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Review

Integration of methods for sustainability assessment of potentially circular processes – An innovative matrix framework for businesses and policymakers

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ABSTRACT

In recent years, Circular Economy (CE) has become a popular topic on policy agendas as a promising, innovative avenue to enhance resource efficiency and economic prosperity. Thanks to a determined encouragement by the European Union, the measurement and assessment of circularity performances are starting to catch up at various levels. However, there is not yet any suitable method or assessment tool that allows one to properly address the sustainability of circularity for decision-making at an organisation and government/regional levels. To find a solution to this problem, the idea of integration of methods, indicators, and assessment tools became popular to abate the shortcomings of single-method applications. In such a rapidly changing research environment where new attempts are being made to better assess the sustainability of circular processes, the misplaced use of assessment methods and tools has become quite an issue amongst practitioners. To address such a risk, this paper attempts to detect, through a critical literature review, which are the existing CE-based sustainability assessment method combinations proposed in the literature. Through a rigorous analysis based on the key findings from the review, we devise a set of matrices that could serve as a positioning framework to help practitioners (stakeholders, policymakers, businesses) in their selection of the right tools and methods for measuring their sustainable transition towards a CE pattern.

1. Introduction

The shift towards circular economy (CE) patterns has gained significant momentum globally as a means to mitigate the negative environmental and socio-economic impacts of the traditional linear economic system (Pacheco et al., 2024). The concept of a circular economy, as simplistic as it is, can find its roots at various points of time in the history of humankind across various places around the globe (Hendriks, 2024; Winans et al., 2017). However, it was indeed the 1960s where the concept started to get its limelight with the work of economist Kenneth E. Boulding, who introduced the idea of sustainable resource management in his seminal paper "The Economics of the Coming Spaceship Earth" (Boulding, 1966). Building upon Boulding's ideas, Stahel (1982) developed his ideas with a prize-winning essay in which he talked about "a spiral-loop system" which may serve as an early definition of the

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Abbreviations:

C&DW	Construction and Demolition Waste
CE	Circular Economy
EMA	Emergy Analysis/Accounting
GIS	Geographic Information Systems
IO	Input-Output
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
MCDM	Multi-Criteria Decision Making
MFA	Material Flow Analysis/Accounting
MFN	Material Flow Network
REC	Renewable Energy Communities
S-LCA	Social Life Cycle Assessment
S-VSM	Sustainable Value Stream Mapping
UEV	Unit Emergy Value

circular economy, thus advocating for closed-loop production systems. Pearce and Turner (1990) furthered the discourse with their environmental and resource economics textbook, contrasting (circular) natural systems with (linear) economic systems.

The academic foundations laid by these pioneers provided the groundwork for the modern concept of the CE, which, after having gone cold for a while, sprung back into the mainstream, thanks to the efforts of Ellen McArthur (EMF, 2013) and then subsequently the European Union (2015). Since then, it has been clear that the concept has arrived in the mainstream, in business, politics and academia (Clube and Tennant, 2023).

In its essence, CE aims to conserve natural resources and ecosystems while promoting economic and social prosperity (Hendriks, 2024). As described by one of its greatest promoters – Ellen McArthur Foundation (2021), a CE is a model of economic development that seeks to create a regenerative and sustainable system by reducing waste, optimising resource use, and creating a closed-loop system (Romani et al., 2024). Built on the principles of minimizing waste, a CE model thus promotes the use of renewable resources while maintaining the value of non-renewable products and materials as long as possible (De Lima, 2022). In a traditional linear economy, resources are extracted, processed, consumed, and discarded as waste (Romani et al., 2023). In contrast, a CE pattern is designed to maintain the value of materials and products throughout their lifecycle (Neves and Marques, 2022). This involves designing products for durability and reuse, using renewable resources, and ensuring that waste is minimized or reused (Vanacker et al., 2022; European Union, 2018).

A CE, however, is not just about the environment (Rask, 2022). The concept of a CE is multi-disciplinary and involves the participation of various actors across multiple value chains, from production to consumption (De Lima, 2022). But despite its widespread popularity, the CE concept is complex and has been interpreted in a variety of ways, giving rise to diverse circular-driven agendas or strategies (Calisto Friant et al., 2020). Within these strategies, we find an array of tools and methods that focus on assessing implications of the circularity of products/services from different dimensions (environmental, economic or social) at different CE system levels. Measuring and assessing a CE presents a significant challenge due to its complex and multidimensional nature. Unlike traditional economic models, a CE involves a wide range of interconnected and interdependent activities, making it difficult to quantify and evaluate its impacts (Geissdoerfer et al., 2017). Circularity can be evaluated at various levels, i.e., micro (product/process level), meso (industrial symbiosis/supply chain) and macro (national or city level) (Harris et al., 2021; Roos Lindgreen et al., 2020). However, it is crucial to acknowledge that the mere adoption of a circularity pattern design does not inherently guarantee improved sustainability outcomes (Blum et al., 2020). This assertion is also supported by Walzberg et al. (2021), wherein the authors emphasise the importance of assessing the sustainability implications of CE strategies relative to their linear counterparts. Their findings highlight the necessity of such comparative analyses to discern and mitigate potential unintended externalities that may arise from the pursuit of circularity. This underscores the nuanced nature of sustainability considerations within CE frameworks. Furthermore, Metic and Pigosso (2022) and Zink and Geyer (2017) also drew attention to the possibility of rebound effects associated with certain CE strategies where the anticipated environmental benefits of circular practices are offset or even reversed due to unforeseen consequences elsewhere in the system (Figge and Thorpe, 2019). By elucidating these dynamics, many such studies have underscored the importance of holistic evaluations that extend beyond immediate circularity metrics (Castro et al., 2022; Zerbino, 2022; Maier et al., 2020).

As the initial promotions of a CE were mainly focused on material and resource circularity or environmental aspects in broad terms, the use of environmental sustainability assessment tools and methods such as Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) became popular in CE transition frameworks. These methods allow for a systematic evaluation of the environmental performance of potentially circular strategies, from the extraction of raw materials to the end-of-life treatment of products. However, as the concept of a CE evolved to encompass social and economic dimensions, there was a need for additional tools and metrics that could capture these aspects. Despite their widespread popularity, these methods, such as LCA itself, have issues of their own, such as the difficulty in accounting for the complexity of circular systems, which often involve multiple feedback loops and dynamic interactions between different components. Regardless of having been used for decades to evaluate complex product systems, also characterised by closed cycles, traditional sustainability assessment methods might require adaptations to fully assess the circularity of a system. For example, traditional LCAs might struggle to account for the potential for waste products to be reused or recycled to indicate appropriate roadmaps toward decreased use of such resources. This might lead to an underestimation of the environmental benefits of circular systems. All in all, there is no one-size-fits-all method for sustainability assessment that can be used in a CE transition framework or roadmap, as each method has its own strengths and weaknesses. As a result, measuring such a CE transition requires an integrated approach that considers the entire system and its interdependencies. In order to successfully use a tool or a method to support and inform the transition to a CE, it is important to be mindful of its limitations and apply it as one tool among many, not as an ultimate single tool or method. Integration of multiple assessment methods would provide a more comprehensive understanding of the potential sustainability of circular processes. Several efforts have been going on in this avenue. Just as an example, Bargigli et al. (2004), Giannantoni et al. (2005), and Ulgiati et al. (2011), among others, have proposed the integration of Energy, Exergy, Emergy analyses, MFA, LCA, micro and macro-economic assessments, by developing multidimensional indicators as well as normalisation and weighting factors.

Amongst these attempts of methods' integration, LCAs are found to be the most favourable choice to combine with other analytical approaches. Being a dominant method to quantitatively assess CE initiatives (Saidani et al., 2019; Petit-Boix and Leipold, 2018; Elia et al., 2017), and despite its limitations, one of the most used methodologies to assess CE is in fact LCA (Corona et al., 2019; Sassanelli et al., 2019). Corona et al. (2019) observed in their literature review the use of LCA for the comparison and selection of various CE strategies. The authors highlight the holistic perspective and extensive experience in end-of-life evaluations as primary attributes of LCA that render it particularly suitable for assessing circularity. LCA enables an examination of whether the purported sustainability advantages of CE solutions can be attained and to what degree. This approach also facilitates the identification of critical aspects of a CE strategy that necessitate enrichment (Peña et al., 2021). Additionally, LCA is commended for its aim to prevent burden shifting, further solidifying its effectiveness as a tool for sustainability assessment. It has, therefore, been hailed as a crucial assessment methodology to inform and improve CE strategies by comparing them in terms of sustainable performance (Larsen et al., 2022; Niero et al., 2021; Rigamonti and Mancini, 2021).

Data collection and sharing, alongside subsequent analysis, are some of the very crucial steps to be followed in employing sustainability assessment tools such as LCA. In this sense, Industry 4.0 technologies are disruptively cross-fertilizing CE throughout society (Acerbi et al., 2022), with digital technologies such as Big Data Analytics, Blockchain and Internet of Things attempting to revolutionise the implementation of sustainability assessment methods for evaluating circularity, substantially enhancing their effectiveness by increasing the capabilities in data analysis and interpretation (Chiappetta Jabbour et al., 2020). The importance of information sharing, connectivity, and transparency is primary for the performance assessment and improvement of firms transitioning to circular processes (Taddei et al., 2024). Such digital technologies can not only help with the sustainability performance assessment of circular processes but also have the potential to reconfigure the manufacturing processes, helping, manufacturers make their supply chain more circular by supporting them in the preliminary stages of decision making for product manufacturing including waste management and utilisation (Acerbi et al., 2024). Even though the use of such digital technologies remains scarce, the discussion of the relevance of the integration of assessment methods and tools for deploying and coupling such technologies remains active (Taddei et al., 2024).

