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LCA based circularity indices of systems at different scales: a holistic approach

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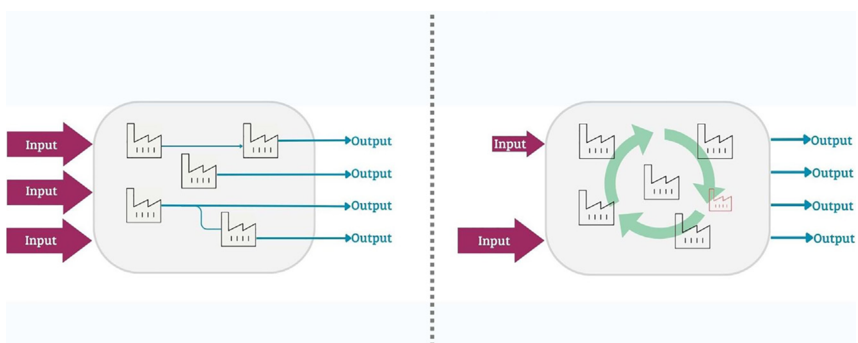
HIGHLIGHTS

- Circular Economy (CE) is investigated by means of input flows and impacts.
- A general method is introduced that produces a set of LCA-based Circularity Indices for generic meso- and macro-systems.
- Indices highlight the presence of CE elements both statically and dynamically.
- As CE is multi-dimensional, the indices account for different LCA-based impacts.
- Indices inform policy makers and managers on trade-offs and help make decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

Many are the definitions of Circular Economy as well as the policies and strategies for its implementation. However, gaps still exist in quantifying the effects of circularity. The existing approaches are usually sector- or product-specific, limited to microscale systems, and/or fail to simultaneously assess the environmental impacts of the studied system. This paper introduces a generally applicable method in which a set of LCA-based indices of circularity are able to detect the effects of circularity/symbiosis strategies on the environmental performance of meso- and macro-systems. These indices quantify the overall system's circularity level by comparing the impacts of a system in which the components interact with each other (with a certain level of circularity) with an equivalent linear system (where no circularity takes place). The method works both on existing and projected systems, being able to track the effects of future circularity policies.

This method obviates the limitations and the gaps mentioned above: it applies to meso- and macro-systems, it is not bound to a specific sector, it allows to capture the environmental impacts, and it is sensitive to the temporal dimension. This approach provides a tool to inform managers and policymakers for planning circularity actions and monitor their effectiveness while also capturing the temporal dimension.

1. Introduction

Circular Economy (CE) has gained momentum in the political agenda as a new promising economic paradigm enabling governments, enterprises and institutions to reduce their environmental impacts, resource use and waste generation. In the last decades, CE was strongly supported at the

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European level by the implementation of different political measures and initiatives that culminated in 2019 with the establishment of the European Green Deal and with the adoption, in 2020, of the new Circular Economy Action Plan (CEAP), promoted by the European Commission (2019, 2022). During 2022, several CEAP proposals, packages of measures and initiatives were adopted (European Commission, 2023a), and in 2023 the European Commission released an update of the circular economy monitoring framework (European Commission, 2023b).

By the end of 2050, the European Union (EU) expects to achieve a competitive and resource-efficient economy, with greenhouse gas emissions decreased and economic growth decoupled from environmental degradation. (European Commission, 2019). However, more sustainable production and consumption patterns must be implemented to achieve these ambitious political and environmental targets.

CE is a popular concept, widely investigated in its conceptualizations and definitions but is still subject to interpretations and debate (Kirchherr et al., 2017; Korhonen et al., 2018; Merli et al., 2018; Prieto-Sandoval et al., 2018; Calisto et al., 2020; Morseletto, 2020; Nobre and Tavares, 2021). CE may be intended as an ‘umbrella concept’ (Blomsma and Brennan, 2017; Sacchi Homrich et al., 2018), which includes several resource-oriented activities to maintain the highest utility and value from products and materials by closing, slowing and narrowing the physical loops (Geissdoerfer et al., 2017). Resource-oriented activities can include a broad range of strategies, such as eco-design, increasing material and energy efficiency, strategies belonging to the three-R waste hierarchy (Reduce, Reuse and Recycle) and the nine-Rs paradigm (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover energy) (Roos Lindgreen et al., 2021) as well as industrial symbiosis and innovation of business models (Corona et al., 2019). Regardless of all the possible definitions and specifications, the ultimate goal of CE is to reduce environmental degradation and the exploitation of natural resources (Murray et al., 2017), minimizing burdens and impacts (Moraga et al., 2019, 2021; Ghisellini et al., 2016). Overall, the core idea of CE is to break the conventional “take-make-disposal” rationale of linear systems (Kirchherr et al., 2017).

