H2020 MSCA-ITN-2018

ReTraCE Project

Realising the **Tra**nsition towards the **C**ircular **E**conomy

D2.5

A roadmap for the integration of assessment methods for the transition towards a Circular Economy

Acronym: ReTraCE

Title: Realising the Transition towards the Circular Economy: Models, Methods and Applications

Coordinator: The University of Sheffield

Grant Number: 814247

Programme: H2020-MSCA-ITN-2018

Start: 1st November 2018

Duration: 48 months

Website: www.retrace-itn.eu

Consortium:

The University of Sheffield (USFD)
Università degli Studi di Napoli Parthenope
University of Kassel (UniKassel)
South East European Research Centre (SEERC)
Academy of Business in Society (ABIS)
Högskolan Dalarna (HDA)
University of Kent (UniKent)
Tata Steel UK Limited (Tata)
Olympia Electronics SA (OE)
Erasmus University Rotterdam (EUR)

Deliverable

Number: D2.5

Title: A roadmap for the integration of assessment methods for the transition towards a Circular Economy

Lead beneficiary: UPN

Work package: WP2

Dissemination level: Public

Nature: Report (RE)

Due date: 30th April 2022

Submission date: 12th May 2022

Authors: Nick Coleman, Gabriella Fiorentino, Sissy Fotopoulou, Andrea Genovese, Patrizia Ghisellini, Serena Kaiser, Amos Ncube, Mariana Oliveira, Renato Passaro, Remo Santagata, Sergio Ulgiati, Sven Kevin van Langen, Jai Verma, Amalia Zucaro.

Table of Contents

1. Introduction

This deliverable of the ReTraCE project further elaborates the results and conceptual frameworks presented in previous reports, dealing with impacts and performance assessment of circular economy policies and processes. This report presents a "conceptual and practical model" that aims at identifying the key stakeholders involved in the transition to a circular economy (CE). Including local communities which assert the roles of both civil society and consumers, these stakeholders span across different organisations and institutions such as companies, state law, and public administration. The transformations that occur at a micro, meso, and macro system level along with the accompanying innovation patterns due to the CE transition, can be evaluated by employing existing sustainability tools, grasping *which* are the potential costs and benefits of implementing CE patterns as well as *which* are main barriers and challenges in implementing them. Therefore, the intended audience of this deliverable will find tools, applications, procedures, and guidelines for an evaluation as complete and organised as possible of the supportive information needed for realising and monitoring the transition from the linear to the CE model in agreement with the three sustainability pillars (environment, economy, and society).

1.1 Goal and Scope

The main goal of this work is to provide support for facilitating a smooth comprehension of the key sustainability tools and the rationale underlying their optimal use (both individually and jointly) to get a synergistic output for facing the CE challenges at stake. The purpose is to show how some of the most used assessment methods (e.g., Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Emergy Accounting (EA), Life Cycle Costing (LCC), Social Life Cycle Assessment (sLCA) can be integrated. The integration has many potential advantages in terms of completeness and effectiveness; however, it retains limitations and challenges. Therefore, we will show:

- A rationale the application of different CE assessment approaches (Section 3);
- An overview of the integration potential of different assessment methods (Section 4);
- Some examples about the most notable integration frameworks, along with their benefits and limitations (Section 5);
- A roadmap for the application of integrated assessment methods, explicitly dealing with different stakeholders' needs (Section 6).

1.2 Target Groups

This deliverable is mainly intended for those stakeholders involved in the decision-making process, both in public and private contexts. However, given the CE and sustainability challenges, the aim is also to achieve the maximum dissemination of the concepts and practices embedded in this framework. In that, academia, governmental bodies, industry organisations, investors, NGOs (including Trade Unions), and communities are considered as potential audiences as well.

1.3 Approach

The approach adopted in this deliverable has followed both a qualitative and quantitative approach, along with deductive and inductive paradigms. The outcome of this study is an integrated sequence of steps and methods, emerging from their application to the systems investigated as case studies.

In turn, this provides useful guidelines on the optimal choice of methods to be adopted depending on the goal to be reached. In this sense, case studies research (offered in this deliverable), in novel topics such as the CE, is very useful for building new theories (Eisenhardt, 1989) using feedback coming from the exploration and understanding of such realities (Prendeville et al., 2018).

1.4 Expected Added Value

The conceptual and practical framework developed in this study is expected to increase the understanding of the role of multi-method approaches in the CE transition and raise the awareness of the importance of developing such assessment tools in tight partnership with all involved stakeholders. This stakeholder engagement approach provides further added value as it increases the effectiveness potential of policy measures for the CE transition, by stimulating awareness and participation (Provasnek et al., 2017)

2.   The transition to a Circular Economy

This section focuses on the transition towards a CE as a timely issue in European Policy; it also highlights the relevance of General System Theory to such a transition, claiming that an overview of the latter is essential for a better understanding of how to address both the challenges in CE transition as well as the current environmental, socio-economic and governance challenges.

2.1 Circular Economy in the current European Political Framework

During the last years, the CE model has received increasing attention within the European Policy. The European Union assigns a relevant role to CE in the European Green Deal adopted in 2020 to tackle the climate change challenges and the high environmental degradation as a consequence of the unsustainable exploitation of the natural environment. In that, the Green Deal should move the EU towards the achievement of climate neutrality by 2050, decoupling economic growth from resource use and achieving a more inclusive and just economy. These goals will also be an opportunity for enhancing the recovery of the European economy and improving its resilience during (and after) the current COVID-19 pandemic. The Green Deal will receive about one-third of the total investments (1.8 trillion euros) of the Next Generation EU Recovery Plan and the EU's seven-year budget, showing the commitment of the EU towards environmental goals (European Union, 2022).

Within this framework, the new CE Action Plan (European Commission, 2020) has been adopted to further accelerate the transformation of the European economy towards the goals of the EU Green Deal by strengthening the actions implemented in 2015 with the first Circular Economy Package (European Commission, 2022). The new CE plan is then a key document for understanding the major areas of action, the type of policy and legislative tools, and goals set by the European Union. The CE Action Plan offers an opportunity for understanding the participative approach of the EU towards the CE since it is championed as: "a future-oriented agenda for achieving a cleaner and more competitive Europe in co-creation with economic actors, consumers, citizens, and civil society organisations". This resembles the more general approach of the environmental policy of the EU by calling for the action and responsibility of all the societal stakeholders.

However, the high number of stakeholders involved in socio-economic relationships adds a level of complexity to the decision-making (Delli Gatti and Gallegati, 2001; Ghisellini et al., 2016). Despite this related level of complexity, CE promotes holism, system thinking, organisational learning, and the development of human resources (Ghisellini et al., 2016; Capra, 1995; Odum, 1996; Swanson, 2001; Jackson, 2003; Senge et al., 2010). As a result, it will be important for research to assist policymakers in developing frameworks and guidelines capable of responding to these needs. In this deliverable our framework will take advantage, among the others, of the principles and instruments of "General System Theory". Subsection 2.3 will briefly provide an overview of this theory and elaborate on how it could be useful in supporting the political agenda.