Many other authors have also made important steps ahead towards parallel, sequential, and integrated assessment procedures, but their use in policymaking, stakeholders' engagement, and business innovation has not yet gained sufficient attention towards increased environmental, social, and economic sustainability. While proposals for the evaluation of the sustainability of circular systems have received considerable attention, there is no critical review of the various combinations of methods that underlie those metrics and a review of the strengths and weaknesses associated with these potential combinations. At the same time, the cruciality of understanding the challenges associated with such method integrations is important, especially at present, where organisations at all systems levels are struggling with time and resource allocation to carry out these measurement and assessment activities for sustainability impacts of circular processes. One of the goals of this paper is to contribute to filling this lack of integration gap.

Rocca et al. (2021) focussed on CE performance assessment, particularly in the context of new business models for reusing secondary resources from WEEEs., discussing various metrics used to evaluate the effectiveness of CE practices, considering factors such as resource efficiency, environmental impact, and economic viability. As a result of their study, the authors devised a quantitative product-oriented assessment model to calculate the circularity performance. Sassanelli and Terzi (2023) explored the integration of CE principles into sustainable business performance management, examining the role of key performance indicators (KPIs) in assessing the impact of CE strategies on business sustainability. Vinante et al. (2021) presented a literature review of CE metrics, proposing a company-level classification framework. The authors synthesized existing research on CE indicators and categorized them based on their relevance to different aspects of organizational performance, highlighting the importance of selecting appropriate metrics that align with organizational goals and provide insights into evaluating CE practices effectively at the company level. Elia et al. (2017) provide a critical analysis of measuring CE strategies using index methods, examining various index-based approaches used to evaluate CE performance and discussing their strengths and limitations. Highlighting the need for a comprehensive and standardized framework to assess CE initiatives effectively, the authors emphasized the significance of selecting appropriate indicators and methodologies for measuring CE strategies accurately. So, while there is a sizable growing literature on CE performance assessment and circularity measurement tools alike, studies focusing on the sustainability assessment of such CEs, or the corresponding circular processes and strategies remain scant.

In this article, we make an attempt to identify the possible synergies and get a deeper understanding, to look at the sustainability performances of a circular system under a multi-dimensional perspective, and to get a more comprehensive assessment in support of sustainable policymaking fostering CE transitions. The article is about the integrated assessment of CE systems and processes, pointing out how integration allows a deeper understanding of CE processes and appropriate policymaking. It is to be noted that the attempt does not aim at an all-in-one exhaustive matrix, acting as a panacea for all sustainability assessment decisions. Rather the results aim to establish a foundational ground in the endeavours of a CE. The subsequent section explains the methodology behind the critical review conducted as part of this study. This is followed by the results wherein we have discussed in detail the identified literature on the various integrations of different methods and tools with LCA. The results culminate into the matrices highlighting the key challenges and the key advantages of such methods' integrations which we have elaborated upon as part of our discussion section, followed by our concluding remarks on the pertinence of the matrices in serving as an assistance tool for sustainability assessment of circular processes, especially in policy and decision making in our world's burgeoning CE-related endeavours.

2. Materials and methods

2.1. Identification and selection of the literature

In order to identify studies for review, the authors carried out a critical review of articles on CE using the Scopus database due to its quality assurance mechanism of yielding impactful research in a particular field or across varied disciplines. As also discussed in the previous section, due to the dominance of the environmental component and particularly LCA within the literature on CE indicators for supply chains (Calzolari et al., 2022), a critical review of the literature was conducted to identify the most common categories of its combinations with other assessment methods. Fig. 1 shows the whole process of selection of the relevant literature.

The starting year was not set within the year range in the Scopus search in order to maximise the yield of the results. After a preliminary identification of the main keywords used to categorise these CE-oriented papers, a search was run on the Scopus database in the "Article title, Abstract, Keywords" field using the following string of keywords: (("hybrid* lca" OR "integrat* lca" OR "combin* lca with") OR ("lca" AND "integrat* methods")).

The search excluded conference papers, book chapters, letters, notes, and editorials from the results, as well as papers in a language other than English. An initial screening was conducted via a manual cross-checking process of the abstracts in order to omit papers that were not related to the goal and scope of this search (i.e., articles not dealing with CE applications). This was followed by a secondary screening, analysing the main text of the articles, especially focusing on the aims and objectives of the papers along with their key findings and conclusions. At the end of the process, thirty-three papers were selected, and key categories that emerged were subsequently used for the development of the correlation matrix, namely, Life-Cycle Costing (LCC), social Life-Cycle Assessment (S-LCA), Emergy accounting (EMA), MFA, Simulation, Optimization along with Spatial modelling together with, of course, LCA.

The following section presents the results in terms of the integration of methods derived from the analysis of the selected literature.

3. Results

The pursuit of CE transitions necessitates a multi-dimensional

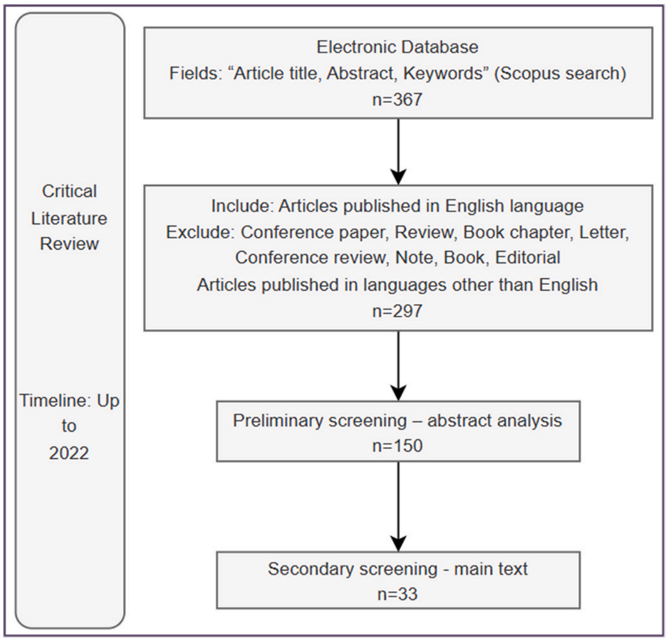

Fig. 1. Scheme of the literature screening and review process.

evaluation framework that could propel and advance CE assessments (Alshehhi et al., 2018; Kuhlman and Farrington, 2010; Seuring et al., 2008). Performance and sustainability indicators, based on robust conceptual understanding and standardised methodological framework, are thus urgently needed to support appropriate environmental, social, and economic policies. Table 1 shows a matrix listing and describing the applicable methods depending on the sustainability dimension in the cases analysed from the current literature. Based on the analysis from our literature review, we found varied levels of integrations of LCA with other methods, which were happening at different stages of the LCA. In this study, we classify them into three levels (Table 1), which are.

- **Integrations occurring at the Data collection level**: This happens during the phase which is focused on describing the system and its components (depending on previously established boundaries). Also, the direct and indirect interactions/relationships of components between and within the socio-economic (e.g., emission from human activity) and the natural system (e.g., a wetland) in past, current or future scenarios are identified and described. This phase also involves the collection of primary and secondary data and the analysis of the data quality. In such attempts of methods' integration, the authors have usually integrated one or more methods with LCA at the database level, wherein the combination occurs at the goal and scope defining moment or at the point of life cycle inventory formation.
- **Integrations occurring at the Assessment level:** These methodological combination(s) of single/multiple methods are the ones occurring at the Life Cycle Impact Assessment phase of the LCA. This phase deals with the evaluation of environmental impacts (e.g. climate change and toxicity) of products and services over their whole life cycle. Integrations of other methods within LCA happening at such system analysis levels usually take place during its evaluation and impact assessment phase, where the different indicators for the different impact categories are at play.
- **Integrations occurring at the Interpretation phase**: In this phase, the results from the assessment level are interpreted and synthesized in a way that they can be easily communicated and understood by the various stakeholders and decision-makers. The main questions are on the most relevant impacts and the most affected components or the trade-offs and synergies. The sensitivity of the study to changes in variables and/or parameters and the uncertainties are also discussed in this phase, along with completeness and transparency of the performed study with, of course, the main conclusions and limitations of the assessment. Hence integrations at such a level generally involve the use of the results obtained from one method and expressing them using another method.

While there are a lot of double-integration examples in the current literature (Tsalis et al., 2022; Jiang et al., 2019; Loiseau et al., 2018) wherein LCA has been coupled with another method, there are also quite a number of triple and quadruple-integration examples, as can be observed in Table 1. Based on our findings, we underline the importance of widening the evaluation framework to meet the needs of all stakeholders underpinned by both bottom-up and top-down approaches at different scales (micro, meso and macro) by developing a methodological integration matrix. Additionally, their application and limitations as single tools are highlighted in the next sections by providing the rationale for proposing a joint application framework consisting of more than one method to compensate for their strengths and weaknesses, leading to more comprehensive and credible matrices consisting of advantages and challenges to the integration of different methods. Such matrices can serve as a reference point for carrying out CE assessments, aiding businesses and policymakers in their decisions to bring about a holistic CE transition. In the following sub-section, we elaborate on the main matrix (Table 1) formed as a result of the literature review, which in turn led to the formation of the guiding matrices in Section 4 and 5, which may help us understand the advantages and challenges associated with these integrations, highlighting their potency in terms of a larger understanding of potentiality for bringing about sustainable circularity.

The evaluation methods just listed in Table 1 emerged from the analysis of the literature are briefly summarised highlighting their main features.

1. LCA accounts and assesses the inflows, outflows and potential environmental impacts of a product or service in the whole life cycle. The method is regulated by the standard ISO 14044:2006 and ISO 14044:2006, reviewed and confirmed last in year 2022.[1] The standard defines the essential elements/stages that must be considered when performing a LCA study guiding the researcher as well as assuring the uniformity in conducting the method and the comparability of LCA studies.[2] The stages of an LCA are: goal and scope definition, life cycle inventory, life cycle impact assessment, interpretation and "*reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements*" (ISO 14044/2006).
2. LCC evaluates the economic costs over the whole life cycle of a product (from production stage until disposal) and that of services or activities. The costs that are considered in the accounting are related to: the purchasing and installation, the use of the product (e.g., consumption of energy and water maintenance and repair) and to its disposal or residual value (e.g. in case of sale of the product). LCC could also include the external costs (e.g. that related to the greenhouse gases). The accounting of the costs by means of the LCC is important since it highlights the competitiveness (in the terms of costs) of green products compared to conventional products.[3]
3. S-LCA analyses the social and sociological aspects of products and the current and potential positive and negative impacts of a product

[1] ISO 14044/2006 available online: https://www.iso.org/standard/38498.html (last accessed: 28/09/2023).

