system. Considering LCA guidelines, Phase 1 defines:

- System’s boundaries (the part of lifecycle to be considered)
- Functional units and reference flows (units of measure needed to quantify performances and quantity of product necessary to satisfy the chosen functional unit, respectively)
- Data characteristics (e.g. precision, completeness, representativeness, etc.)
- Allocation procedures and multi-process case resolution (e.g. closed-loop versus open-loop allocations)
- Hypotheses and limitations.

3.3.2 CPA Phase 2—Inventory Analysis and Resource Flows Decomposition

Phase 2 includes the compilation and quantification of inputs and outputs of each phase for a product/functional unit during its lifecycle. Data must be collected for each lifecycle phase included within the system’s boundaries and referred to each functional unit. Coherently with the identified system’s boundaries, the phases analysed will be p (ranging from 1 to P).

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 CE, the repair of a product triggers a retroactive flow in the technical sphere of the system. This allows a saving of resources compared to the case in which a new product was created and in addition allows the extension of the product lifecycle. For this reason, the circularity level is quantified as the ratio between saved resources and those used in case of a new production. Since not all products can be repaired (e.g. fast-moving consumer goods) and repairable ones can have an uncertainty of non-repairability, the maintenance phases present a binary variable that is activated only if needed. Then, another uncertainty to consider is related to the lengthening of the product lifecycle. To

this aim, a coefficient expresses the extension of the lifecycle due to maintenance, compared to the average lifespan of the product itself.

- f [0, 1, ..., F] = number of repairs
- 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)
- $Z_f = \frac{(f+1)\text{-th useful life}}{\text{average useful life}} =$ coefficient expressing the product lifecycle extension thanks to maintenance and repairs. f is the number of times the product is repaired. Consequently, “ $(f+1)$ -th useful life” represents the useful lifespan after the f -th maintenance, so “[$(f+1)$ -th useful life]/(average useful life)” indicates the product lifecycle extension after the f -th maintenance (with respect to its average duration).

After having described all the system phases, the methodology moves on to the inventory phase of all the resources used to create the product: (i) energy flows (electricity and thermal energy); (ii) material flows (materials constituting the product); (iii) complementary resource flows (e.g. water, cooling fluids, chemical additives, consumables, etc.).

These three types of flows will be quantified and allocated in the respective phases, so allowing the subsequent calculation of the different types of circularity. The definition of precise system’s boundaries 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 considered. This logic creates a bridge between the concept of product lifecycle and Industrial Symbiosis (IS). 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 recovery of discarded materials and resources
- Material flows (or other non-virgin resources) in input from other systems
- Material flows (or other non-virgin resources) in input from the same system (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.

3.3.3 CPA Phase 3—Weights and Indexes Calculation

Phase 3 calculates weights and indexes used in CPA. In particular, the focus is on “physical” weight of materials (and other resources) and on weight of each phase in terms of resources used (energy, materials and other resources). Subsequently,

the recyclability characteristics of materials have been considered to calculate their potential reuse. The following weights and indices are proposed:

- W_p^E : energy weight in phase p
- $W_{m,p}^{M,P}$: m-th material weight in phase p
- $W_{r,p}^{R,P}$: r-th resource weight in phase p
- W_m^M : m-th material relative weight
- W_r^R : r-th resource relative weight
- CRI_m : composed recyclability index of the m-th material

W_p^E : Weight of energy consumed in phase p out of the total energy of the system

$$W_p^E = \frac{EE_p + TE_p}{E_{\text{system}}}$$

In case of maintenance phase ($A = 1$; $p = f1 \rightarrow ff$), the energy weight of the generic maintenance phase f will become:

$$W_{f_f}^E = \frac{E_{\text{maint}_f}}{E_{\text{system}}}$$

- EE_p = Kwh of Electricity consumed in phase p
- TE_p = Kwh of Thermal Energy consumed in phase p
- $EE = \sum_{p=1}^P (EE_p)$ = Kwh of Electricity consumed in the lifecycle, including consumption of all recycling activities necessary to recover resources
- $TE = \sum_{p=1}^P (TE_p)$ = Kwh of Thermal Energy consumed in the lifecycle, including the consumption of all recycling activities necessary to recover resources.

Total energy within the lifecycle:

$$E_{\text{system}} = EE + TE + \left(A * \sum_{f=1}^F E_{\text{maint}_f} \right)$$

W_p^E represents the “energy weight of phase p”. This is the amount of energy consumed in phase p out of the total energy consumed within system’s boundaries. The total energy balance (denominator of the formula) is obtained by adding together any type of energy consumption present in the product lifecycle. It refers to its functional unit. In addition to energy consumptions related with production, energy consumptions related to any resource recovery activity are also considered. The amount of energy consumed is subtracted from the amount of energy generated if the product (or part of it) is destined to energy recovery, thus creating an energetic circularity.