Many authors have pointed out gaps in the measurement of the level of circularity and the assessment of environmental performance (e.g., Linder et al., 2017; Elia et al., 2017; Saidani et al., 2019; Moraga et al., 2019; Corona et al., 2019; Parchomenko et al., 2019; Harris et al., 2021; Ramakrishna and Jose, 2022).

The CE approach can be used at three different levels: the micro-level is the one involving a single production process, the meso-, involves several enterprises and productive processes forming an industrial symbiosis; and the macro-level is an entire territory (Kirchherr et al., 2017). We focused on the meso- and macro-levels for which Silvestri et al. (2020) stated that there is an “inadequate monitoring and evaluation of CE implementations through the use of composite indicators”.

Multiple and various indicators are available in the scientific literature; most are product- or sector-specific and not extendible to general cases (Walker et al., 2021). The same situation is evident in the grey literature, documents published by non-academic bodies (e.g., consultancy organizations or policy institutes) that provide a variety of approaches to assist companies in the measurement of their transition to a CE, usually at a micro-level. Grey literature CE indicators are not always appropriate for assessing specific sectors (Roos Lindgreen et al., 2021). This constitutes a critical gap that needs to be filled with a generally applicable approach.

According to Harris et al. (2021), most studies focus on improving material circularity and resource productivity by adopting aggregated indicators. Similarly, Alaerts et al. (2018) observed that the Chinese, French, Dutch and EU monitoring frameworks refer to macro-indicators based on: materials, wastes and recycling, generation of municipal or other wastes, recycling rates and derivatives of such scores. However, Harris et al. (2021) argued that while such indicators aid in monitoring the CE's implementation on a territory, they do not quantify the environmental implications. As highlighted by Haupt and Zschokke (2017) and Zeller et al. (2020), it is not certain that the most circular solution is the most environmentally preferable option; therefore, more validation studies are necessary. Similarly, Roos et al. (2020) identified a low level of maturity in the CE assessment field, arguing that it is difficult to manage or implement in practice something that cannot be measured. This constitutes a further knowledge gap that must be addressed with an approach delivering in terms of environmental impact.

Walker et al. (2021) identified five categories to group the various indicator-based approaches for the assessment of circularity, according to the method applied: i) Life cycle thinking, ii) Mass-balance/Input-output analyses, iii) Indicator frameworks, iv) Indices – based on aggregation or weighting of various indicators, v) Other ad hoc methodologies. Life Cycle Assessment (LCA) belongs to the cycle thinking approaches, and it is usually considered as one of the most robust and well-established tools for assessing the environmental performance of complex systems (Daddi et al., 2017; Sassanelli et al., 2019).

LCA has its major strength in assessing the environmental impacts at the micro level – even coupled with other methodologies (Niero and Kalbar, 2019), whereas a remarkable gap has been identified for its application on meso- and macro-systems (Corona et al., 2019; Haupt and Zschokke, 2017). In fact LCA has been applied to assess circular strategies even at the macro-level, but with the aim of evaluating the environmental performance limited to individual sectors (Eckelman and Chertow, 2009; Hadzic et al., 2018; Suh and Rousseaux, 2002; Houillon and Jolliet, 2005; Liu et al., 2018).

Considering the existing circularity assessment approaches reviewed by Walker et al. (2021), the approach proposed in the present work falls into the “life cycle thinking” group. However, it allows to overcome the limitation of existing methods and to fill the gaps mentioned above: It applies to meso- and macro-systems, it is not bound to a specific sector, it allows to capture the environmental impacts, and it is sensitive to the temporal dimension.

This paper introduces a set of LCA-based Circularity Indexes to measure the progress towards circularity within a meso- or macro-system while assessing the environmental performance for several impact categories. The approach is holistic: it looks at the system as a whole, more than as a sum of parts, and avoids weighting and aggregating operations. Section 2 introduces the underlying methodological framework based on LCA. Section 3 describes the proposed model based on which the indexes are calculated, as detailed in Section 4. Section 5 presents examples of linear and circular macro and meso-systems to contextualize the proposed framework. Section 6 discusses the implications of the proposed method, while Section 7 summarizes the conclusions drawn from the proposed work.

2. Methods: LCA framework for meso- and macro-system investigations

LCA is a standardized method that assesses a product's or process's potential environmental impacts. It is based on ISO 14040 (2006) and ISO 14044 (2018) standards which identify four main phases to perform a robust evaluation. During the first phase, ‘Goal and Scope definition’, the aim of the study must be clearly defined together with other relevant elements, such as the functional unit (FU, that represents the unit of reference of the system to which all the entering and exiting flows are referred), system boundaries, data quality, assumptions and limits. The second phase, ‘Life Cycle Inventory’, consists of data collection of all the physical inputs and outputs respectively used and produced by the system, considering all the processes included in the system boundaries. The third phase, ‘Life Cycle Impact Assessment’, aims at attributing an environmental load to all the physical flows used by the systems according to several impact categories. Impact categories must be considered as environmental issues of concern to which the Life Cycle Inventory results are assigned regarding specific characterization factors and methods, for example, climate change, acidification, eutrophication, etc. Lastly, the fourth phase, ‘Life Cycle Interpretation’, elucidates the results generated and suggests possible improvements.