[2] European Platform on lCA, available online: https://eplca.jrc.ec.europa.eu/lifecycleassessment.html (last accessed: 28/09/2023).

[3] Life cycle costing, available online: https://green-business.ec.europa.eu/green-public-procurement/life-cycle-costing_en (last accessed: 28/09/2023).

Table 1
Matrix of integration of evaluation methods.

	Life Cycle Assessment (LCA)	Life Cycle Costing (LCC)	Social Life Cycle Assessment (S-LCA)	Emergy Accounting (EMA)	Material Flow Analysis (MFA)
Life Cycle Costing (LCC)	Alejandrino et al. (2022) (A) Angulo-Mosquera et al. (2021) (A) Cobo et al. (2019) (D) Diaz et al. (2021) (I) Garcia-Muiña et al. (2018) (A) Miah et al. (2017)(A) Santillán-Saldivar et al. (2021)(A) Schaubroeck et al. (2021) (A) Subramanian et al. (2021) (A)				
Social Life Cycle Assessment (S-LCA)	Angulo-Mosquera et al. (2021) (A) Garcia-Muiña et al. (2018) (A) Kaiser et al. (2022) (I) Santillán-Saldivar et al. (2021) (A) Schaubroeck et al. (2021) (A) Subramanian et al. (2021) (A) Tsalis et al. (2022) (A)	N/A			
Emergy Accounting (EMA)	Jiang et al. (2019) (A) Oliveira et al. (2021) (A) Wang et al. (2021) (A)	N/A	N/A		
Material Flow Analysis (MFA)	Cobo et al. (2019) (D) Meglin et al. (2021, 2022) (A) Millward-Hopkins et al. (2018) (A) Sun et al. (2017) (D)	Cobo et al. (2019) (D) Nakamura and Kondo (2018) (A)	Hosseinijou et al. (2014) (A) Wallsten (2015) (D)	Sun et al. (2017) (D)	
Simulation, Optimization and Spatial Modelling	Cobo et al. (2019) (D) Loiseau et al. (2018) (D) Oliveira et al. (2022) (I) Solis et al. (2021) (A) Senán-Salinas et al. (2021) (D) Taskhiri et al. (2019) (I) Thakker and Bakshi (2021) (I)	Byrne et al. (2007) (D) Cobo et al. (2019) (D)	Hosseinijou et al. (2014) (A) Wallsten (2015) (D)	Kocjančič et al. (2018) (I) Mellino et al. (2014) (D) Taskhiri et al. (2010) (A)	Cobo et al. (2019) (D) Hosseinijou et al.(2014) (A) Lambrecht and Thiβen (2015) (A) Tirado et al. (2021) (D)

Integration Levels: (D) Data Collection Level, (A) Assessment and (I) Interpretation.
N/A: No integration available.

or service in the whole life cycle. This method conforms to UNEP/SETAC "guidelines for social life-cycle assessment of products" and includes the classical LCA four main phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation (UNEP, 2020). The system boundaries of an S-LCA could consider the full life cycle of products or services from cradle to grave as well as some parts of the life cycle such as cradle to gate or gate to gate or gate to grave (Petti, 2021; D'Eusanio et al., 2018). An S-LCA study considers data (generic or specific) that can be quantitative, semi-quantitative or qualitative. Within the framework of life cycle sustainability assessment (LCSA), the S-LCA integrates social aspects to the environmental and economic data coming from LCA and LCC with social data.[4]

4. EMA is based on the concept of "Emergy" that can be defined as: "*the available energy (exergy) of one kind required to be used up previously, directly and indirectly, to generate the inputs for an energy transformation*" (Odum, 1996). The Emergy method takes into account the thermodynamic basis of all forms of energy and materials and converts them in one form of energy that is the solar energy. In this way, the method normalises all products and services into a unique unit of measure that is the quantity and quality of work created and maintained by the system under investigation (Brown and Ulgiati, 1999; Pulselli et al., 2008).
5. MFA or accounting is a fundamental method of the industrial ecology field of study that accounts for the flows of materials and their use, reuse, and loss within an investigated human system (Graedel, 2019). It is an important method to monitor and evaluate the environmental sustainability and burdens of material flows including the identification of waste flows for the purpose of their minimization and eventual reuse/recycling (Pincetl, 2012). MFA classifies material flows into biotic or renewable, abiotic or non-renewable raw materials, water, air, earth consumption, solid waste, emissions and stocks. These flows can also be retrieved in the LCA since it is an element of that method (Ghisellini et al., 2022).
6. GIS is the acronym for Geographic Information System tools that combines computer hardware and software allowing to perform

[4] Life cycle initiative, United Nations Environment Programme, available: https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca/(last accessed: 29/09/2023).

multiple operations such as storing, management, analysis, visualisation, edit, sharing and presentation of data. By means of the GIS it is possible to associate data to their geographical position and process them with the purpose of extracting information (Bolstad, 2019; Berry, 1993).

7. i-tree is a peer-reviewed software elaborated by the USDA Forest Service useful in identifying and quantifying the availability of rural and urban trees and forests in a particular spatial area and the associated environmental benefits. In that, it is a relevant tool for strengthen the management of trees and forests in the pursuit of better environmental quality of urban and rural ecosystems and well-being of local communities[5]
8. Random Forest GENIE-3 is a commonly used machine learning algorithm elaborated by Leo Breiman and Adele Cutler that can be used for both regression analysis and obtaining classification rules by constructing multiple decision trees[6].
9. Value stream mapping or material and information flow mapping is a method used in business management to evaluate the current and future state of a product until it is delivered to the customer. The goal of using this method is to identify and minimise/eliminate waste for the purpose of improving the efficiency of a given value stream.[7]

3.1. Integration occurring at the assessment level of LCA

3.1.1. Integration of LCA and LCC

The integration of LCA and LCC has been proposed by several authors in the literature covering varied system levels. LCA and LCC methods have been combined to evaluate CE strategies in organisations, such as in the paper from Alejandrino et al. (2022), which proposed a combined framework that follows the requirements of ISO (2014, 2006a, 2006b), Martínez-Blanco et al. (2020, 2015), and UNEP/SETAC Life Cycle Initiative (2015) for integrating organisational-LCA with a proposed organisational-LCC methodology. Two differentiated environmental (based on secondary data) and economic (based on primary data collection) inventory models were developed in this study, ensuring they are consistent with the goal and scope of the study. LCA indicators (CML-IA; ReCiPe) were combined with the most common economic indicators (Total Annual Cost; Payback Period) in the impact assessment phase. Results successfully showed the possibility of combining environmental and economic assessment with circular indicators, along with the challenges in doing so, to ensure the effective and efficient transition of the organisation under study toward circularity. In a different level of integration, Miah et al. (2017) combined LCA with LCC at the assessment level in order to devise a novel hybridised integrated framework capable of carrying out six types of LCA and LCC integration with an aim to provide decision-makers a comprehensive method to navigate environmental and economic analysis. Diaz et al. (2021) integrated LCA with an LCC at result's interpretation level to investigate potential energy efficiency measures to promote industrial symbiosis scenarios referring to a proposed baseline scenario in the beef production industry. Some of the other widely used approaches combine LCC with LCA to evaluate CE projects in waste management (Di Maria et al., 2018) or in building or material design in the construction industry (Motuziene et al., 2016). In these two cases too, the integration of these approaches occurs in the results' interpretation level, through multi-criteria decision-making methods.

3.1.2. Integration of LCA and social LCA

A notable integration of the Social and Environmental Life-Cycle Assessment was developed by Kaiser et al. (2022). Social and environmental impact assessments were applied to a Solidarity Oriented Energy Community in an Italian municipality of the Campania region. S-LCA accounts for the social impacts of products and services, highlighting positive and negative impacts, respectively named "opportunities" and "risks". In this study, the goal and scope of the S-LCA are based on identifying the social impacts of the Solidarity Oriented REC, thus suggesting good practices for policymakers within the energy transition framework (both from the point of view of energy production and socio-cultural activities). The S-LCA inventory is based on implementing appropriate questionnaires. For each stakeholder, data were collected using both face-to-face and remote interviews. Following the canonical stages, for both cases, a cradle-to-gate approach was used. Thus, the selected system boundary (Fig. 2) accounts for the physical limits of the investigated community, including the installation and maintenance of PV panels and electricity production with partial supply to the national grid. While the integration of the methods is mainly at the system boundary level (which is shared by the two approaches) and at the interpretation level of results, the study provides a notable example of a simultaneous application that demonstrates the potential of the integration between social and environmental LCA findings. It also opens perspectives about further investigations of the same case study, which could also result in an iterative extension of the system boundary for considering further inputs. The study also provides some useful considerations on the complexity of performing S-LCA. Indeed, several elements are currently discussed among practitioners.

One of the most relevant elements is the appropriate use of functional units (FU) (D'Eusanio et al., 2018). Since social impacts need to be considered from a comprehensive perspective, the study follows the idea - proposed by many other works - to assess the impacts associated with the general behaviour of the involved subjects instead of the impacts related to a functional unit. The reason is that a specific company/subject might produce no negative social impacts to producing a single good or service while having a wide negative social impact to produce other ones. In this case, the production of "virtuous" goods and services may be conceived as participating in the negative impacts since ethical issues are way more pervasive and unrestrained than polluting emissions and environmental impacts. This may cause challenging situations when the integration between LCA and S-LCA is needed. The necessity to adopt a behaviour-oriented S-LCA instead of a functional unit-oriented one was even more motivated by the nature of the case study, represented by a solidarity project, whose outcomes are not only detectable as products and services. The integrated interpretation of LCA and S-LCA results was made feasible due to the qualitative and semi-qualitative nature of S-LCA indicators, characterised by the possibility of being flexibly adapted to any FU that S-LCA might have needed. S-LCA was performed with no use of databases, choosing indicators related to energy justice studies and adapted to the specific situation of a solidarity-oriented REC.