2.2. Who are the stakeholders in the transition towards a Circular Economy?

"The transition to the circular economy will be systemic, deep, and transformative, in the EU and beyond. It will be disruptive at times, so it has to be fair. It will require an alignment and cooperation of all stakeholders at all levels - EU, national, regional, and local, and international."

European Commission (2020). A new Circular Economy Action Plan For a cleaner and more competitive Europe.

A stakeholder is anybody (internal or external, at senior or junior levels) who can affect or is affected by an organisation, process, strategy, or project. Stakeholders' identification is the first important step for communication, engagement, and the success of the actions taken (Bonnafous-Boucher and Rendtorff, 2016; Freeman, 2010). The identification should consider different variables (such as liability, influence, proximity, dependence, and representation) and, different methods can be applied to properly investigate the relationships between them, and their consequent involvement in the appropriate stages of decision making (Arsova et al., 2021). Moreover, for an effective transition to the Circular Economy, at least six groups of stakeholders should be considered: academia, governmental organisations, industry, investors, NGOs (including trade unions), and Communities (Arsova et al., 2021). More details can be found on the previously published Deliverables: D3.1 - A framework for Engaging Stakeholders in the Transition towards a Circular Economy and D4.2 - Mapping stakeholder interactions for designing CE policies in regional contexts.

2.3 Systems thinking, beyond linear approaches

The complexity of nature (evolution, biodiversity, resources, ecosystems) as well as of human societies with their diverse aspects and trade-offs (culture, economies and resource trade, environmental issues, local community lifestyles, well-being level, population growth, among others) clearly shows the impossibility of managing one aspect per time in a deterministic way, as if they were independent and not affecting to each other.

When designing a circular economy policy, the most important thing is to remember that we are dealing with a complex system; as such, implementing a process that reduces some impacts locally might increase the same or other impacts elsewhere or on another time scale. For this reason, it is crucial to integrate different approaches at different spatial-temporal scales, to allow an evaluation of the different dimensions and control over the whole process. In so doing, all aspects are highlighted and the process is considered in its multidimensional feature, which makes it easier to

develop a transparent and productive discussion with stakeholders, to adequately appreciate criticisms and new proposals, to promote collaborative efforts, and finally to prevent conflicts about the policy to make and its related consequences.

Since one of the main pillars of the CE is preventive planning, aimed at radical changes and innovations in the process structure and dynamics, system thinking is the most appropriate way of looking at the process itself in a perspective that helps prevent impacts (for example, excessive or inefficient consumption of resources) rather than remedying a posteriori through forms of recycling (and perhaps generating new impacts).

Linear approaches most often disregard the relations of the local system with its surrounding environment as a source and sink of resources and ignore the links among different activity sectors and the environmental impacts these activities generate (resource depletion, emissions). In so doing, they are unlikely to ensure the sustainability of economic processes and, in the long run, the survival of human societies within a diverse and resilient environmental framework. Some aspects of a system's functioning cannot be understood and properly managed if they are only looked at from the inside. As systems ecologist H.T. Odum used to say, systems can only be understood from the next larger scale, i.e., looking at them through a "macroscope", not just a microscope, capable to highlight the evolving relations of each system´s component with the other inside components and, very important, the relations of inside components with the external environment where resources and driving forces come from. Finally, relations are based on exchanged flows that must be assessed and measured in terms of their quality (chemical, environmental, thermodynamic, social, embodied generation time, footprints) to integrate quantitative mass and monetary measures. Consequently, the quality of exchanged flows and feedback relations become a crucial aspect to understand and manage complexity.

Systems thinking is still unfamiliar to businesses and policymakers. Looking at a system instead of the sum of its parts, is a very infrequent exercise. Developed after the pioneering works by Lotka (1922), von Bertalanffy (1969), Georgescu-Roegen (1971), and Odum (1988; 1994; 1996) systems thinking is increasingly becoming the most appropriate framework tool to face the complex challenges posed by increasing population, shrinking resource basis and increased demand for quality of life on planetary sustainability.

In short, systems thinking stems from the awareness that a sufficiently complex system, be it physical, ecological, social, or economic, exhibits nonlinear and self-organising behaviours, that cannot be reduced to a set of linear cause-and-effect chains ruling the behaviour of components at a local level. As stated by Perosa et al. (2019): "Typically, the existence of a network of feedbacks in the system allows it to react and rearrange in ways that can be described or predicted only considering its entire structure. In the systems thinking framework, a pivotal role is played by the creation of a systemic diagram, which also plays the epistemic role of clarifying the feedback loops operating the system and the basis for the setting up of analytical systemic simulators." (Perosa et al., 2019).

2.4 System diagrams

Complexity is not easily described through words. Components, processes, storages, inflows, outflows, feedbacks, and positive as well as negative interactions, are all concepts and aspects that need to be graphically shown for a deeper understanding of a system's wholeness. H.T. Odum (2002) has developed a stock-flow system diagramming language to explain and describe ecological

relationships using energy systems concepts, capable to fit ecological systems, including human-dominated sub-systems and processes. Brown (2004) further stressed the set of potential uses of the systems language, showing how it represents a concise way of visualising systems, describing them mathematically, and developing programs for simulating their dynamic behaviour. Figure 1 provides an example of an urban system embedded within the regional area, and the main economic processes taking place, highlighting its main components and steps of socio-economic activities, its driving forces from the environment (renewables and non-renewables), and the economy (imported), its waste and polluting emissions, feedbacks, labour flows, economic flows. In so doing, each system can be managed and improved while its performance can be evaluated more comprehensively. Further, Figure 7 in the following Section 5.4 clearly shows the recycling patterns (feedback flows) and the boundaries of interest for each assessment method within a circular economy framework.

2.5 Systems thinking and circular economy policymaking

Having in mind the main characteristics of a circular economy, i.e., its so-called pillars (preventive design, use of renewables, recycling and reusing, environmental system regeneration, appropriate circular governance) it is not difficult to identify in systems diagramming and system thinking the main features of circular approaches. No matter which method is selected to assess the performance of a process, there is no doubt that the complex nature of economic and environmental processes requires a comprehensive understanding of the whole system, the identification of steps and hotspots, the implementation of suitable feedbacks, an appropriate assessment of the quality of resource flows and conversion processes, within the larger frameworks of global economy and biosphere.