For the construction of the Circularity Indexes, LCA phases will have the following characteristics:

- 'Goal and Scope definition': the functional unit is simply the whole set of outputs of a specific territorial or composite system; system boundaries are based on the administrative ones (macro-scale) or more functional borders in the case of industrial symbiosis (meso-scale); time boundaries will have to be consistent in the comparison of systems.
- 'Life Cycle Inventory': data are collected in relation to the established system boundaries, not considering the life cycle stages of single products or processes: only the inputs entering from outside the system boundaries are considered.
- 'Life Cycle Impact Assessment': several Impact Categories are evaluated in creating the Circularity Index.
- 'Life Cycle Interpretation': it will not be oriented to identify hotspots along the life cycle stages or correction measures but to support managers and administrators of the whole system, guiding their policies and priorities.

3. The model

To create the LCA-based Circularity Indexes, we investigate a meso- or macro-system by constructing a model with a two-stage procedure and adopting LCA as a framework.

The system under study comprises several productive sub-systems (enterprises), not including the population and its relative consumption. This system produces different goods and services as final outputs: outputs are only those exiting the system's boundaries.

Let us start considering two systems configurations, the "real" and the "linear". The "real" system is $\overline{Q}$ with its sub-systems (S_i, $i = 1, \dots n$) producing a certain amount of goods and services (O_j, $j = 1, \dots, p$) (Fig. 1a); it may feature circular behaviors.

As a counterpart, we introduce the "linear" system Q, working according to a perfect linear rationale (Fig. 1b) that acts as a control system. Notice that the bold arrows (both in Fig. 1a and b) exiting sub-systems S_i represent the main products of each sub-system.

We assume that: 1) $\overline{Q}$ and Q are characterized by identical boundaries and the same sub-systems (S_i) working with equal efficiencies; 2) $\overline{Q}$ and Q produce equal outputs (O_j) in quality and quantity; 3) while in $\overline{Q}$ by-products of one sub-system can contribute to another sub-system, all the sub-systems in Q have linear productions: there is no recirculation of energy and materials among them.

For calculation purposes in the system $\overline{Q}$ internal relations between the several sub-systems are not considered, and only inputs provided from outside the system's boundaries are significant and have to be trackable and quantifiable. If there are circularity actions within the system $\overline{Q}$, they will be revealed through a decrease of the inputs needed from outside. If the system $\overline{Q}$ has no internal circularity, there is a perfect overlapping with Q, and no differences will emerge. It is essential to underline that, comparing Q and $\overline{Q}$, systems boundaries as well as the quality of the outputs obtained must be the same.

It is important to consider that if one or more of the sub-systems are working in series (e.g. S_1-S_3 and S_2-S_{n-1} sub-systems shown in Fig. 1, a), the input to the receiving system shall not be accounted for in LCA of Q, since they are provided by the output of "donor" systems, in order to avoid double counting (S_1 and S_2 in Fig. 1b).

Fig. 2 represents the environmental impacts of the systems $\overline{Q}$ and Q through arrows exiting the systems. The environmental burdens caused by the production activities can affect different impact categories, represented by A_k, where k (= 1, …, m) indicates the assessed impact categories. Impacts A and outputs O have different indexes (k and j, respectively) to show no one-to-one correlation between output and impact.

The proposed model adopts LCA as the framework for creating Circularity indexes. The functional unit is assumed to be the whole set of outputs produced, in a specific time interval, by the macro-system $\overline{Q}$ and exiting the system boundaries.

For the system $\overline{Q}$ data inventory is created by considering all and only the inputs from outside the system's borders and associated with functional unit.

On the contrary, the data inventory for Q is compiled by summing the inputs to every production sub-system (S_i), (excluding the inputs provided internally to Q for working in series sub-systems), and by referring to the same functional unit.

Once created the inventories, environmental impacts are calculated for different impact categories. The selection of impact categories can be based on different criteria such as political priorities, scientific purposes or European recommendations (e.g. ILCD handbook).

3.1. First-stage model: quantifying the environmental impacts for the linear system

Figs. 1b and 2b show Q as a perfectly linear system with no recirculation of energy and materials among the sub-systems and for which all the relevant inputs come from outside. In the case of internal flows between two sub-systems working in series (e.g. sub-system represented by S_1 and S_3 in Fig. 2b), to avoid double counting, no hypothetical external inputs should be considered since we already account for the internal ones. For example, if S_1 produces bolts and S_3 cars, the external input of bolts for S_3 should not be included since S_1 has already accounted for them.