$W_{m,p}^{M,P}$: Weight of the m-th input material in phase p out of the total m-th material used in the system

$$W_{m,p}^{M,P} = \frac{MF_in_{m,p}}{MF_in_m + \left(A * \sum_{f=1}^F MF_maint_in_{m,f} \right)}$$

In case of maintenance phase ($A = 1$; $p = f1 \rightarrow ff$), the material weight of the generic maintenance phase f will become:

$$W_{m,f}^{M,F} = \frac{MF_maint_in_{m,f}}{MF_in_m + \left(A * \sum_{f=1}^F MF_maint_in_{m,f} \right)}$$

$W_{r,p}^{R,P}$: Weight of the r -th resource in input in phase p out of the total resources used in the system

$$W_{r,p}^{R,P} = \frac{RF_in_{r,p}}{RF_in_r + \left(A * \sum_{f=1}^F RF_maint_in_{r,f} \right)}$$

In case of maintenance phase ($A = 1$; $p = f1 \rightarrow ff$), the resource weight of the generic maintenance phase f will become:

$$W_{r,f}^{R,F} = \frac{RF_maint_in_{r,f}}{RF_in_r + \left(A * \sum_{f=1}^F RF_maint_in_{r,f} \right)}$$

W_m^M : Weight of materials used in input out of the total input materials used to make the product

$$W_m^M = \frac{MF_in_m + \left(A * \sum_{f=1}^F MF_maint_in_{m,f} \right)}{\sum_{m=1}^M (MF_in_m) + \left(A * \sum_{f=1}^F \sum_{m=1}^M MF_maint_in_{m,f} \right)}$$

MF_in_m : Mass of m -th material in input within the production process.

$[m: \text{from } 1 \text{ to } M \rightarrow \text{materials}]$.

W_m^M represents the “weight of the m -th material” out of the total materials embedded in the product. This is the first weight used for the material’s circularity calculation. It represents a “physical” index since it is a ratio between masses.

W_r^R : Weight of input resources used out of the total input resources

$$W_r^R = \frac{RF_in_r + \left(A * \sum_{f=1}^F RF_maint_in_{r,f} \right)}{\sum_{r=1}^R (RF_in_r) + \left(A * \sum_{f=1}^F \sum_{m=1}^M RF_maint_in_{r,f} \right)}$$

RF_in_r : Mass (or volume) of r -th resource in input within the production process.

$[r: \text{from } 1 \text{ to } R \rightarrow \text{other resources}]$.

W_r^R represents the “weight of the r-th resource” out of the total amount of other resources used to make the product. Constraints dictated by the mass and energy balances impose that $\sum_{p=1}^P$ of both W_p^E , $W_{m,p}^{M,P}$ and $W_{r,p}^{R,P}$ will be equal to 1. For the same reason, also $\sum_{m=1}^M$ of W_m^M and $\sum_{r=1}^R$ of W_r^R will be equal to 1.

In order to calculate material’s recyclability, both physical properties (and their evolution) and economic value of materials must be considered. From one side, the Substitution Rate (R_s) is a good approximation of the physical property evolution of recycled materials compared to the number of reuses [3]. If not available from standard lists, it can be easily calculated for a generic m-th material. From another side, the economic value of materials can be estimated through the Recyclability Index [8]. Here, the quality of the recycled material can offer a good estimate of the final material’s value. The higher the quality, the lower the difference between virgin and secondary materials market values. In order to calculate material’s recyclability (R), the following values must be considered:

- V_m : minimum material value (€/kg) before its processing or forming.
- V_r : material’s residual value (€/kg) after its primary use and before its recycling.
- V_p : material’s post-recycling value (€/kg) before its processing or forming. If a material has both high recyclability and high-quality, V_p will be close to V_m .

Therefore, the Recyclability Index (R) is:

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

If $V_p \ll V_m$, the material is reused, sent to landfill or used for energy recovery. If $V_p \ll V_m$, the recycling process is not economically sustainable.