The challenge to business and policymakers as well as stakeholders is to change the way and the perspective we look at resources and processes, from "take, make, dispose" to "design, understand, process & use, recover, regenerate". The sustainability of our economies does not depend on a "more of the same" attitude (extracting additional energy and minerals from underground, designing new energy technologies, growing the economy by increasing markets and accelerating trade flows, and so on), but instead designing new lifestyles and production and consumption patterns capable to enhance the system's features of the biosphere (constraints, regeneration, synergies) and take the largest benefit out of the limited amount of planetary resources.
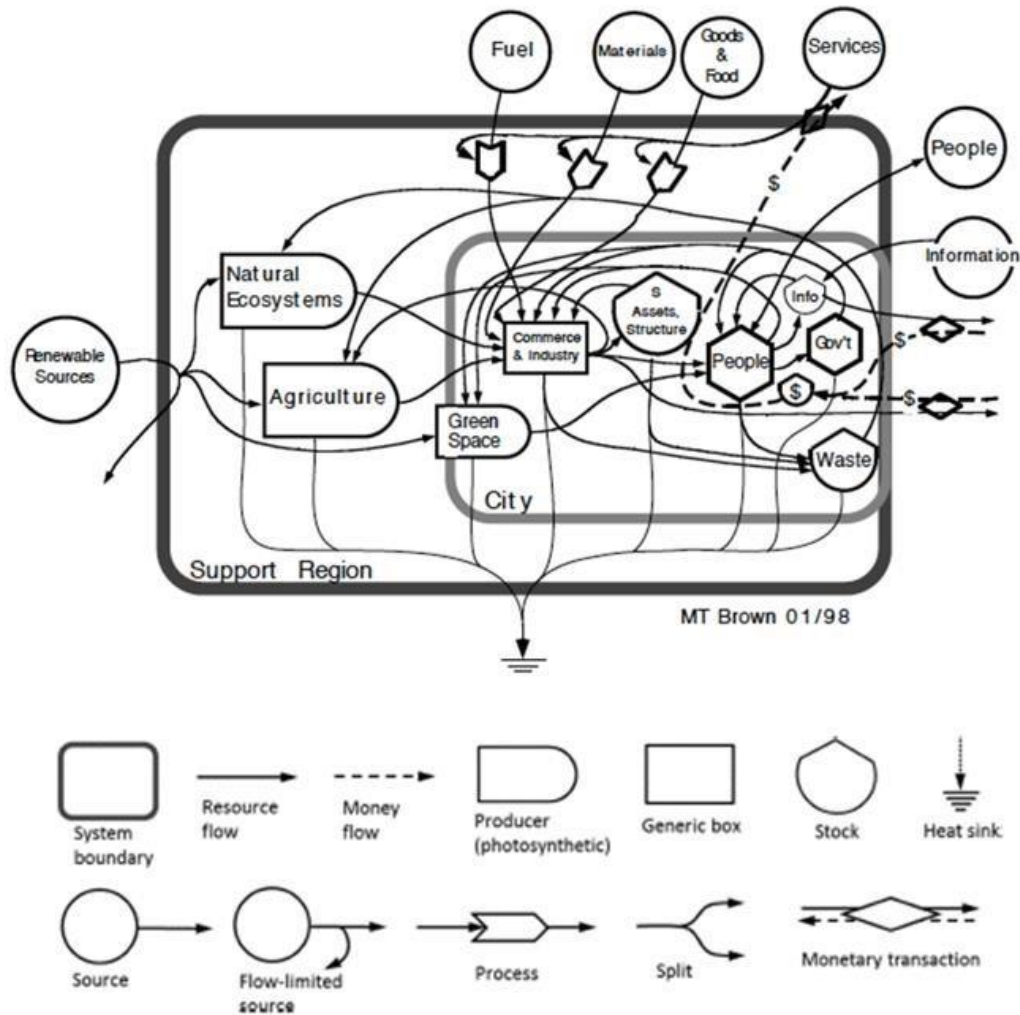
Figure 1. Stock-Flow system diagram of an urban system and its supporting region (downloaded from the open access Emergy Systems Website, Center Environmental Policy, University of Florida, USA). Systems symbols from Odum, 1996.

3.   How do assessment methods interact?

The focus of this section is aimed at further advancing the assertions and contentions of the previous ReTraCE deliverables, particularly D2.1. *(Integrated Assessment of Sustainability Profiles in Circular Production Systems. A Framework towards a comprehensive understanding).* Appropriate tools for assessing CE implications are much needed to assist decision-making at different sustainability dimensions (i.e., environmental, economic, and social) and different scales (i.e., micro, meso, and macro). Figure 2 provides an overview of some of the assessment methods, scales of implementation, and their contribution to understanding and pursuing sustainability challenges and policies. An exhaustive description of the methods indicated in Figure 2 can be found in Deliverable ReTraCE D2.1 as well as in Oliveira et al. (2021a). Instead, a summary of these methods can be found in the following Section 5.4.

In the present deliverable D2.5, we aim to expand the focus towards the development of a comprehensive roadmap that can clearly define the steps and desired outcomes towards circular economy-related assessments. The roadmap will act as a communication and referral tool, helping to indicate appropriate methods that can be used to measure and monitor progress towards the CE transition. The development of a roadmap will follow relevant steps for it to be robust and capable of providing practical assistance to practitioners and different stakeholders in choosing the appropriate tools and method(s). The first steps entail searching for the relevant background data and information through various means including the following: data mining, reviews of literature, analysis of national and international statistical data, reviews of existing and emerging regulations, questionnaires, on-site investigations, and meeting stakeholders to understand their needs and determining the scope of a CE assessment. The scope of a CE assessment can be based on the following sustainability dimensions: environmental, social, and economic. The second step is to then choose and select the most appropriate methods for CE assessment. While each method may answer specific questions, there is also the possibility of synergies and interactions. As such, an appropriate methodological selection should depend on the following: (i) the needs and challenges of the stakeholders; (ii) the sustainability dimension(s) to be assessed; (iii) the scale of assessment; (iv) expected outcomes for decision making.