To each final output O_j a set of impacts A_{jk} ($j = 1, \dots, p$; $k = 1, \dots, m$) is associated. Impacts have two indices: j to account for the different outputs and k to distinguish impacts according to the different impact categories.

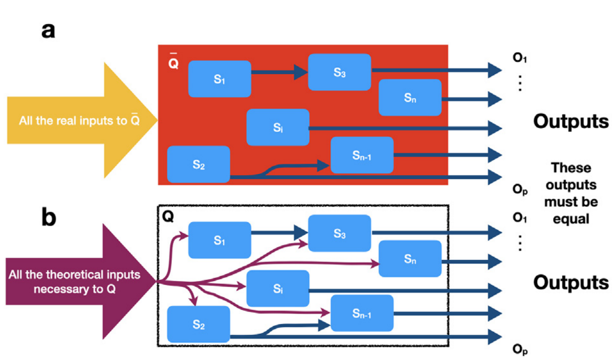

Fig. 1. At the top (a) the real macro-system $\overline{Q}$ is represented, while at the bottom (b), its perfect linear counterpart, Q, is shown. $\overline{Q}$ and Q represent the same system characterized by the same sub-systems (S_i) with the same efficiency levels. The macro-systems $\overline{Q}$ and Q are assumed to produce an equal quantity of goods and services (O_j) represented by the blue lines.
Please note that the main output of S_1 is totally used by S_3, while a part of the output of S_2 is used by S_{n-1}. This would imply a double counting for system Q if the flow from S_1 to S_3 and from S_2 to S_{n-1} were not excluded.

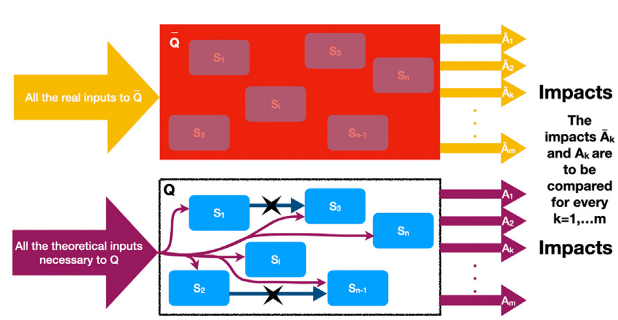

Fig. 2. At the top (a) the real macro-system $\overline{Q}$ is represented, while at the bottom (b), its perfect linear counterpart, Q, is shown. $\overline{Q}$ and Q represent the same territory characterized by the same sub-sistems (S_i) with the same efficiency levels. The macro-systems $\overline{Q}$ and Q are responsible for the environmental impacts represented by the arrow exiting the system. The environmental impacts affect different impact categories indicated as A_k.

The impacts A_k, for each impact category k, represented in Fig. 2b by the purple arrows exiting Q, is the sum of all the impacts A_{jk}, referred to each output O_j, it can be calculated by the following formula:

$$A_k = \sum_{j=1}^{p} A_{jk}$$

For example, suppose we assume that output O_1 and output O_2 increase the acidification potential (one of the possible k impact categories, e.g. $k = 1$). In that case, their impacts can be summed to find the overall impact A_1, for the whole Q system: in our example $A_1 = A_{11} + A_{21}$.

The set of A_k ($k = 1, \ldots, m$) for Q is the reference point for comparing the impacts of the real system $\overline{Q}$.

3.2. Second-stage model: quantifying the environmental impacts for the real system

$\overline{Q}$ can be assessed simply by identifying and quantifying all the external inputs entering the system, which are, from a systems viewpoint, used to produce the outputs O_j.

The rationale for the calculation of the environmental impacts caused by the activities occurring in $\overline{Q}$, is the same applied to quantifying them for the system Q: impacts associated with the total production of the macro-system $\overline{Q}$ are estimated by summing all the environmental impacts associated to each output produced that contribute to the same impact category ($\bar{A}_{jk}$) according to the following formula:

$$\bar{A}_k = \sum_{j=1}^{p} \bar{A}_{jk}$$

A_k and $\bar{A}_k$ may differ since in $\overline{Q}$ circularity features may be present, making it less dependent on external inputs.

Once A_k and $\bar{A}_k$ are calculated, it is possible to compare Q and $\overline{Q}$ based on the impacts they potentially cause. It is essential to point out that the results of comparisons can be inconsistent among the categories. There might be, for example, a substantial improvement in one category and a much lower improvement or even a worsening in another. For example, some circularity processes might produce savings in materials used but increase energy use: in this case, impacts like eutrophication or acidification might be lower at the expenses of a larger GHG emission.

Since final outputs are produced in the same amounts and in the same time frame (e.g. one year) by systems Q and $\overline{Q}$, if $\bar{A}_k < A_k$, it means that $\overline{Q}$ has implemented effective circular strategies in its production: it is reasonable to assume that, if the external inputs that feed $\overline{Q}$ are lower than the ones that feed Q, within the macro-system $\overline{Q}$, there are positive relations and connections between some of the sub-systems, i.e. that they are creating relations and networks that stimulate circular measures such as the reuse, the recovery, the recycling, and the "cascading" to reduce impacts maintaining at the same time the same amount of outputs O_j.