Starting from the Recycling Index, a binary variable (β) is added to the calculation in order to check the economic sustainability of a recycled material. $\beta = 1$ means that it is economically feasible to use recycled material. Otherwise, $\beta = 0$. However, the economic aspects associated to resource circularity will be considered by the CCA methodology. Once calculated the substitution rate (R_s) and the Recyclability Index (R), it is possible to calculate the Composed Recyclability Index (CRI):

$$CRI = \beta * R_s$$

Even if one between β and R_s is null, CRI is null because for either technical or economic reasons it is not possible (or profitable) to use the recycled material. Although materials have a specific weight, CRI does not consider the danger and toxicity degrees of materials and other resources present in the production process. This calculation will be done by the CEA methodology.

3.3.4 CPA Phase 4—Circularity Indexes Calculation

Phase 4 calculates the circularity indexes for each type of resource. Circular shares are weighted in each system phase and grouped under a single index named Circularity Product Indicator (CPI). Then, circularity yields are calculated both for materials and other resources and their values come from the relationship between “generated” and “absorbed” circularities.

EEC_p: Percentage share of electricity from renewable energies used in phase p out of the total energy consumed in phase p

$$EEC_p = \frac{EE_R_p}{(EE_p + TE_p)}$$

TEC_p: Percentage share of thermal energy from renewable energies or recovered through heat recovery out of the total energy consumed in phase p

$$TEC_p = \frac{TE_R_p}{(EE_p + TE_p)}$$

ECI_p: Energy Circularity Indicator of the product in phase p

$$ECI_p = W_p^E * (EEC_p + TEC_p) * 100$$

EC_{maint_f}: Energy Maintenance Circularity of the f-th maintenance

$$EC_{maint_f} = \frac{E_{saved_f}}{E_{system}} = \left\{ 1 - \left[\frac{E_{maint_f}}{E_{system}} \right] \right\} * 100$$

E_{saved_f}: Total kWh saved doing the f-th maintenance, compared to a new product cycle.

$$E_{saved_f} = (E_{system}) - E_{maint_f}$$

ECI: Overall Energy Circularity Indicator

$$ECI = \sum_{p=1}^P (ECI_p) + A * \sum_{f=1}^F (EC_{maint_f} * W_f^E * z_f)$$

MCI_{m,p} = Material Circularity Indicator (absorbed circularity) of the m-th material in phase p.

$$MCI_{m,p} = \frac{(MFC_{in_{m,p}}^{short} + MFC_{in_{m,p}}^{long} + MFC_{in_{m,p}}^{eol} + MFC_{in_{m,p}}^{OS})}{MF_{in_{m,p}}}$$

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

$$MC_maint_{m,f} = \left[1 - \frac{MF_maint_in_{m,f}}{MF_in_m} \right]$$

This way, savings coincide with masses of the m-th material not used to repair the product, but to build a new one. $MF_maint_in_{m,f}$ is the mass of m-th material in input in the maintenance phase f. It is the mass used for making the spare part or for direct repair.

MCI_m = Material Circularity Indicator (absorbed circularity) of the m-th material

$$MCI_m = \sum_{p=1}^P \left[MCI_{m,p} * W_{m,p}^{M,P} \right] + A * \sum_{f=1}^F \left[MC_maint_{m,f} * W_{m,f}^{M,F} * Z_f \right]$$

MCI = Overall Material Circularity Indicator (absorbed circularity)

$$MCI = \sum_{m=1}^M \left[(MCI_m * W_m^M * CRI_m) * 100 \right]$$

$RCI_{r,p}$ = Resource Circularity Indicator (absorbed circularity) of the r-th resource in phase p

$$RCI_{r,p} = \frac{\left(RFC_in_{r,p}^{short} + RFC_in_{r,p}^{long} + RFC_in_{r,p}^{eol} + RFC_in_{r,p}^{OS} \right)}{RF_in_{r,p}}$$

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

$$RC_maint_{r,f} = \left[1 - \frac{RF_maint_in_{r,f}}{RF_in_r} \right]$$

This way, savings coincide with masses (or volume) of the r-th resource not used to repair the product, but to build a new one. $RF_maint_in_{r,f}$ is the mass (or volume) of r-th resource in input in the maintenance phase f.

RCI_r = Resource Circularity Indicator (absorbed circularity) of the r-th resource

$$RCI_r = \sum_{p=1}^P \left[RCI_{r,p} * W_{r,p}^{R,P} \right] + A * \sum_{f=1}^F \left[RC_maint_{r,f} * W_{r,f}^{R,F} * Z_f \right]$$

RCI = Overall Resource Circularity Indicator (absorbed circularity)

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

CPI can have values between 0 and 1 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).