While such integrations at the interpretation level are not quite common, combining LCA with S-LCA at an assessment level in pursuit of creating holistic sustainability assessment frameworks to perform Life Cycle Sustainability Assessments is abundant within the present literature. Many authors (Garcia-Muiña et al., 2018; Angulo-Mosquera et al., 2021; Santillán-Saldivar et al., 2021; Schaubroeck et al., 2021; Subramanian et al., 2021) have devised such frameworks, integrating the two methods at the assessment level. Tsalis et al. (2022) developed a framework to evaluate the social impacts of circular products and materials throughout their life cycle. The authors proposed a four-step framework to evaluate product circularity by identifying indicators through S-LCA, Global Reporting Initiative indexes, and socio-economic footprint logic, selecting suitable indicators, designing composite indexes for LCA phases, and offering a composite index to assess the overall social impact/footprint of CE products.

[5] I-Tree, available: https://www.itreetools.org/about (last accessed: 29/09/2023).

[6] IBM, Random Forest, available: https://www.ibm.com/topics/random-forest (last accessed: 29/09/2023).

[7] ISO 14040. (2006). Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization. https://www.iso.org/standard/37456.html (last accessed: 29/09/2023).

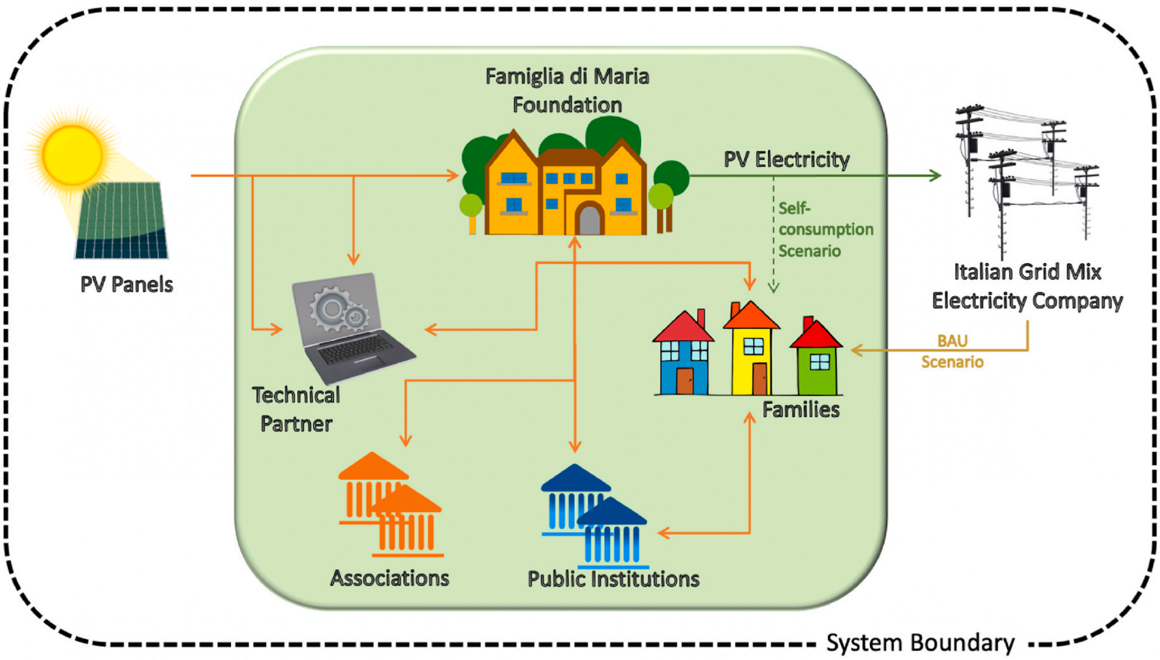

Fig. 2. The system boundary of the investigated Solidarity Oriented Renewable Energy Community of San Giovanni a Teduccio (Naples) (Kaiser et al., 2022).

3.1.3. Integration of LCA and EMA

Lyu et al. (2021), taking agricultural chemicals as a case study, have developed an interesting integration of the databases used by LCA and EMA by designing a procedure to apply the Emergy algebra (no allocation to co-products and special attention to the circularity of feedbacks) to data extracted from the Ecoinvent LCA database (allocation default). In so doing, the Emergy conversion factors (so-called UEV, Unit Emergy Value) are calculated by tracing the LCA procedure back to the input flows before allocation takes place. Double counting in circular patterns to calculate UEVs of co-products is prevented, according to the

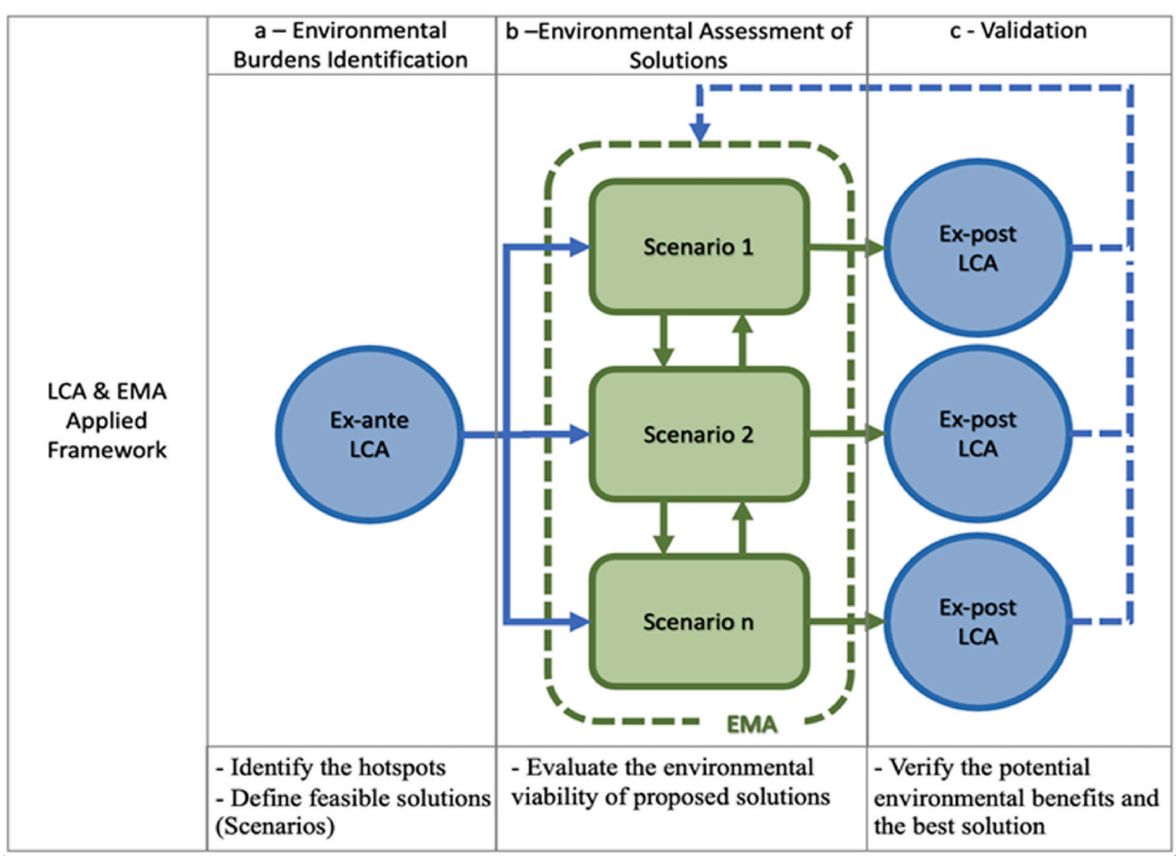

Fig. 3. LEAF Framework based on the integration of LCA and EMA methods (Santagata et al., 2020 & Oliveira et al., 2021).

Emergy algebra and the general LCA procedures that suggest allocation to be avoided to the largest possible extent. Further, the Lyu et al. (2021) procedure includes in the UEV calculation data from LCA Land Demand and Water Demand categories and the renewable fraction of Cumulative Energy Demand, in so allowing a reliable estimate of the renewable biosphere work (resource contribution) to the process, a piece of crucial information for UEVs and Emergy performance indicators. In so doing, the large amount of data available in the LCA database supports the expansion of the EMA database for a more comprehensive process investigation.

For the environmental dimension, there has been an earnest attempt within the EU Horizon 2020 funded ReTraCE project in which Ncube et al. (2021) apply and integrate exergy-aided LCA and EMA methods in agri-food case studies to measure environmental burdens related to the current business-as-usual situation with a "linear" approach and to make a comparison with the environmental performances calculated for several proposed circular scenarios. LCA and EMA show great potential for integration, as the two methods are implemented similarly by adopting quasi-similar inventories and multiplying input flows by proper conversion factors to achieve the intended results. LCA focuses on understanding the environmental burdens of anthropogenic activities from a downstream perspective, while EMA focuses on the biosphere performances in delivering products and/or services from an upstream perspective. The developed combination of both LCA and EMA is expressed within the LEAF (**L**CA and **E**MA **A**pplied **F**ramework) (Santagata et al., 2020 & Oliveira et al., 2021) procedure, described in Fig. 3. The evaluation procedure starts with an ex-ante LCA to identify the hot spots of the business-as-usual system. Based on the recognised hot spots, several improvement scenarios are developed and analysed using the EMA method. The validity of the developed scenarios is then tested by means of ex-post LCA analysis to verify the achieved reduction in terms of environmental impacts.