4. The circularity indices

Creating an index based on the two series of aggregated indicators, $\bar{A}_k$ and A_k, is used to monitor the effectiveness of circular measures in terms of sustainable environmental performance within a system. The indices are created through the following formula, in which C_k represents the index of circularity while $\bar{A}_k$ and A_k, the total environmental impacts for a particular impact category quantified for $\overline{Q}$ and Q, respectively

$$C_k = \frac{A_k - \bar{A}_k}{A_k}$$

The index, for each k, quantifies the system's circularity level. More in detail, the index is sensitive to the increased integration and connections among the several sub-systems and to the application of circular principles within the system.

A number m (number of impact categories considered) of indices C_k are derived. In principle, C_k can vary between 0 and 1. If C_k is close to 1, it means that circularity is implemented and positively affects the environmental performance of the real system $\overline{Q}$, since the impacts are significantly reduced compared to the impact of Q. On the other hand, if C_k is 0, it means that: (i) circular measures are not implemented in the macro-system (for the k-th impact category) or (ii) circular measures have been implemented, but they do not provide any environmental improvement (for a k-th impact category) since the impacts of $\overline{Q}$ anyhow remain equal to the overall theoretical impacts of the linear macro-system Q. C_ks have the same formula for every k, and this allows for a certain level of comparison among impact trends: if $C_1 = 0{,}5$ and $C_2 = 0{,}2$, it means that improvements of 50 % for impact 1 and 20 % for impact 2 occur.

It is important to specify that the C_k index cannot be equal to 1: this can only occur when $\bar{A}_k$ is zero. On the other hand, there might be cases in which C is negative, i.e., $\bar{A}_k > A_k$: if, for example, more energy is required for allowing circularity to be implemented and this energy is produced with fossil fuels: the impact in terms of contribution to climate change may rise.

Comparing our approach with others in literature we can highlight the fact that mass balance based indices provide information just on the percentage or rate of recyclability of materials, not considering the energy cost and the environmental impacts of recycling (e.g. Moraga et al., 2021). The ones based on LCA are tailored on specific supply chains with no general applicability (e.g. Liu et al., 2018; Zeller et al., 2020).

4.1. The circularity indices in a dynamic perspective

Up to now, we have compared just the actual situation of system $\overline{Q}$ with a hypothetical linear system Q that acts as a (negative) benchmark. This approach can be extended to quantify the possible improvements that can be obtained for a system if circularity policies are planned and (possibly) implemented. To address this point, we have to consider not only Q and $\overline{Q}$ (at time $t = t_0$) but also $\overline{Q}$ at time $t = t_1$ namely $\overline{Q}'$, where t_1 is the time at which we assume that the circularity policy is fully operative. $\overline{Q}'$ represents the evolution of the real system with a new (planned or realized) organization, including circularity solutions or technological innovations conveying an increase of sub-systems efficiencies(intended as fewer inputs per unit output). To distinguish between improvements in circularity or efficiency, we have to consider Q', the theoretical "linear" system corresponding to $\overline{Q}'$, in which the same technological and efficiency improvements occur, but without any circularity solutions (Fig. 3 pink line).

It is possible to quantify and compare the environmental impacts of $\overline{Q}$ and $\overline{Q}'$ to determine whether a macro-system implemented environmentally sustainable circular measures or strategies between two different points in time. When impacts of $\overline{Q}'$ are lower than the ones of $\overline{Q}$, it means that efficiency measures or circular strategies were implemented within the system and proved to be environmentally sustainable, diminishing the overall impacts. To know which of the two options occur in practice, Q

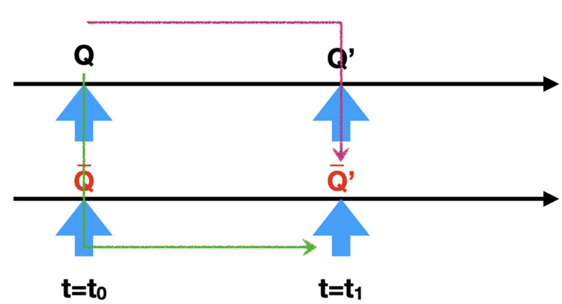

Fig. 3. The scheme of comparison among the considered systems in time: Q and Q' are different if technological improvements are implemented in one or more sub-systems; $\overline{Q}$ and $\overline{Q}'$ are different if circularity or efficiency measures occur. Q remains the benchmark to which all improvements have to be referred. Q' is introduced in order to disambiguate between efficiency and circularity.

and Q', the linear systems at time t_0 and t_1 respectively, must be compared. If the environmental impacts of Q' are lower than in Q, it means that in $t = t_1$, one or more of the subsystem within Q' are characterized by higher efficiencies or more advanced technological solutions. On the other hand, if the environmental impacts of Q' and Q are equal (i.e., the performances of each separate sub-system did not change), this means that the environmental improvements achieved by $\overline{Q}'$ are the consequences of more effective, interconnected and integrated relations based on circular principles among the sub-systems that compose the system.