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”). We can, therefore, consider the “total circularity of the system” as a sphere centred in the origin of ECI, MCI and RCI axes, with a radius K:

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

If we consider the maximum radius of the sphere ($K_{\max} = \sqrt{3}$), CPI will be:

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

$$0 \leq CPI \leq 1.$$

CPI quantifies the generated circularity (i.e. resources available for the same system or others) less the absorbed one (i.e. received from the same system or from others). In order to make CPI as complete as possible, we need to consider how much a system can generate flows of reusable resources, compared to those received in input. They are measured through a set of circularity performance indexes (e.g. η_{EC} = energy circularity performance, η_{MC} = material circularity yield, η_{RC} = resource circularity yield).

η_{EC} quantifies the generated circular energy flows compared with the absorbed one. Considering that:

- $MFC_out_{m,p}^{en_rec}$: Mass of m-th material discarded by phase p and sent to energy recovery
- $RFC_out_{r,p}^{en_rec}$: Mass of r-th resource rejected by phase p and sent to energy recovery

If ($p = EoL$), then:

$MFC_out_{m,p}^{en_rec} = MFC_out_{m,eol}^{en_rec}$ e $RFC_out_{r,p}^{en_rec} = RFC_out_{r,eol}^{en_rec}$: Mass of m-th material (or r-th resource) discarded by EoL phase and sent to energy recovery. This mass is part of the finished product at EoL phase.

If ($p = f_f$), then:

$MFC_out_{m,p}^{en_rec} = MFC_out_{m,ff}^{en_rec}$ e $RFC_out_{r,p}^{en_rec} = RFC_out_{r,ff}^{en_rec}$: Mass of m-th material (or r-th resource) discarded by maintenance activity f_f and sent to energy recovery.

LHV_m = Lower heating value of the m-th material sent to energy recovery.

LHV_r = Lower heating value of the r-th resource sent to energy recovery.

$\eta_m^{en_rec}$ = Energy recovery process yield, where m-th material is used.

$\eta_r^{en_rec}$ = Energy recovery process yield where r-th resource is used.

E_rec^M = Energy circularity generated by discarded materials sent to energy recovery

$$E_rec^M = \left\{ \left[\sum_{p=1}^P \sum_{m=1}^M \left(MFC_out_{m,p}^{en_rec} * LHV_m * h_m^{en_rec} \right) \right] + \left[\sum_{m=1}^M \left(MFC_out_{m,eol}^{en_rec} * LHV_m * h_m^{en_rec} \right) \right] \right\}$$

$E_rec_max^M$ = Maximum energy circularity, potentially generable from discarded materials sent to energy recovery

$$E_rec_max^M = \left\{ \left[\sum_{p=1}^P \sum_{m=1}^M \left(MF_out_{m,p} * LHV_m \right) \right] + \left[\sum_{m=1}^M \left(MF_FP_{m,eol} * LHV_m \right) \right] \right\}$$

E_rec^R = Energy circularity generated by other resources discarded and sent to energy recovery

$$E_rec^R = \left\{ \left[\sum_{p=1}^P \sum_{r=1}^R \left(RFC_out_{r,p}^{en_rec} * LHV_r * h_r^{en_rec} \right) \right] + \left[\sum_{r=1}^R \left(RFC_out_{r,eol}^{en_rec} * LHV_r * h_r^{en_rec} \right) \right] \right\}$$

$E_rec_max^R$ = Maximum energy circularity, potentially generable by other resources discarded and sent to energy recovery

$$E_rec_max^R = \left\{ \left[\sum_{p=1}^P \sum_{r=1}^R \left(RF_out_{r,p} * LHV_r \right) \right] + \left[\sum_{r=1}^R \left(RF_FP_{r,eol} * LHV_r \right) \right] \right\}$$

ECI_out = Energy Circularity Indicator regarding circularities generated

$$ECI_out = \frac{(E_rec^M + E_rec^R)}{(E_rec_max^M + E_rec_max^R)}$$

If $ECI \neq 0$ it is possible to calculate:

η_{EC} = Energy Circularity Yield of the system

$$\eta_{EC} = \frac{ECI_{out}}{ECI}$$

η_{MC} considers the generated material circularity performance compared to the absorbed one. For materials going in other systems, after being used for making the product, we need to consider:

- t_m : number of times the m-th material has been used
- T_{m_max} : maximum number of times the m-th material can be used

These measures allow to assign a “temporal weight” to the m-th material destined for recycling (or re-use) in other systems: $W_m^T = (T_{m_max} - t_m)/T_{m_max}$.

The higher this ratio is, the greater the number of potential reuse cycles of the m-th material in other systems (or in the same system). For materials flows going to energy recovery or to landfill $W_m^T = 1$.

$MFC_out_{m,p}^{OS}$: Mass of m-th material discarded by phase p and used in other systems.