3.2. Integration of MFA occuring at various levels

3.2.1. Integration of MFA and LCA

Meglin et al. (2021, 2022) integrated MFA and LCA, with Input-Output Analysis (IOA) as the connecting element. Such an assessment method considers indicators for environmental impacts and economic benefits and provides the necessary data and indicators for a holistic and comprehensive evaluation of a region or industry. The model is employed to analyse which processes in the material flow system of construction minerals are decisive for formulating mass-related or financial policies encouraging a CE. An application to the construction sector of a Swiss canton is proposed to show the potential of the method. Extending their work, Sensitivity Analysis and Monte Carlo Simulation were used (Meglin et al., 2021) to check the robustness of the model and to see if it has reasonable uncertainties to confirm if the combination of MFA and LCA with an IO approach leads to a reliable assessment of a region. The authors then use the uncertainties and sensitivities to formulate initial indications of how business models are affected by the shift to CE and conclude that vertical integration of different sectors makes sense regarding a CE to buffer price volatilities but also to secure the supply of raw materials. Results provide initial indications of which policies should be applied to which sectors and help formulate effective policies tailored to specific aspects with clear objectives.

Millward-Hopkins et al. (2018) presented an integrated modelling approach for value assessments, focusing on resource recovery from waste in another endeavour of methodological integration of MFA and LCA at the assessment level. The devised method tracked and forecasted a range of values across environmental, social, economic, and technical domains by attaching these to material flows in so building upon and integrating unidimensional models of MFA with LCA. The authors argue that classifying metrics into these domains is not relevant to the modelling stage of multidimensional assessments and that these four domains are only useful for understanding the real-world implications of model outputs. They suggest performing multidimensional assessments by integrating the calculation methods of unidimensional models rather than their outputs. To achieve this result, they proposed a novel five-metric typology encompassing modified metrics from the fundamental ones (including chemical elements and substances) to embodied carbon emissions and working hours, to economic and social ones, and a final metric covering the technical value of the flow. The work focuses on a particularly important interaction that is usually left out in most models, namely the technical values of resources and their flows: the inclusion of which enables easy identification of the technical reasons for tipping points observed across other dimensions of value. The model is applied to an illustrative case study linking the UK coal-based electricity-production sector to the UK concrete and cement industries, examining some of the aggregate impacts that may follow the increased use of low-carbon fuels. Tipping points, i.e., the upstream conditions under which total GHG emissions rise due to downstream impacts of electricity production, are investigated. The results highlight the advantages of approaching such analysis to make high-level inferences of complex system dynamics, including important interactions between background and foreground systems and distributional effects, rather than taking market-centric approaches and devoting disproportionate attention to optimising incommensurable sets of outputs using limited and subjective constraints.

3.2.2. Integration of MFA and EMA

Sun et al. (2017) developed an integrated MFA and Emergy evaluation model to investigate the environmental and ecological benefits of urban industrial symbiosis implementation in one typical industrial city in China. An urban industrial symbiosis network was analysed. Inter-firm flows and related environmental benefits of a symbiosis network were quantified by means of the MFA approach, while further ecological impacts were evaluated through the EMA and an Emergy index development. Specifically, the integration of the two methods allowed the conversion of material flows into emergy ones.

3.2.3. Integration of MFA and LCC

Cobo et al. (2019) developed a combined LCA-MFA-LCC model aimed at optimising the circular economy performance of a waste management system in the Spanish region of Cantabria. The model was optimised in order to find system configurations that minimise the total annual cost and the global warming impacts while maximising several circularity indicators. A bottom-up model of the system was developed through the combination of MFA, LCA, and LCC approaches. A Multi-Objective Optimization Model was built and solved through the ε-constraint method; MFA and LCA of each waste management unit process were carried out with EASETECH 2.3.6 (Environmental Assessment System for Environmental Technologies). Nakamura and Kondo (2018) also integrated MFA with LCC as part of their dynamic Waste Input-Output model that explicitly attempted to address quality issues of recycling originating from unintentional mixing in the recycling phase.

3.2.4. Integration of MFA and S-LCA

The paper from Wallsten (2015) provided one of the first "social" extensions of MFA, connecting the analysis of the stock of materials to the social practices that oversee material flows in the city, thereby enabling an assessment of the socio-economic conditions for urban mining. Hosseinijou et al. (2014) recognised the need to assess the social impacts of materials along the full life cycle, not only in order to address the "social dimension" in sustainable material selection but also to potentially improve the circumstances of affected stakeholders. To achieve that, they applied the S-LCA method. However, in the life cycle inventory analysis phase of the S-LCA, the authors perform a hot spot assessment using MFA and interviews with stakeholders and experts. Based on the findings of their case study, a pairwise comparison method was proposed for life cycle impact assessment applying the analytic hierarchy process (AHP), which constitutes a well-established multi-criteria decision-making technique. A case study was conducted to perform a comparative assessment of the social and socio-economic impacts on the life cycle of concrete and steel as building materials in Iran.

3.3. Simulation, optimization and Spatial Modelling

3.3.1. Integration of Spatial Modelling with LCA

Another attempt at methodological integration has been the application and convergence of the i-Tree Canopy tool and the LCA methods to evaluate the potential circularity benefits by augmenting tree cover within the Metropolitan City boundaries of Naples in Italy (and elsewhere). The results highlighted that a potential tree cover increase in 16% of the entire Metropolitan Naples City area by planting 2.4 million trees would generate 51% more benefits in terms of pollutants removal (CO, NO2, O3, PM10, PM2.5, and SO2), carbon sequestration, and stormwater management (Oliveira et al., 2022). The i-Tree Canopy software is a modelling tool to create scenarios before starting any activity to check the order of magnitude of the results achievable by certain actions e.g., by planting trees (as described above) or quantifying the available construction waste to be recovered (Cristiano et al., 2021).

3.3.2. Integration of resource use simulation with economic modelling

The Multi-objective Optimization Model is a sophisticated modelling tool to assess the links among and the consequences of specific policies (e.g., water, energy, economy nexus) and suggest optimization of benefits based on improved use of water and energy resources. A Multi-Objective Optimization Model based on the Random Forest-GENIE3 algorithm and improved Quantum Particle Swarm Optimization algorithm was developed by Liu et al. (2022) and used to dynamically analyse the interdependence of water, energy, and economic performance as well as potential changes required for coordinated development in the steel industry chain. These authors investigated, from 2013 to 2019, the “water-energy-economy” dependency relationships and the trends of the coordinated development, followed by simulations of 16 different steel industry scenarios aiming at an optimal development path. Results first pointed out the weakness of the analysed “water-energy-economy” triple dimension dependence relationship in China’s steel industry. The simulation of scenarios suggested that prioritising the reuse of scrap steel (increased circularity, beyond the still insufficient 10% scrap use in China) and, at the same time, restricting pig iron and primary steel use may help optimise the coordinated development of “water-energy-economy” in the steel industry chain. The integration is clearly among simulation modelling tools, economic assessment, and resource use efficiency.

Kocjančič et al. (2018) presented an innovative attempt to incorporate biophysical criteria into a standard socio-economic optimization model, illustrated through a study of the Slovenian dairy sector, where the biophysical perspective on the system’s functioning is determined by the EMA approach. Authors develop an optimization procedure based on a preceding analysis of socio-economic and Emergy-based performance characteristics of different production types at the farm level that, when aggregated, constitute the sector. The Multi-Criteria Optimization Model was supported by weighted goal programming and aimed to investigate the effects of two opposing agricultural policy paradigms on the organisation of the sector at the national level. Results confirm the complementarity of economic (anthropocentric) and emergy-based (eco-centric) approaches, showcasing the importance of such an integration which considers a network of direct and indirect links with natural and economic processes, enabling a more comprehensive evaluation of the agricultural system’s performance and providing a deeper insight into the potential circularity consequences of structural changes in the sector.

Recognizing the potential of material flow networks’ (MFN) flexibility for mapping industrial supply chains, Lambrecht and Thißen (2015) provided an interesting integration of MFA and optimization techniques. While MFNs can be employed in a purely descriptive way to visualise material flows and metabolic rates within production systems, it is also possible to build detailed explanatory models that can be used for scenario analyses or to investigate the impact of individual improvement measures. The authors present a method for material flow-based optimization that combines the intuitive modelling approach of material and energy flow analysis with the particularly efficient analytic solvers of mathematical programming in order to foster sustainability optimization of complex production systems, potentially increasing circularity.

Also, in recent years, several papers attempted to integrate, within a simulation framework, Value Stream Mapping (VSM) with LCA (An et al., 2021). Generally, two approaches are adopted. The first approach is to integrate LCA and VSM into a new method (Paiu et al., 2010; Mousavi et al., 2016). The second approach is to jointly use VSM and LCA directly in a single study (Vinodh et al., 2016; Djatna and Prasetyo, 2019). VSM is most suited to be used in a gate-to-gate LCA study of a manufacturing process, either at the initial production of a product or within the end-of-life treatment.

The VSM variant Sus-VSM (short for Sustainable Value Stream Mapping) is ideally suited for allocating the right energy, material, and labour used for any given industrial process. Integrating Sus-VSM with LCA also allows for the proper study of any hypothesised improvement in a production process with one or more circular scenarios (Salvador et al., 2021). In addition to directing improvements in the current state, the LCA-VSM model lists the more meaningful actions using a multi-criteria prioritisation, potentially driving circularity in manufacturing operations.

3.3.3. Integration of Spatial Modelling with EMA and MFA

Wallsten (2015) combined geographic information systems (GIS) and MFA for the analysis of urban mining solutions. The approach couples spatially informed size estimates of urban metal stocks to the equally spatially contingent social efforts required to extract them, overcoming the classical limitations of MFA assessments that stop at the first of these two phases. The authors point out how the inclusion of social factors in MFA by combining it with GIS data can help inform the design of detailed recycling schemes, thus promoting circularity.