Performance and sustainability indicators, based on robust conceptual understanding and standardised methodological framework are urgently needed, to support appropriate environmental, social, and economic policies. We propose to look beyond single-dimensional to a multi-dimensional evaluation framework that could propel and advance CE assessments. In doing so, we suggest 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) through the development of a methodological matrix.
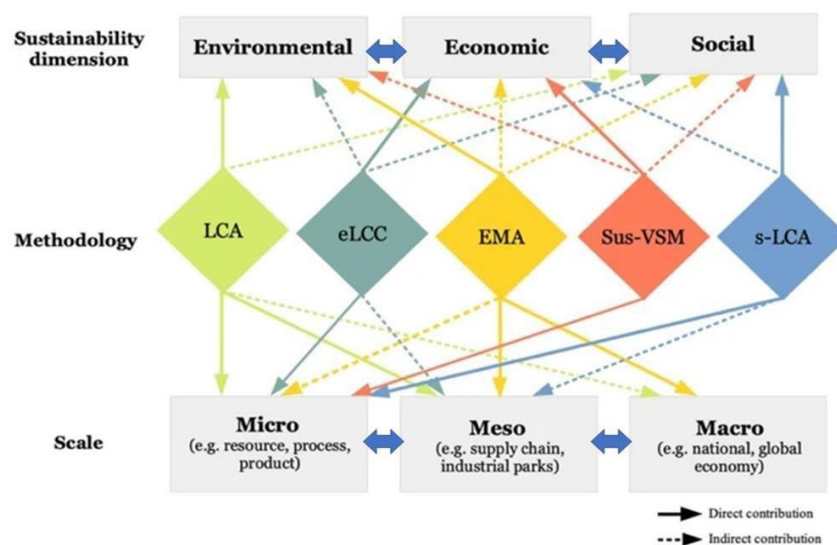

Figure 2. Overview of the assessment methods, scales of implementation and their contribution to understanding and pursuing sustainability challenges and policies (from ReTraCE deliverable D2.1 and Oliveira et al., 2021a). See Section 5.4 for a short summary of these methods.

4. Matrix of the integration of the methods

Table 1 contains the matrix lists and describes all the adopted methods that can be applied depending on the sustainability dimension. The matrix presents methods in the current literature. Moreover, their application and limitations as single tools will be highlighted in the next subsection 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 a more comprehensive and credible roadmap. Of course, in this regard also a multi-method roadmap has its weaknesses requiring the identification of the optimal balance.

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 review was conducted to identify the most common categories of combinations with other assessment methods. Following a preliminary search to identify the main keywords that were used to categorise these papers, a search was run on the Scopus database using the following string of keywords:

("hybrid*LCA" OR "integrat* LCA" OR "combin* LCA with") OR ("LCA" AND "integrat* methods"))

Excluding conference papers, book chapters, letters, books, notes, and editorials from the results, as well as papers in a language other than English, a manual cross-checking process was conducted to eliminate papers that were not related to the scope of this search. At the end of this process, 150 papers were selected out of 367. The key categories that emerged and were subsequently used for the development of the matrix are namely, Life-Cycle Costing (LCC), social Life-Cycle Assessment (s-LCA), Emergy accounting (EMA), Material Flow Analysis (MFA), and Simulation, Optimisation along with Spatial modelling.

Table 1. Matrix of integration of evaluation methods

	Life Cycle Assessment (LCA)	Life Cycle Costing (LCC)	Social Life Cycle Assesment (s-LCA)	Emergy Accounting (EMA)	Material Flow Analysis (MFA)
Life Cycle Costing (LCC)	Alejandrino et al. 2022 (A) Diaz et al. 2021 (I) Miah et al., 2017(A) Cobo et al., 2019 (D) Angulo-Mosquera et al. 2021 (A) Santillán-Saldiva et al. 2021(A) Schaubroeck et al. 2021 (A) Subramanian et al. 2021(A) Garcia-Muiña et al. 2018 (A)				
Social Life Cycle Assessment (s-LCA)	Kaiser et al. 2022 (I) Tsalis et al. 2021 (A) Angulo-Mosquera et al. 2021 (A) Santillán-Saldiva et al. 2021(A) Schaubroeck et al. 2021 (A) Subramanian et al. 2021(A) Garcia-Muiña et al. 2018 (A)	N/A			
Emergy Accounting (EMA)	Oliveira et al. 2021b (A) Wang et al. 2021 (A) Jiang et al., 2018(A)	N/A	N/A		
Material Flow Analysis (MFA)	Meglin et al. 2022a and 2022b (A) Cobo et al., 2019 (D) Sun et al., 2017 (D) Millward-Hopkins et al. 2017 (A)	Cobo et al., 2019 (D) Nakamura and Kondo, 2018 (A)	Wallsten, 2015 (D) Hosseinijou et al., 2014 (A)	Sun et al., 2017 (D)	
Simulation, Optimisation and Spatial Modelling	Santagata et al. 2022 (I) Thakker and Bakshi, 2021(I) Solis et al. 2021 (A) Senan-Salinas et al.2020 (D) Taskhiri et al. 2019 (I) Loiseau et. al, 2018 (D) Cobo et al., 2019 (D)	Cobo et al., 2019 (D) Byrne et. al., 2007 (D)	Hosseinijou et al., 2014 (A) Wallsten, 2015 (D)	Kocjančič et al., 2018 (I) Mellino et al., 2014 (D) Taskhiri et al., 2010 (A)	Tirado et al. 2021 (D) Lambrecht and Thißen, 2015 (A) Hosseinijou et al., 2014 (A) Cobo et al., 2019 (D)

Integration Levels: (D) Database, (A) Assessment, and (I) Interpretation

N/A: No integration available

5. Methods integration

The integration of different assessment methods has been the research effort of many analysts in the last decades. 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 possible synergies and 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 the human societies which interact dynamically and influence the transition to CE.

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, Material Flow Accounting, Life Cycle Assessment, micro-, and macro-economic assessments, by developing multidimensional indicators as well as normalisation and weighting factors. Many other authors have made important steps ahead towards parallel, sequential, and actually integrated assessment procedures, but their use in policymaking, stakeholders' engagement, and business innovation have not yet gained sufficient attention towards increased environmental, social, and economic sustainability. One of the goals of this deliverable is to contribute to filling this gap. In the next sections, some of the contributes listed in the matrix of previous Table 1 are discussed highlighting the potential of integration in terms of a larger comprehension of the phenomenon under analysis.

5.1 Material Flow Analysis

5.1.1 Integration of MFA and LCA

Meglin et al. (2022a; 2022b) integrated Material Flow Analysis (MFA) and Life Cycle Assessment (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., 2022b) to check the robustness of the model and to see if it has reasonable uncertainties to confirm 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 can help formulate effective policies that are tailored to specific aspects and have clear objectives.

In another endeavour of methodological integration of MFA and LCA at the assessment level, Millward-Hopkins et al. (2018) presented an integrated modelling approach for value assessments, focusing on resource recovery from waste. The devised method tracked and forecasted a range of values across environmental, social, economic, and technical domains by attaching these to material

flows, thus 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. And hence 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 type typology encompassing varied 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; 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 impacts downstream 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.

5.1.2 Integration of MFA and EMA

Sun et al. (2017) developed an integrated material flow analysis (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 with MFA, and further ecological impacts were evaluated with the Emergy approach and an Emergy index. Specifically, the integration of the two methods allowed the conversion of material flows into Emergy ones, as shown in the following Figure 3.