It is also possible that both efficiency and circularity are improved between t_0 and t_1. In this case, efficiency measures are highlighted by comparing Q with Q', while the contribution of circularity is the reminder of the comparison between $\overline{Q}'$ and Q (Fig. 3, green line).

To assess the improvements between t_0 and t_1 we must quantify the respective impacts for each category introducing $\bar{A}'_k$ and A'_k and the Circularity Indices C'_k that are still referred to Q as the benchmark and have the same formula as C_k.

5. Examples of macro and *meso* systems interpreted by means of the LCA-based framework

An actual example of a macro-level application can be derived from Patrizi et al. (2013) and depicted in Fig. 4: a territory (the Province of Siena, Italy) characterized by agricultural and geothermal electricity production, besides its other economic sectors (including transport). All the economic sectors operate linearly within the territorial borders (linear system Q, Fig. *4*a) and produce a certain amount of goods and services.

Let us now hypothesize the deployment of the residues from the two productions: the linear Q system becomes a more circular system ($\overline{Q}$ in Fig. 4b) producing 2nd generation bioethanol through a biorefinery that exploits residues from cereal production occurring inside its administrative boundaries using residual geothermal energy (Fig. 4b) to drive the process of all other economic sectors (including transport).

In this hypothetical scenario, "investing" around 5000 tons of CO_2eq (the emissions associated with the implementation of the collection and transportation of the lignocellulosic residues and the plant construction) would lead to a reduction of 15,000 tons of CO_2eq in the net GHG balance of the Province of Siena (Patrizi et al., 2013). Considering the type of investment required, it can be hypothesized that a saving could also be obtained for other impact categories.

Moving to the meso-level, we can consider three firms operating within the same territory: the first one is a factory for producing engines for the automotive sector, the second one is a foundry that produces manhole covers, and the third one is a brick factory. The three firms operate as a linear system (Q) and produce three main outputs (engines, storm drains, and bricks) and residues (metallic scraps and inert sand). The residues are suitable for upcycling that can avoid expensive disposal in special landfills. Through appropriate and ad-hoc investment, the three firms can operate in symbiosis. The metallic scraps can substitute the virgin metals used in the foundry, and the inert sand (used as a medium for producing the manhole cover) can become input for the bricks production. Additional steps to clean up the metallic scraps and crash the sand mold should be added to implement the hypothesized circular use of residues. The additional steps require energy and materials, thus increasing the environmental impact. At the same time, they foster the implementation of a circular system and avoid environmental impacts related to the disposal of sand and the transport of virgin materials (metals for the foundry and sand for the brick factory). Thanks to our approach, possible improvements and/or worsening in all the considered impact categories can be apprised.

6. Consequences of the adoption of the circularity Indexes

The proposed approach has a number of implications:

1. The approach creates a set of indexes based on impact indicators (one for each impact category assessed) calculated for a real system (composed of interacting sub-systems) and its linear counterpart. The set highlights the interacting CE elements inside the system while simultaneously assessing the overall environmental performance. The assessment of the potential impacts does not specifically evaluate the performance of a system referred to a specific CE strategy (e.g., recycling, utilization of renewable energy sources, efficient use of resources). Still, it is sensitive to all the circular strategies implemented and gives an overview of their environmental performance. This approach has a different purpose than the other studies performed at the meso- and macro-level that focus, for example, on material cycles (e.g., Helander et al., 2019), on built environment (O'Grady et al., 2021) or on different dimensions of CE, i.e., economic prosperity, energy-efficiency or zero-waste, low-carbon economy, etc. (e.g., Avdiushchenko and Zajac, 2019). It provides indexes sensitive to the reduction (or the increase) of different kinds of environmental impacts related to the application of circular principles in production, regardless of the studied product or sector.
2. The values of the indexes vary according to the impacts analyzed. Let us hypothesize a system where the Circularity Index related to the acidification potential is 0.3, while the one related to ozone layer depletion is 0.1. These two different results highlight the complexity of developing more circular systems: achieving a real Circular Economy is not a one-dimensional problem, and trade-offs may arise. Achieving circularity for specific materials can increase the use of other physical inputs or even the necessity to introduce new sub-systems (as in Q').
3. Trade-offs may emerge in adopting a strategy to improve circularity: a policy limiting one impact category (e.g., climate change) may generate no variation or even worse results in others (e.g., resource depletion). The LCA based end-point approach - that gives different weights to impact categories, producing scores - may allow for solving the trade-off issue by reducing the number of indicators considered. However, we suggest keeping the impact category indicators separate for the Circularity Index interpretation and use to highlight where weaknesses occur, allowing a more conscious transition, in line with what was proposed by Bastianoni et al. (2019) on the need for a systems approach to properly assessing the sustainability of any system.
4. A particular case of the trade-off issue is the Circularity Index connected to energy use. Implementing circularity measures may increase energy demand; in this case, one or more Circularity Indices C_k may even be negative. Considering, for example, a situation in which fossil fuels drive circularity, the GHG emissions due to the energy investment might exceed the saving in GHG emissions due to circularity, the Circularity Index would have a negative value and highlight the trade-off issue. Nonetheless, simultaneous changes in different impacts (e.g., eutrophication vs. GHG emissions) must be examined considering contextual conditions (e.g., eutrophication has a different relevance in eutrophic or oligotrophic areas).
5. Introducing new links or new sub-systems may allow the transition of some of the linear flows into circular ones. There can be particular systems in which the introduction of new sub-system(s) may lower the overall impact of those systems. This may occur if the added sub-system (s) is (are) able to use waste materials and/or energy to produce a valuable product for other sub-systems.
6. Using the Circularity Index for monitoring a specific system in time allows, except for the baseline at $t = t_0$, to collect data just on the inputs from outside the territorial system under investigation and on the outputs produced and sold. Therefore, a database should be created to report all the inputs and outputs of the meso- or macro-systems; it is not strictly necessary to deepen the analysis within each specific production sub-system. This reduces the detail typically needed to assess specific production processes, diminishing the effort required for data collection.
7. Our approach can be used to assess the effectiveness of structural investments planned to increase the level of circularity at the system level. Suppose investments facilitate the transition to a more circular pattern. In that case, they have to be treated considering their life span while their effects can be measured or foreseen by an a priori analysis using the dynamic approach proposed in this paper.