Another unique integration pathway was proposed by Mellino et al. (2014). In their study, the Emergy synthesis is used to evaluate the natural and the human-made capital of the Campania region (Italy) by accounting for the environmental support directly and indirectly provided by nature to resource generation. Furthermore, GIS models are integrated with the EMA procedure to generate maps of the spatial patterns of natural and human-made capital distribution. Through the application of these methods, authors highlight that only 19% of the regional natural capital appears to be concentrated within protected areas, while most of it (81%) can be found outside. These findings suggest that efforts for the conservation of natural resources are also necessary outside protected areas employing suitable policies, directives, and investments. The proposed Emergy-GIS framework offers to be a useful tool for environmental planning and resource management aimed at conserving and protecting the regional environmental heritage.

4. Discussion

4.1. An integrated sustainability assessment view of circularity

Fig. 4 from Coleman et al. (2020), which uses the systems diagram language developed by the energy ecologist H.T. Odum (Odum, 1996), graphically highlights how selected different methods can approach systems from different perspectives, simultaneously assessing environmental, social and economic features. In this section we discuss the system diagram in Fig. 4, highlighting the applicability and specific

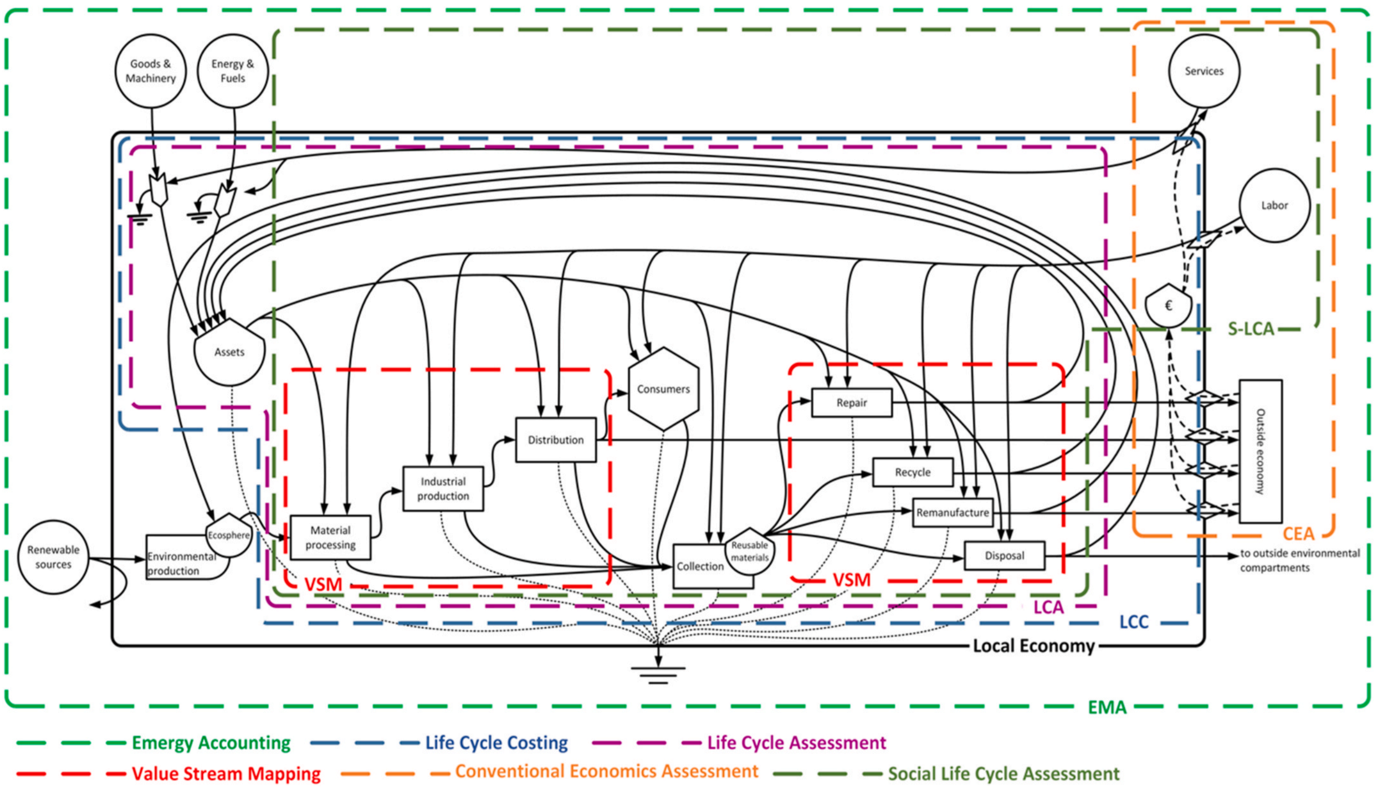

Fig. 4. System diagram highlighting the applicability and specific scopes of different methods (Coleman et al., 2020).

scopes of different sustainability assessment methods.

The illustrated local economy receives support from local renewable resources, namely sunlight, wind, rain, deep heat and tides, enabling the environmental production of raw materials. These flows are provided by or extracted from the ecosphere and made ready for industrial processing and distribution to consumers inside and outside the considered local economy. End-of-life materials and products, waste and scraps are collected and then re-inserted into the economy after repairing/recycling/remanufacturing, while non-reusable fractions are directed to the final disposal. The system is supported by external direct and indirect labour (i.e., services), interacting with external sources of goods, machinery, fuels, and energy to feed the virtual storage of assets. Assets and products exchanged with the external market deliver the needed economic support to the system. Of course, all transformation steps follow the second principle of thermodynamics, generating a loss of energy expressed as a heat sink.

A multi-perspective assessment of a system is only possible by applying different methods. Each implemented method analyses a different aspect of the system within different boundaries (as shown in Fig. 4), providing a distinct set of insights that can be used and integrated for a holistic understanding. The methods used can be shortly summarised as follows.

- LCA: This method analyses the environmental impacts and resource use in different environmental compartments of human-dominated processes in a cradle-to-grave perspective, from resource extraction to final disposal. Different kinds of indicators can be calculated based on several impact methods that can be used for the classification and characterization of environmental impacts.
- S-LCA: This method adopts a perspective similar to environmental LCA, accounting for the social impacts of products and services on different kinds of stakeholders, highlighting positive and negative impacts, named respectively “opportunities” and “risks”.
- LCC is an economic evaluation method that accounts for the cost of a product/service over its entire life cycle, taking into account planning and design, acquisition and installation, operation and maintenance, renewal and reform, and scrap and recycling.
- VSM is a technique for visualisation and management of material and information flows needed for products and services. It represents a method to review and improve the flows and steps for delivering a product to final users.
- EMA expresses the direct and indirect available energy (exergy), with all flows measured as solar em-joules, used in transformations for delivering products and services. It accounts for local and non-local, renewable and non-renewable sources from a supply-side point of view.
- Conventional Economics Assessment indicates different measures and indicators conceived for the analysis of linear systems (e.g., turnover, GDP, etc.) that can provide only a limited understanding of the complexity of CE systems.

These methods have been implemented, throughout the scientific work described in this paper, to achieve a holistic understanding of such complex systems of CE and circularity implementation patterns. Crucial in the use of these methods (and each method in general) is the correct identification of the reference boundary within which the method can be applied without the risk of misunderstanding perspectives and results: each method has been designed to answer specific questions within a specific boundary of interest (e.g. the biosphere, an entire country, an urban system, an industrial plant, an agricultural field) so that the “best method” illusion can be busted and instead an integrated method, which is rational and most appropriate to a specific boundary can be identified and applied. The different integration procedures show a high potential in providing a multi-perspective analysis system, allowing a wide understanding of the investigated case studies and, by extension, of the feasibility of CE scenarios. This can promote a holistic, multi-criteria approach for decision-making to promote CE transition and management.

4.2. Strengths and weaknesses of integration of assessment methods

In addition to the integrations of LCA, EMA and other approaches, SWOT analysis (a qualitative research tool adopted by companies and business consultants to identify strengths, weaknesses, opportunities and threats of a given situation) can be applied to the results' interpretation level to further evaluate the achieved results step-by-step, taking into consideration the risks and the challenges of each method applied. It is a way to involve experts in judging, for example, to what extent methodological interpretations and applications have been effective or not. The SWOT analysis can be applied at the interpretation level of the results achieved in the planning, implementation or evaluation of a system or a process (be it an organisation, a process or its selected products, municipal waste management and so on). Its origin dates to the sixties in the business administration academic domain (Hill and Westbrook, 1997; Andrews, 1971, 1980). However, over time its use has been considerably expanded beyond private organisations towards local public administrations and national or European institutions (European Union, 2017).

SWOT was used, for example, to evaluate the effectiveness of LCA, EMA and other environmental assessment tools in assessing the urban metabolism of a city (Voukkali and Zorpas, 2022). The SWOT analysis is a way to involve experts in judging the key elements of a system, namely its "Strengths" and "Weaknesses" (positive and negative internal factors of the investigated system), "Opportunities" and "Threats" (external positive and negative factors affecting the investigated system) (Table 2). SWOT is a multicriteria evaluation and integration-oriented tool since it collects and evaluates data of different natures and origins by means of different assessment methods in order to provide a comprehensive and updated picture of the investigated system (Voukkali and Zorpas, 2022; Cristiano et al., 2021). In so doing, SWOT also provides a multi-dimensional judgement about the evaluation methods used to design, understand, and support a policy or a project.

Cristiano et al. (2021) evaluated spatial data about the available buildings in the Metropolitan City of Naples and primary data on construction and demolition waste (C&DW) flow streams. In doing so, the authors adopted the i-Tree Canopy tool and the official cartography for the identification of the number of existing buildings available in the area and as a basis for the original quantitative estimation of the materials stored in such buildings. Discussing the documented relevance use of SWOT analysis in performance assessments of socio-economic systems and in public programs as a tool for ex-ante, intermediary, or ex-post evaluation (European Union, 2017), the authors used it to evaluate the performances of the whole C&DW management system as well as to provide the policymakers with an overall picture of the main features of the system.

By employing SWOT analysis at the interpretation level of the achieved results, businesses and consultants can gain a holistic perspective of the methods used in their assessments, gaining a more nuanced understanding of the outcomes. Such an approach would ensure that the evaluation process is not solely focused on numerical metrics but also incorporates qualitative insights and considerations, including business implications, market dynamics, and potential risks. This can help policymakers and businesses to make informed choices, refine strategies, and effectively address the challenges associated with the methods employed. By considering the risks and challenges, organisations can optimise their decision-making processes and develop strategies that align with their objectives while mitigating potential obstacles.