5.1.3 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 to find system configurations that minimize 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 tools, deploying a deep integration of individual databases through a structured integration framework involving multiple layers of exchanges of data. A multi-objective optimisation 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. Further integration of MFA and LCC was proposed by Nakamura and Kondo (2018), who developed a dynamic Waste Input-Output model.
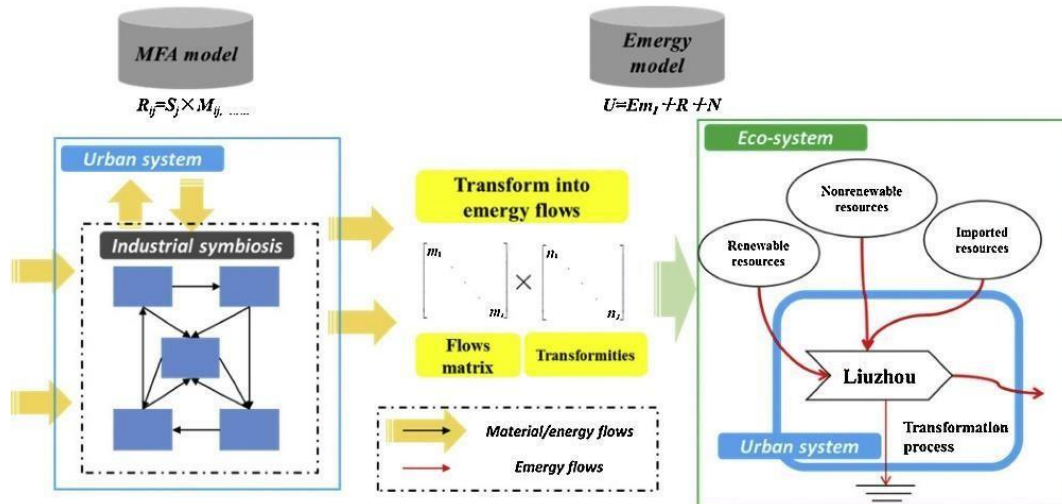
Figure 3. Integration of MFA and EMA methods (Sun et al. (2017)

5.1.4 Integration of MFA and sLCA

Hosseinijou et al. (2014) recognised the need to assess the social impacts of materials along the full life cycle, not only to address the "social dimension" in sustainable material selection but also to potentially improve the circumstances of affected stakeholders. To achieve that, they the social life cycle assessment (sLCA) method. The method conforms to UNEP/SETAC "guidelines for social life-cycle assessment of products" and includes the classical four main phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation. However, in the life cycle inventory analysis phase, a hot spot assessment is carried out using material flow analysis 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. The above-mentioned paper from Wallsten (2015) also 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 socioeconomic conditions for urban mining.

5.2 Life Cycle Assessment

5.2.1 Integration of LCA and Life Cycle Costing

The integration of LCA and LCC has been proposed by several authors in the literature. The paper from Alejandrino et al. (2021) introduces a combined framework that follows the requirements of ISO (2014, 2006a, 2006b), Martínez-Blanco et al. (2015), and UNEP/SETAC Life Cycle Initiative (UNEP, 2015). Specifically, the goal of the study is to obtain the environmental and economic performance of some scenarios; the same system boundary is adopted for the environmental and economic analyses. Finally, this stage also needs to define the reporting unit (UNEP/SETAC Life Cycle Initiative, 2015). Two differentiated environmental (mainly based on secondary data) and economic (mainly based on primary data collection) inventory models are developed ensuring they are consistent with the goal and scope of the study. In the impact assessment phase, classical LCA

indicators (CML-IA; ReCiPe) are combined with the most common economic indicators (Total Annual Cost; Payback Period). Results are presented in an integrated way, through eco-efficiency graphs. On the x-axis, these graphs present the environmental impact and on the y-axis, they show the economic impact, which allows each alternative scenario to be located in one of the four eco-efficiency areas.

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 cases, the integration of these approaches happens at the results interpretation level, through Multi-Criteria Decision-Making methods. LCA and LCC methods have also been combined to evaluate CE strategies in organisations (Alejandrino et al. 2022). In this study, several CE scenarios were assessed in terms of their eco-efficiency.

5.2.2 Integration of LCA and Social LCA

A notable integration of 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. Social life cycle assessment (sLCA) accounts for 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 sLCA 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 sLCA 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 analyses, a cradle-to-gate approach was used. Thus, the selected system boundary (Figure 4) accounts for the physical limits of the investigated community, including the installation and maintenance of the PV panels and the electricity production and 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 reflections on the complexity of sLCA performance. Indeed, several elements are currently discussed among practitioners.

One of the most relevant is the use of functional units (FU) (D'Eusanio et al., 2018). Since social impacts need to be considered in a comprehensive perspective, the study follows the idea - proposed by many other works - to assess the impact caused by 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 the "virtuous" goods and services may be conceived as participating in the negative impacts as well, since ethical issues are way more pervasive and unrestrained than polluting emissions and environmental impacts. This may cause challenging situations when the integration between sLCA and sLCA is needed. The necessity to adopt a behaviour-oriented sLCA 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 sLCA results was made feasible due to the qualitative and semi-qualitative nature of sLCA indicators, characterised by the possibility to be flexibly adapted to any FU that sLCA might have needed. sLCA was performed with no use of databases, choosing indicators related to energy justice studies and adapted to the specific situation of the Solidarity Oriented REC.
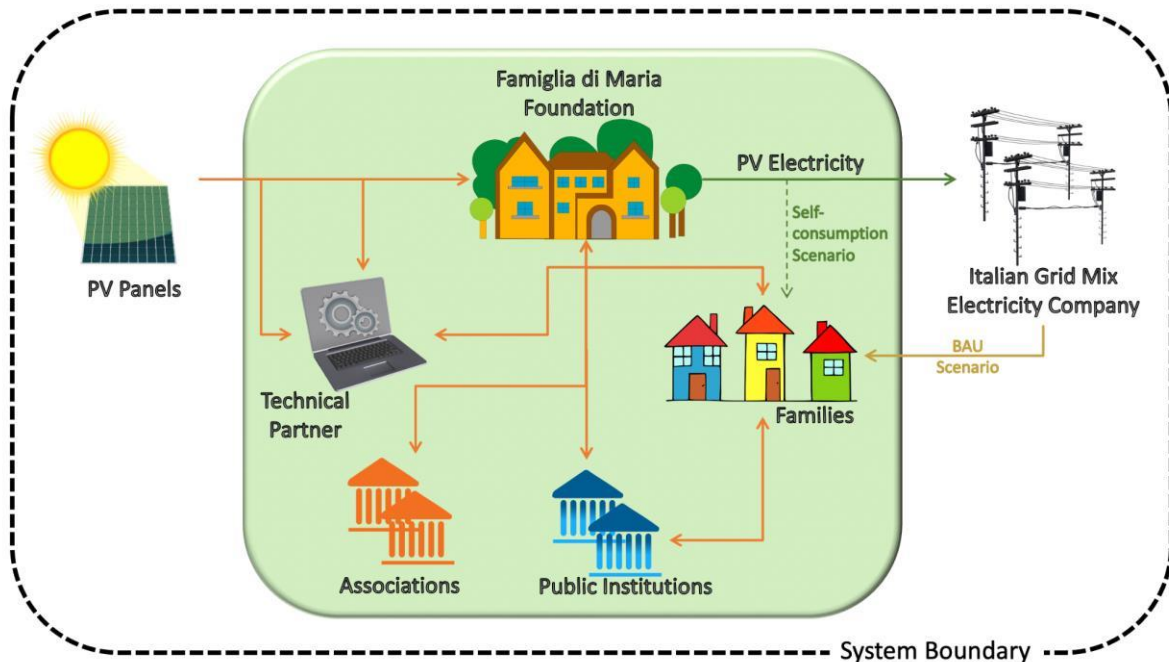