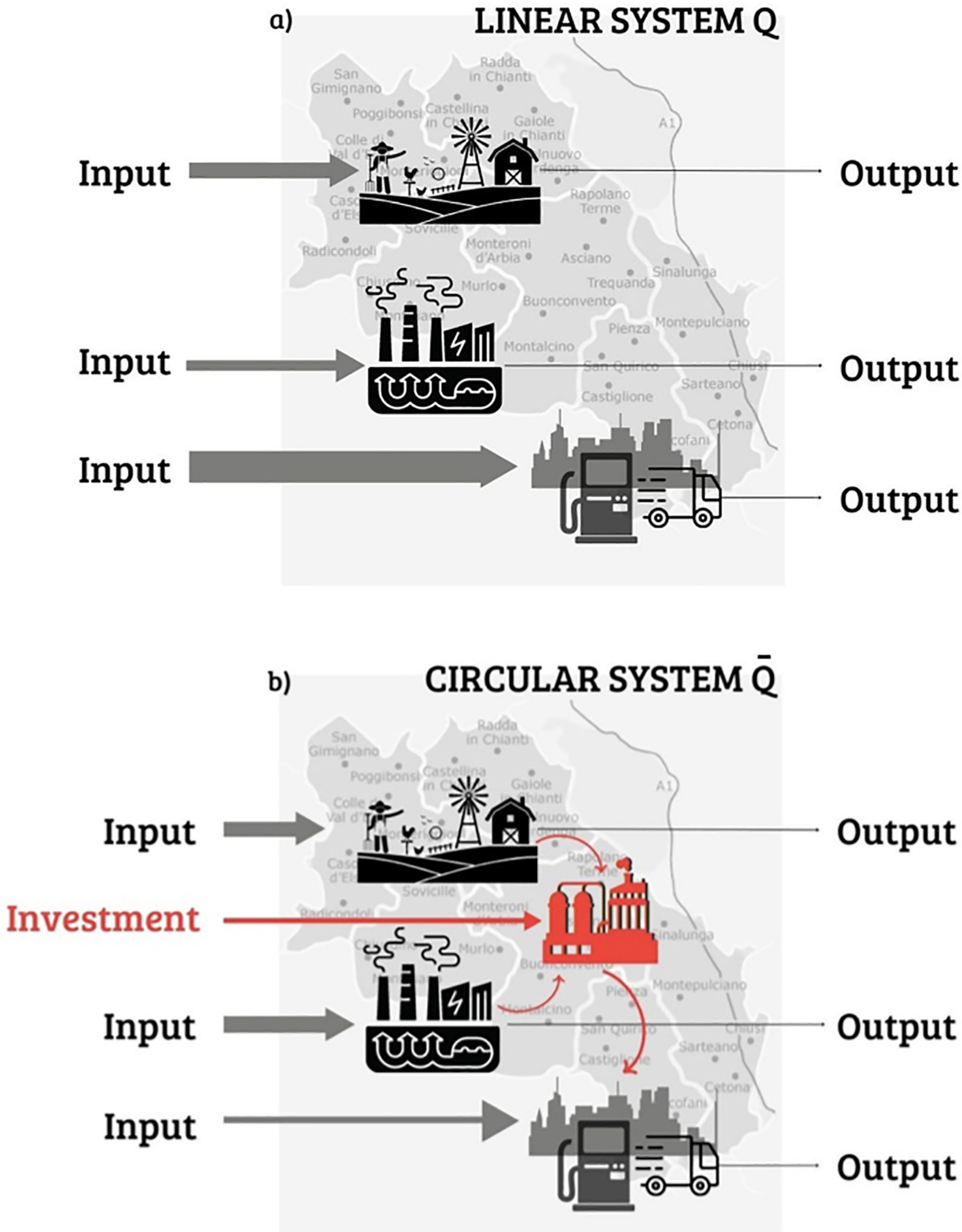

Fig. 4. Example of how the approaches work a t territorial level. Fig. 4a: The linear macro-system Q represented by the territory of the Province of Siena. Three sub-systems are shown (from top to bottom): agricultural production (top), geothermal electricity production (middle), and all other economic sectors (including transport) at the bottom. Each sub-system is fueled by respective inputs (arrows on the left entering the systems) and produces a certain amount of outputs represented by arrows exiting to the right from each sub-system. Fig. 4b: The circular macro-system $\overline{Q}$ is represented by the territory of the Province of Siena. Residues from agricultural production and geothermal electricity production become inputs for the biorefinery (depicted in the middle) and are represented by the red arrows. The output of the biorefinery fuels the remaining economic sectors (including transport). Inputs feeding each sub-system and outputs of each sub-system remain the same as those depicted in Fig. 4.

8. The model is based on a holistic perspective, considering the system as a whole. In an ideal scenario, sub-systems have to pursue circularity within their production systems, and they collaborate by adopting strategies such as recovering materials and reusing products. The index allows to detect the results of connections/relations that can be implemented or enhanced in order to improve CE mechanisms, providing additional information for planning further CE strategies, as encouraged by the European Environment Agency in its report (European Environment Agency (EEA), 2020). This can be considered an operational demonstration of the conclusion drawn by Haupt and Zschokke (2017), who stated that LCA is a suitable tool to assess movement towards a more circular economy and can support its adoption. The proposed Circularity Indices represent a step towards the enlargement of the LCA application field to a district/territorial/regional level, as invited by Corona et al. (2019).
9. The set-up of the Circularity Indices is a methodological advancement on how to use LCA for assessing CE of any given system: it is not an improvement of the methodology per se, but rather a proposal to deploy its strong points and rationale.

The set of Circularity Indices is also suitable for Industrial Symbiosis assessment since it can be considered as a way to optimize resource use by retrieving residues from an entity and using them in another (Chertow, 2000). As such, Industrial Symbiosis becomes a sub-field of CE (Salomone et al., 2020), being a meso-scale version of it, and recognized as an operational tool to boost circularity implementation (Domenech et al., 2019).

10. The main limits of the model might consist in the availability of data necessary to assess the overall impacts. The inventory construction must be scrupulous in ensuring a high accuracy level in determining the starting point of the analysis. The problem of data availability is common to all sustainability studies, including CE issues. The need for data, primarily environmental, since economic and social ones have a long history of records, is one of the leading "needs" to pursue sustainability (and circularity): without the necessary data, it is challenging to plan policies in any direction (Bastianoni et al., 2019).

7. Conclusions

This paper presents an LCA-based model that can be applied to monitor the development of circularity of a meso- or macro-system by considering the impacts according to multiple categories. Decision makers in the public or the private sector can use it to visualize the system's circularity level and investigate how the sub-systems interact (e.g.in terms of exchange and recovery of materials and energy). The Circularity Indices can be considered a synthetic representation of the level of circularity and be used to formulate goals (and monitor their realization) on a political or management level.

This approach does not provide one single indicator able to judge if a solution is better than another - since we believe that there is no way to compare different impacts. The use of the proposed Circularity Indices is subject to policy choices and contextual conditions: they do not provide the "best" available solution but quantitatively show the cumulative consequences of adopting different alternatives, among which trade-offs may emerge. If it is better to diminish one impact to the expenses of another one, for example, it will always depend on political will and/or local environmental priorities. Due to the systems viewpoint, our approach does not deliver details about the role of individual circularity actions (e.g., among the three Rs or nine Rs) or about applied inter-firm exchanges. However, it fills multiple existing knowledge gaps since it is generally applicable regardless of the system's characteristics and size, simultaneously providing information about the different environmental impacts.

The possibility of refining the approach to include the role of single components of the circular network represents a crucial challenge for future development.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT authorship contribution statement

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Federico M. Pulselli, conceptualization, finalization of the paper, supervision

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