Table 2
SWOT matrix with example queries for each quadrant. Adapted from European Union (2017).

Strengths	Weaknesses
● *What does the system do well?* ● *What unique resources is the system able to leverage?* ● *What do third parties consider as strengths of the system?*	● *What needs improvement in the system?* ● *What do competitors do better than the system?* ● *What resources does the system lack?*
Opportunities	**Threats**
● *What market or other kind of opportunities are present for the system?* ● *How can the system leverage its strengths?* ● *What trend can the system take advantage of?*	● *What is the competition of the system currently doing?* ● *Do the weaknesses of the system expose its business or main activities?* ● *What threats can hurt the business or main activities of the system?*

4.3. Benefits and limitations

The methodological integrations of real case studies, as demonstrated by the reported examples in this paper, have highlighted the possibility of complementary and more comprehensive approaches, thus minimizing the risk posed by single methods in analysing complex systems. The integrations are thus beneficial in increasing indicator metrics for a CE. In terms of space and time scales as well as upstream and downstream points of view, LCA and EMA seem the easiest and most profitable methods to be integrated for sustainability assessment, although they can be complemented by other methods according to the specific needs. Therefore, the valuable contributions provided by other methods should not be disregarded.

LCA can provide a deep focus on the different scales of processes, thanks to its ability to monitor inflows and outflows in each process step and assign to these flows an impact characterization that allows making decisions for process improvement. LCA starts from resource extraction ending up at resource disposal, with all the intermediate impacts linked to processing and use. EMA benefits from LCA, step-by-step, detailed inventories, and expands the assessment to the time and spatial scales of the biosphere through characterization factors (UEVs) that consider the area and time needed for input resource generation (instead of just extraction and transport) and degraded resources regeneration (instead of just disposal). In doing so, the two approaches benefit from each other, even when they are used separately depending on the investigation goal (local scale economic market and its impacts or biosphere scale environmental and sustainability policymaking, respectively). When applied sequentially or together, the two methods help stakeholders, managers, and policymakers to understand, quantify, and plan consequences and needed actions of economic processes, improvements in consumer behaviour, planned policies, or needed investments in innovative research and infrastructures. Therefore, the combination of LCA and EMA indicators provides a much broader and more comprehensive analysis of the environmental dimension.

It should not be disregarded that the large availability of process inventories in LCA databases provides a huge starting point for EMA analyses, contributing to its easier application. A problem still is identified (and needs to be worked out) in the different algebra of the two methods. LCA allocates according to different criteria, although the ISO 14040/2006 and 14044/2006 (ISO, 2006a, 2006b) norms discourage allocation in favour of boundary expansion, while EMA never allocates to co-products, always assigning to each of them the total Emergy driving the investigated process. Within the LCA method, the largest allocation fraction is commonly assigned to the main function or product in so recognizing the specific reason for which a process is conducted. This represents a problematic area in LCA studies as most production systems can generate co-products that, if not treated as waste, are essential as feedback inputs in the same system or, through industrial symbiosis, an input for another supply chain.

Different LCA allocation procedures are generally suggested and applied based on physical (energy, exergy, mass) or economic criteria. The difference in allocation choices sometimes gives different and misleading results, and as such, when dealing with multi-output systems, careful evaluations and choice of allocation are much needed to characterise different co-products. On the other hand, the EMA procedure assigns a biosphere value (donor- or supply-side) to all co-products and does not categorise the burdens of the main product and by-products, as they are all considered to be generated by the same natural emergy. When one method applies allocation and the other does not, it then becomes difficult to compare their results, leading to potential disagreements in reaching conclusions for policymakers and other stakeholders. Lyu et al. (2021) have suggested a procedure to overcome the allocation present in most LCA databases by tracking back to a correct full inventory and thus generating appropriate UEVs. Additional studies however, are needed to generate a full EMA inventory and an EMA software to benefit from LCA databases and software.

Both LCA and EMA tend to be biased towards analysing the environmental pillar of sustainability and not being strongly oriented to measuring social and economic impacts. Of course, EMA can take into consideration the human resources factor, but this is not the only social metric of importance (e.g., gender and racial injustices, which are most often linked to labour and human capital issues).

Research has also been furthering in developing LCC and S-LCA approaches and databases, although this still relatively remains in the infancy phase. However, LCC and S-LCA, as well as other footprint and flow-oriented methods (Carbon Footprint, Water Footprint, Material Flow Accounting, and Value Stream Mapping, among others), should all be considered complementary and very imperative methods that planners should take into account and apply when needed to integrate information from LCA and EMA and thus reach a more complete set of impact indicators, useful for decision making. None of the investigated referenced methods, on their own, can be considered sufficient to fully understand the cost-benefit consequences and advantages of a planned process or policy. Instead, only a sequential and integrated use of them, depending on the case, would provide the ability to capture sufficient information to support discussion among stakeholders that could develop policies capable of considering the environmental, social, and economic dimensions. What the present study has therefore provided in terms of theoretical approaches and applied case studies is the demonstration that the set of methods investigated (potentially expanded via integration with other approaches) relies on a scientifically strong and comprehensive basis and can be applied in the decision-making process for sustainability assessments of CE processes. A concerned administrator, business operator, policymaker, and stakeholder will find in these sets of integrated methods' matrices a solid starting point to deeply understand the details of the issues at stake.

From the analysis of the benefits and limitations of the pursued integration process, we can observe that the goal of the integration of methods allows us to look beyond mono-dimensional towards a multi-dimensional framework to advance the assessment of CE policies and processes performance. This integration is likely to ensure several potential advantages in terms of completeness and effectiveness that are useful to achieve a deeper understanding of environmental, social, and economic complex and dynamic systems and promote appropriate policies. The integration process is not an easy task since many problems limiting methodological integration have emerged (e.g., factors of scale,

Table 3
Key advantages from methods integration.

	Life Cycle Assessment (LCA)	Life Cycle Costing (LCC)	Social Life Cycle Assessment (S-LCA)	Emergy Accounting (EMA)	Material Flow Analysis (MFA)
Life Cycle Costing (LCC)	Offers detailed insights into **both Environmental** and **Economic accounts/impact** of a product or service for its **Entire Life Cycle.**				
Social Life Cycle Assessment (S-LCA)	Offers the **Benefits** of shedding light on **Both Environmental** and **Social Impacts** via a **Life Cycle Perspective.**	N/A			
Emergy Accounting (EMA)	Offers a **Unified Measure** of the provision of **Environmental** Support, with **Emergy** Adding a **"Donor-side" Perspective**, measuring the work of the environment that would be needed to replace what is consumed.	N/A	N/A		
Material Flow Analysis (MFA)	Allows for **Both**, Assessing **Environmental Impacts** & **Considering System Constraints**, e.g., capacity restrictions & resource availability of waste.	**Connecting** the **Input-Output Economics** to **Material Flows**, this integration **helps** to **Transform** a **Monetary input-output** table into a **Physical input-output** table in terms of the Masses of the Materials of concern.	**Linking** the **Social Impacts** to **Material Flows**, this Combination **helps** the user in identifying the **Social Impacts w.r.t the Masses of Materials** part of the product/service's Life Cycle.	By converting **Material Flows** to **Emergy**, it becomes possible to **understand Ecological Benefits in terms of Environmental Savings.**	
Simulation, Optimization and Spatial Modelling	**Augmenting Spatial** and **Temporal Boundaries** of **LCA**, this integration **adds** the **Spatial Dimension**. Supporting methodological choices in LCA, **Simulation & Optimization** techniques **Compliment LCIA** development & attribute **Significance** to **Impact Categories**. Also, **MCDM** methods can help **s**tructuring **multi-dimensional** assessment approaches.	This Integration Offers to **add** the **Spatio-Temporal patterns** of **Stocks and Flows** quantified by **Spatial Analysis** to the **Life Cycle based Economic Assessment.** Also**, MCDM** methods can **help structuring multi-dimensional** assessment approaches.	**Geographical Information** plays a vital role in **Social-LCAs**. This combo **helps** Better **Understand** the **Effects of Spatial Proximity** on **Social Impacts.** Also, **MCDM** methods can help **structuring multi-dimensional** assessment approaches.	Such an integration **Compliments** the **Donor Perspective** based **Natural Ecosystem Assessment** by **Adding** the Understanding of the **Effects of Spatial Dynamics** to the study. Also, **MCDM** methods can help **structuring multi-dimensional** assessment approaches.	**Supplementing** the **Material Flow Account** with the **Spatial Dimension**, this integration **helps** to **Analyse**, **Diagnose**, and **Model the Spatial Dependence** of **Material and Stock Flows**. Also, **MCDM** methods can **help structuring multi-dimensional assessment** approaches.

the boundary of systems, distinct characteristics of environmental, social, and economic issues, etc) and still need further solving.

The adoption and the development of roadmaps for the implementation of such a multi-dimensional and multi-perspective integration process is crucial to the success of transitioning to CE consumption and production patterns, to strengthen the effectiveness of available evaluation methods and, at the same time, to develop a shared vision and consensus around this goal within the community of stakeholders which are aware of and may be affected by circular socio-economic models. The use of the matrices proposed in this paper to devise roadmaps to a circularity transition, based on a stakeholders' engagement approach, will support policy makers towards the adoption of the appropriate set of integrated methods in line with the context to be analysed and the goals to be addressed. Specifically, advantages and challenges related to the integration of individual methods are presented in Tables 3 and 4.

4.4. Practical implications of the devised matrices

Through the integration matrices developed as a result of this comprehensive study, both industry practitioners and policymakers stand to gain significant advantages in their decision-making processes. These matrices, presented in Tables 3 and 4, serve as valuable tools for navigating the complex landscape of sustainability assessment in

Table 4
Key challenges related to methods integration.