Figure 4. The system boundary of the investigated Solidarity Oriented Renewable Energy Community of San Giovanni a Teduccio (Naples) (Kaiser et al., 2022).

5.2.3 Integration of LCA and EMA

For the environmental dimension, there has been an attempt within the ReTraCE project to apply and integrate exergy-aided LCA and eMergy accounting 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 similar inventories and multiplying input flows by proper conversion factors to achieve the 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 (LCA and EMA Applied Framework) procedure, described in Figure 5. 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 analyses, to verify the reduction in terms of environmental impacts.

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 and preventing double-counting in circular patterns, to calculate UEVs of co-products according to the Emergy algebra and the general LCA procedures that suggest allocation to be avoided to the largest possible extent. Further, the Lyu et al. 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.
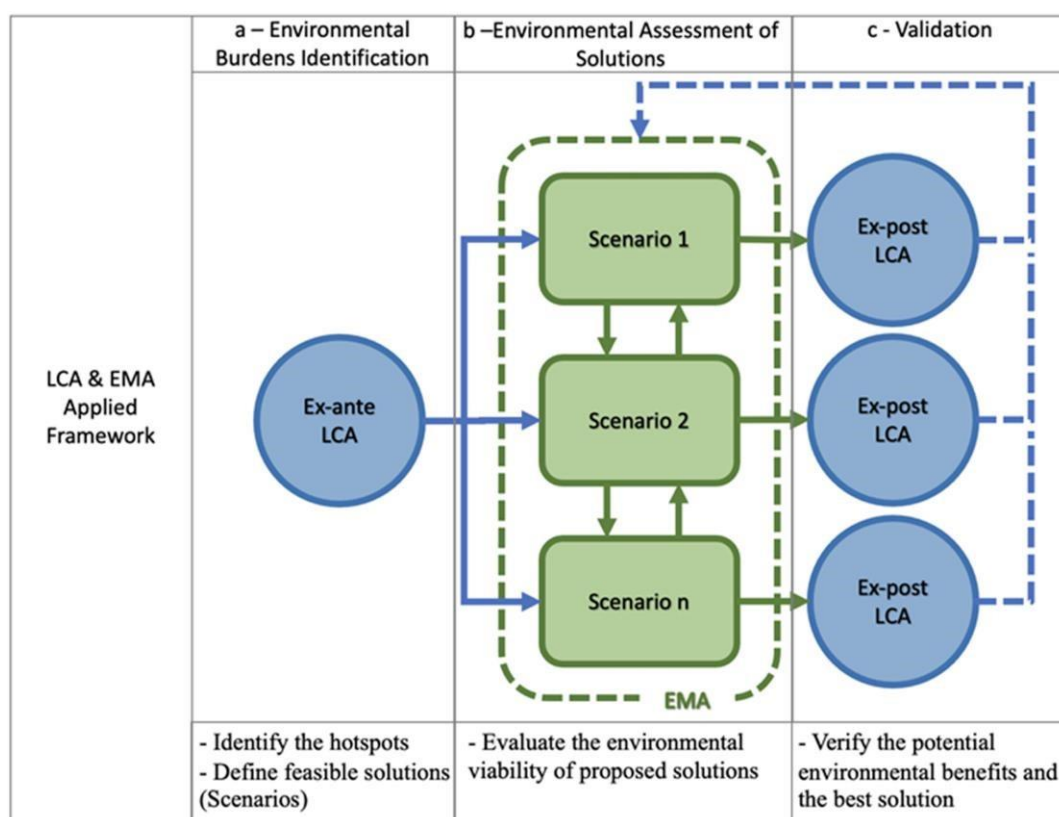
Figure 5. LEAF Framework based on the integration of Life Cycle Assessment (LCA) and Emergy Accounting (EMA) methods (Santagata et al., 2020; Oliveira et al., 2021b).

5.3 Simulation, Optimisation and Spatial Modelling

5.3.1 Integration of Spatial Modelling with LCA

Another attempt at methodological integration has been the application and convergence of the iTree Canopy tool and the life cycle assessment (LCA) methods to evaluate the potential for and the benefits of augmenting tree cover within the Metropolitan City boundaries of Naples in Italy. The results highlighted that tree cover could potentially increase by about 16%, thus generating 51% more benefits in terms of pollutant removal (CO, NO2, O3, PM10, PM2.5, and SO2), carbon

sequestration, and storm-water management. 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, or quantifying the available construction waste to be recovered, as described above) (Cristiano et al., 2021).

5.3.2 Integration of Resource Use Simulation with Economic Modelling

The Multi-objective Optimisation 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 optimisation of benefits based on improved use of water and energy resources. A Multi-Objective Optimisation Model based on the Random Forest-GENIE3 algorithm and improved Quantum Particle Swarm Optimisation algorithm were developed 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 (Liu et al., 2022). The 2013-2019 "water-energy-economy" dependency relationships and the trends of the coordinated development have been investigated, followed by simulations of 16 different steel industry scenarios aiming at an optimal development path. Results firstly point out the weakness of the current "water-energy-economy" triple dimension dependence relationship in China's steel industry. The simulation of scenarios suggests that priority to the reuse of scrap steel (increased circularity, beyond the still insufficient 10% scrap use in China), while 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 here is clearly among simulation modelling tools, economic assessment, and resource use efficiency.

Kocjančič et al. (2018) present an innovative attempt to incorporate biophysical criteria into a standard socio-economic optimisation model, illustrated through a study of the Slovenian dairy sector. The biophysical perspective on the system's functioning is determined by employing EMA. Authors develop an optimisation 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 optimisation model is supported by weighted goal programming (WGP) and aims 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 and Emergy approaches and provide implications for more comprehensive planning of an agricultural activity.