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

$MFC_out_{m,p}^{en_rec}$: Mass of m-th material discarded from phase p and sent to energy recovery.

$MFC_out_{m,eol}^{OS}$: Mass of m-th material discarded from the EoL and reused in other systems.

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

$MFC_out_{m,eol}^{en_rec}$: Mass of m-th material discarded by the EoL and sent to energy recovery.

$MFC_out_{m,eol}$: Mass of m-th material discarded from the EoL and reused in the same system or outside it.

$MC_out_{m,p}^{OS}$ = Generated circularity of the m-th material in phase p for other systems

$$MC_out_{m,p}^{OS} = \frac{MFC_out_{m,p}^{OS}}{MF_out_{m,p}}$$

$MC_out_{m,p}^{SS}$ = Generated circularity of the m-th material in phase p for the same system

$$MC_out_{m,p}^{SS} = \frac{MFC_out_{m,p}^{SS}}{MF_out_{m,p}}$$

$MC_out_m^{OS}$ = Generated circularity of the m-th material for other systems

$$MC_out_m^{OS} = \sum_{p=1}^P \left[\frac{MFC_{out\ m,p}^{OS}}{MF_out_m + MF_{FPm}} \right] + \left[\frac{MFC_out_{m,eol}^{OS}}{MF_out_m + MF_{FPm}} \right]$$

$MC_out_m^{SS}$ = Generated circularity of the m-th material for the same systems

$$MC_out_m^{SS} = \sum_{p=1}^P \left[\frac{MFC_{out\ m,p}^{SS}}{MF_out_m + MF_{FPm}} \right] + \left[\frac{MFC_out_{m,eol}^{SS}}{MF_out_m + MF_{FPm}} \right]$$

MCI_out^{OS} = Material Circularity Indicator regarding the circularity generated by the product for other systems

$$MCI_out^{OS} = \sum_{m=1}^M (MC_out_m^{OS} * W_m^M * IRC_m) * 100 * W_m^T$$

MCI_out^{SS} = Material Circularity Indicator regarding the circularity generated by the product for the same system

$$MCI_out^{SS} = \sum_{m=1}^M (MC_out_m^{SS} * W_m^M * IRC_m) * 100$$

MCI_out = Material Circularity Indicator regarding the circularity generated by the product

$$MCI_out = MCI_out^{OS} + MCI_out^{SS}$$

If $MCI \neq 0$ it is possible to calculate:

η_{MC} = Material Circularity Yield of the system

$$\eta_{MC} = \frac{MCI_out}{MCI}$$

η_{RC} quantifies the circularity performance generated by other resources compared to absorbed ones. η_{RC} calculation follows the same structure presented for η_{MC} calculation.

η_{RC} = Resource Circularity Yield of the system

$$\eta_{RC} = \frac{RCI_out}{RCI}$$

Finally, all these indexes can be used to construct a circularity function (Φ). This way, the state of the system is evaluated both considering the circularity quantity in input (CPI) and the capacity of generating circularity in output (yield vector). The yield vector length is calculated as follows:

$$\eta_C = \sqrt{\eta_{EC}^2 + \eta_{MC}^2 + \eta_{RC}^2}$$

Subsequently, the circularity function is calculated as follows:

$$\phi = \{[\phi * CPI^2] * (1 + \eta_C)\}$$

Considering CPI as the radius of the base circumference of a cylinder whose height is $(1 + \eta_C)$, the circularity function is equal to the volume of this cylinder. The circularity level of the system is given by CPI, but the higher the yield, the more the circularity function will grow:

- If $CPI = 0$, η_C does not exist So, $\phi = 0$
- If $CPI \neq 0$ and $\eta_C = 0$, $\phi = \{[\pi * CPI^2]\}$
- If $CPI \neq 0$ and $\eta_C \neq 0$, $\phi = \{[\pi * CPI^2] * (1 + \eta_C)\}$.

3.4 Conclusions

This chapter described a quantitative analysis model focusing on the product and calculating its circularity level. The proposed CEPA methodology is composed by three different sub-methodologies (CPA, CCA and CEA). The first one has been presented in detail, while the others have been only mentioned in a qualitative manner. Specifically, CPA allows to calculate circular shares of resource flows used in a product lifecycle, in order to obtain an exhaustive index regarding the circular percentage share of the product compared to the total resources used. Since CPA is linked with technological peculiarities and resources used for making a generic product, it is useful to compare the three different CBMs detected in Chap. 22. Outputs consist in a set of KPIs about resources circularity levels and the quantification of their economic and environmental benefits.

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