	Life Cycle Assessment (LCA)	Life Cycle Costing (LCC)	Social Life Cycle Assessment (S-LCA)	Emergy Accounting (EMA)	Material Flow Analysis (MFA)
Life Cycle Costing (LCC)	**LCC indicators** which can be both quantitative and qualitative, are **dynamic**, and seen from the **producer's point of view. LCA indicators** are quantitative and static in nature, accounting for adverse negative impacts from an **environmental perspective**. This **diversity** can be a **challenge.**				
Social Life Cycle Assessment (S-LCA)	The **integration of databases** might be extremely **difficult**, as it might be **problematic** having **site-specific LCA data**, and there are **no standards** for **S-LCA.**	N/A			
Emergy Accounting (EMA)	The **"Donor-Side"** nature of **EMA** and the **"Receiver-Side"** one of **LCA** represent an **inherently difficult** integration. The **peculiarities** of the **'Emergy algebra'**, along with the treatment of **uncertainty** within **EMA,** can present a **stumbling** block.	N/A	N/A		
Material Flow Analysis (MFA)	In contrast to **LCA**, there is **no norm** or **standard regulating** the **MFA**. Thus, it **does not represent** a method with **universal applicability**. The approach might **depend strongly** on the **individual research question.**	As **no method** to **translate material flows** into **environmental costs** is **unanimously accepted**, there is a **constant challenge** with the **temporality** of **LCC** while **merging** an **MFA** into it.	**Dataset integration** for **S-LCA** and MFA is a **challenge** as **most** of the **available datasets** reflect the **country** or **sector level**, whereas **MFA** deals with **data** of **material/ substance flows** at the **process level.**	**Diverging** temporal horizons, **mismatching** system boundaries, data quality and availability, and the **underrepresentation** of industrial processes are some of the **key challenges** in combining **EMA** and **MFA.**	
Simulation, Optimization and Spatial Modelling	**Spatially specifying LCI data** for successful integration of **Spatial Modelling** with **LCA** can be a **challenge.**	**Optimization** results might be strongly **influenced** by the **initially selected value** yielded from the **LCC analysis. Spatially specifying costs** for seamless integration of Spatial and Temporal Modelling with **LCC** can be a **challenge.**	**Social LCA outputs** as **objective functions** in a **multi-objective optimization model** can be a **tricky task**. The **troubles** in getting **primary data** which are **deeply site-specific**; resorting to **social hotspots** databases can consequently strongly **bias** the results of the **analysis optimization**. **Spatial explicit** modelling due to a **lack** of **site-specific data** can be an obstacle in **social databases.**	**Optimization** under **uncertainty issues** within **EMA** can be **complex. Spatial** and **temporal modelling** around **eco-centric indicators** of EMA is also **challenging.**	The **spatialisation** of **stocks** and **flows might not** be **immediate.** In **stock-driven models**, it is easy to estimate **net flows** during a specific period, **but** usually, **total input** and **output flows** are **underestimated** because **parts of flows are ignored**. This **affects accuracy** in **MFA.**

circular processes. By providing a clear and concise overview of the advantages and challenges associated with integrating various assessment methods, these matrices aim to simplify and streamline the decision-making process for stakeholders involved in CE initiatives.

Table 3, which outlines the key advantages of integrating five different assessment methods with each other, offers a panoramic view of the potential benefits that can be realised through such integrations. This matrix allows practitioners to quickly identify which combinations of assessment methods might yield the most valuable insights for their specific context. For instance, the integration of LCA with MFA might offer enhanced visibility into resource efficiency and environmental impacts throughout a product's lifecycle. Similarly, combining a Simulation, Optimization and Spatial Modelling technique with S-LCA could provide a better understanding of the relationship between social proximity and social impacts in or throughout the lifecycle of a product resulting from potentially circular processes. By referring to this matrix, practitioners can make informed decisions about which integration approaches are most likely to yield the desired outcomes for their specific sustainability assessment needs. This targeted approach can lead to more efficient use of resources and time in the assessment process, as well as more robust and comprehensive results that can better inform strategic decision-making. Complementing this, Table 4 presents an equally important perspective by enlisting the various challenges and disadvantages posed by such integrations. This balanced view is crucial for practitioners to make well-rounded decisions, as it helps them anticipate and prepare for potential obstacles they might encounter in the assessment process. For example, while integrating LCA with EMA might offer a more holistic view of the environmental impacts associated with a circular process, it could also present challenges arising from the very nature of such methods wherein one inherently adopts a donor-perspective, whereas the other one belongs to the receiver-side.

By considering both the advantages and challenges presented in these matrices, practitioners can make more balanced and informed decisions about which integration approaches to adopt. This comprehensive understanding allows them to weigh the potential benefits against the possible drawbacks, ensuring that they choose the most appropriate and effective assessment strategy for their specific needs and constraints. Knowing the potential risks associated with a methodological integration would not only make decision-making efficient but also effective in terms of the reliability and accuracy of the performed assessment.

Moreover, these matrices can serve as a valuable tool for fostering dialogue and collaboration between different stakeholders involved in CE initiatives. By providing a common framework for discussing assessment approaches, they can facilitate more productive conversations between industry practitioners, policymakers, and researchers. This shared understanding can lead to more aligned and effective strategies for implementing and assessing circular processes across different sectors and scales.

The matrices also highlight the dynamic nature of sustainability assessment in the context of CE. As new assessment methods emerge and existing ones evolve, these matrices can be updated to reflect the latest developments in the field. This adaptability ensures that the tool remains relevant and useful in the face of rapidly changing technological and methodological landscapes. Furthermore, the matrices can serve as a starting point for more in-depth exploration of specific integration approaches. Practitioners who identify potentially beneficial integrations through the matrices can then delve deeper into the literature or consult with experts to gain a more nuanced understanding of how to implement these approaches effectively in their specific context.

In the broader context of CE transitions, these matrices contribute to the development of more standardised and comprehensive assessment practices. By encouraging practitioners to consider multiple dimensions of sustainability and the potential synergies between different assessment methods, they promote a more holistic approach to evaluating circular processes. This, in turn, can lead to more robust and reliable assessments that better capture the full range of impacts and benefits associated with CE initiatives.

5. Conclusions

The integration of different assessment methods has been the research effort of many analysts in the last decades. While the approach to using multiple assessment methods to evaluate the sustainability of a product or process has several advantages, such as providing a more comprehensive understanding of the system's impacts, it also has its weaknesses. For example, using too many assessment methods, in parallel or sequentially but not yet integrated, can lead to confusion and inconsistencies in the results, making it challenging to compare the outcomes of different studies. Moreover, each assessment method has its limitations and biases, which can affect the accuracy of the results. In the context of sustainability assessment tools for CE, the dominance of LCA and the environmental component can also be a weakness. Despite being a revered assessment tool, LCAs can have their shortcomings not just in being uni-dimensional but also in terms of its non-absoluteness in being a go-to environmental assessment method. Therefore, a multi-method approach that combines LCA with other assessment methods can provide a more holistic understanding of the system's sustainability performance. While the more commonly known integrations of LCA with its popular counterparts such as the LCC or the S-LCA or with them both via LCSA are quite abundantly found in literature, even in context of a CE, the same cannot be said for the other lesser-known LCA combinations that have been covered within this study. This is even more prominent especially in case of their applications to sustainability assessment of CE systems and processes.

The comprehensive review conducted during this study resulted in the identification of vast categories of combinations of LCA with other assessment methods used in the literature on sustainability assessment tools for CE processes. The identified categories include LCC, S-LCA, EMA, MFA, Simulation, Optimization, along with Spatial Modelling. These methods can provide additional insights into the economic and social dimensions of sustainability, as well as the system's material and energy flows and spatial patterns. However, it is important to note that the optimal balance of assessment methods will depend on the specific context and objectives of the study. Therefore, the review's findings should be interpreted with caution and balanced against the limitations of each method. Moreover, using multiple assessment methods can be resource-intensive and require a significant amount of data, making it challenging to apply in practice. Hence, researchers and practitioners need to carefully consider the trade-offs and practical implications of using a multi-method approach.

The devised matrices, which were among the main results of this study, concisely highlight the key advantages of the different method combinations along with the key challenges in implementing and deploying such integrated methods into practice by the various stakeholders across different system levels. As the field of CE continues to evolve, such tools will play an increasingly important role in guiding the development and implementation of sustainable circular systems across various sectors and scales. Going a step ahead from CE performance assessments to the very point of their sustainability, the proposed methods' integration matrix could be used as a helpful methodological tool for sustainability assessments of various CE activities, facilitating decision-making by policymakers (national/regional governments, communities and corporations) for taking the right steps in the prospect of a CE. It can also help in proposing improvements, changes and key elements for the economic, energy, and especially environmental optimization of processes at varied system levels. It is important to remark that this was not to develop a super-method or a super-indicator to account for every situation or process performance. Instead, the aim was to identify the possible synergies and get a deeper understanding, to look at the performances of a system under a multi-dimensional perspective, and to get a more comprehensive assessment in support of sustainable policymaking. These research efforts are in line with both the complexity of the natural system and the complexity of human societies, which interact dynamically and affect the transition to a CE.

CRediT authorship contribution statement

Jai Verma: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Meletios Bimpizas-Pinis:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Amos Ncube:** Writing – review & editing, Writing – original draft. **Sven Kevin van Langen:** Writing – review & editing, Writing – original draft. **Andrea Genovese:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Amalia Zucaro:** Writing – review & editing. **Gabriella Fiorentino:** Writing – review & editing. **Nick Coleman:** Writing – review & editing. **Patrizia Ghisellini:** Writing – review & editing, Writing – original draft, Methodology. **Renato Passaro:** Writing – review & editing, Supervision. **Remo Santagata:** Writing – review & editing. **Serena Kaiser:** Writing – review & editing. **Spyridoula Fotopoulou:** Writing – review & editing. **Sergio Ulgiati:** Writing – review & editing, Writing – original draft, Supervision.

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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Data availability

Supplementary information is available only upon request.

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