Lambrecht and Thißen (2015) provided an interesting integration of MFA and optimisation techniques, recognising the potential of material flow networks' flexibility for mapping industrial supply chains. MFNs can be particularly useful for analysing complex industrial production systems. While MFNs can be employed in a purely descriptive way to visualize 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. Authors define a material flow-based optimisation problem (MFBO) as a mathematical program (MP) through an *algebraic transformation*, which also renders the application of powerful and efficient state-of-the-art solvers of mathematical programming possible.

Also, in recent years, several papers attempted to integrate, within a simulation framework, Value Stream Mapping with LCA. Generally two approaches are adopted. The first approach is to

integrate LCA and VSM into a new method (Paju et al., 2010; Mousavi et al., 2016). The second approach is to jointly use VSM and LCA directly in a single study (Djatna and Prasetyo, 2019; Vinodh et al., 2016). 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 with 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 use for any given industrial process. The output of Sus-VSM makes for good input data for an LCA study. Integrating Sus-VSM with LCA also allows to properly study any hypothesised improvement on a production process with one or more scenarios (Salvador et al., 2021), as shown in Figure 6.
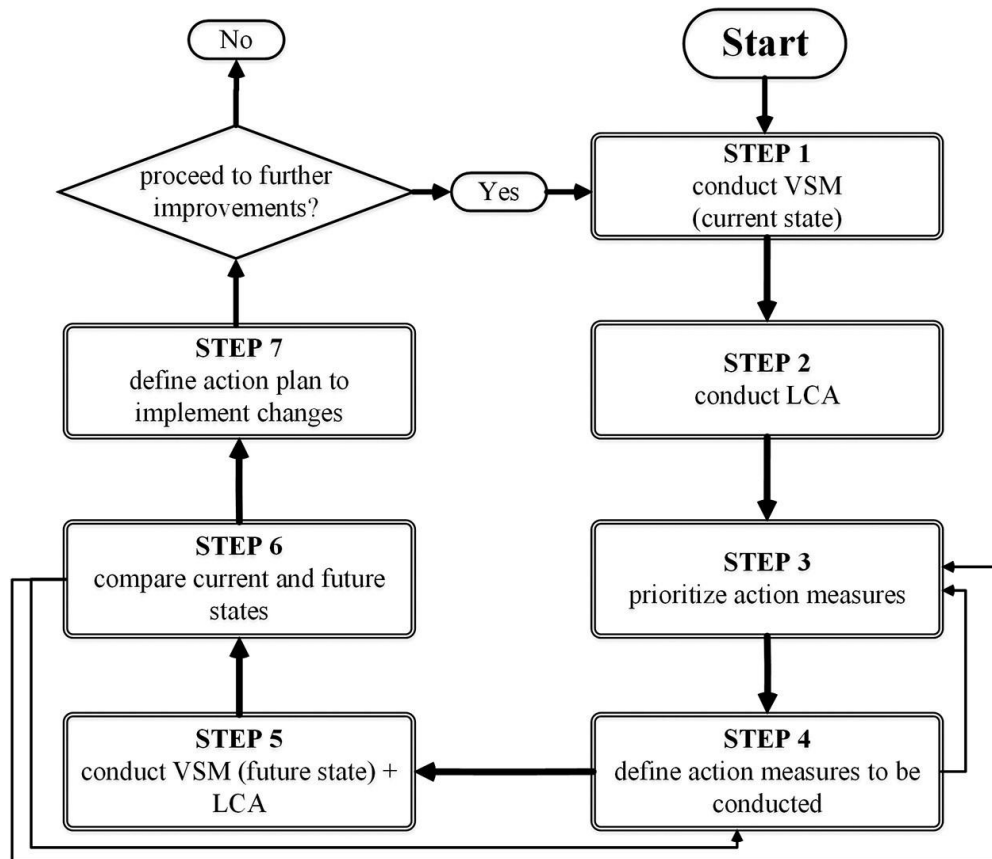

Figure 6. Steps to take when analysing an existing and future state scenario using both VSM and LCA (Salvador et al., 2021).

5.3.3 Integration of Spatial Modelling with EMA and MFA

A further 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 (southern Italy) by accounting for the environmental support directly and indirectly provided by nature to resource generation. Furthermore, geographic information system (GIS) models are integrated with the Emergy accounting procedure to generate maps of the spatial patterns of both natural and human-made capital distribution. Through the application of these methods, authors highlight that only the 19% of the regional natural capital appears to be concentrated within protected areas, while most of it (81%) is concentrated outside; these findings suggest that the conservation of natural resources is also necessary outside protected areas employing suitable

policies, directives, and investments. The proposed Emergy-GIS framework reveals to be a useful tool for environmental planning and resource management aimed to conserve and protect the regional environmental heritage.

Wallsten (2015) combined geographic information systems (GIS) and material flow analysis (MFA) for the analysis of urban mining solutions. The approach couples spatially informed size estimates of urban metal stocks to the equally spatially contingent efforts required to extract them, overcoming the classical limitations of MFA assessments, which often stop at the first of these two phases, meaning that essential information needed to facilitate resource recovery is missing from their results.

5.4 An integrated view of circularity assessment

Figure 7, which uses the systems diagram language developed by Odum (1996), graphically highlights how selected different methods can approach systems from different perspectives, simultaneously assessing environmental, social and economic features. 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 materials are 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 in the economy after repairing/recycling/remanufacturing, while non-reusable fractions are directed to 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 a virtual storage of assets. Assets and products exchanged with the external market deliver the needed economic support for 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 Figure 7), 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: the LCA 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. Based on several impact methods that can be used for the classification and characterisation of environmental impacts, different kinds of indicators can be calculated.
- S-LCA: this method adopts a perspective similar to the environmental LCA, accounting for 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 recycle.
- VSM is a technique for the 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 energy, measured as solar emjoules, used in transformations for delivering products and services. It accounts for local and non-local, renewable and non-renewable sources from a donor 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 circular economy systems.
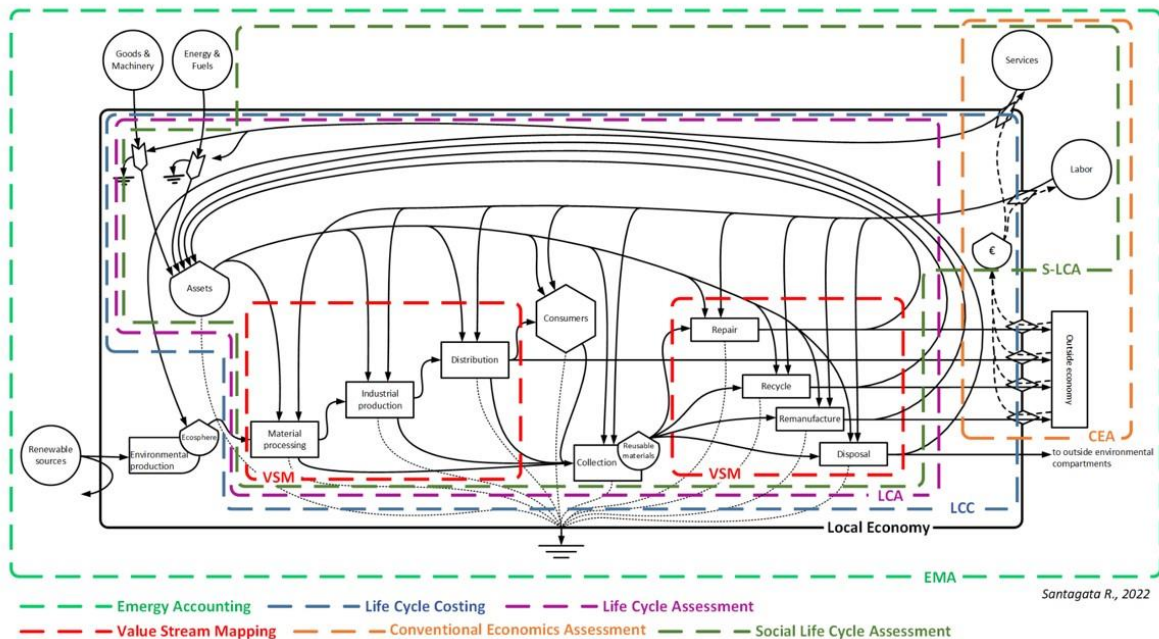
Figure 7. System diagram highlighting the applicability and specific scopes of different methods.

These methods have been implemented, throughout the scientific work described in this deliverable, to achieve a holistic understanding of such complex systems as Circular Economy and circularity implementation. 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 risk of misunderstanding perspectives and results: each method has been designed to answer to 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" does not exist, but a method 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 circular economy scenarios. This can promote a holistic, multi-criteria approach for decision making and environmental/social/economic management.

5.5 Strengths and weaknesses of assessment integration

In addition to the LCA and EMA integration at the results interpretation level, the 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 further evaluate the achieved results step by step by 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 LCA and EMA interpretations 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 back to the sixties in the business administration academic domain (Hill and Westbrook, 1997; Andrews 1971, 1980). However, over time its use has been expanded considerably beyond private organisations towards local public administrations, 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 multi-criteria evaluation and integration tool since it collects and evaluates data of different nature and origin 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 judgement about the evaluation methods used to design, understand and support a policy or a project.

In the most recent study by Cristiano et al. (2021), the authors evaluated spatial data about the available buildings in the Metropolitan City of Naples and primary data of C&DW flow streams. Spatial data have been collected by means of the i-Tree Canopy tool in order to estimate the amount of C&DW stocked in the existing buildings of the Metropolitan city of Naples, while primary data (annual amount of C&DW flows and material composition) were collected by the Regional Agency for the Protection of Environment and by means of qualitative analysis on field (Interviews) (see Figure 8).

Table 2. SWOT matrix with example queries for each quadrant. Adapted from https://www.semrush.com/blog/swot-analysis-examples/

| 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 better do than the system?* *What resources do 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?*
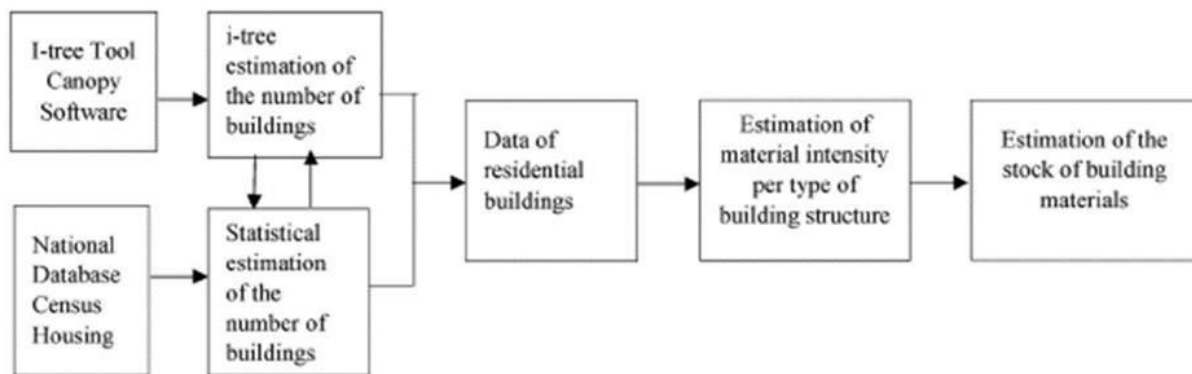
Figure 8. Procedure for the estimation of the building materials available in the Metropolitan City of Naples. (Source: Cristiano et al., 2021)

5.6 Benefits and limitations

The methodological integrations of real case studies as demonstrated by the reported examples have highlighted the possibility of complementary and more comprehensive approaches, thus minimising the risk posed by single methods in analysing complex systems. The integrations are beneficial in increasing indicator metrics for 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. However, the valuable contributions provided by other methods should not be disregarded. LCA provides a deep focus on the local scale of processes, thanks to its ability to "monitor" inflows and outflows in each process step and assign to these flows an impact characterisation 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 characterisation 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 so doing, the two approaches benefit from each other in that they can be 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, of needed investments in innovative research and infrastructures. Therefore, the combination of LCA and EMA indicators provides a much broader and 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 norms discourage allocation in favour of boundary expansion, while EMA never allocates to co-products assigning to them the total Emergy driving the investigated process. However, within the LCA method, the largest

allocation fraction is commonly assigned to the main function or product, in so recognising 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 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-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 energy. When one method applies allocation, and the other does not, it then becomes difficult to compare their results, thus leading to 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 to track back to a correct inventory and generate appropriate UEVs. Additional study is 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 so 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).

Some steps ahead have been performed by developing LCC (Life Cycle Costing) and sLCA (Social Life Cycle Analysis) approaches and databases, although still in a phase of relative infancy.

However, LCC and sLCA as well as other footprint and flow-oriented methods (Carbon Footprint, Water Footprint, Material Flow Accounting, Value Stream Mapping, among others) should all be considered complementary and very important 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 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 that consider 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 to other approaches) relies on a scientifically strong and comprehensive basis and can be applied through a flexible roadmap. A concerned administrator, business operator, policymaker, and stakeholder will find in this set of integrated methods a solid starting point to deeply understand the details of the issues at stake.

From the analysis of 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 circular economy policies and processes performance. This integration is likely to ensure several potential advantages in terms of

completeness and effectiveness, which 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, the boundary of systems, different characteristics of environmental, social, and economic issues) and still need to be solved. The adoption and the development of a roadmap for the implementation of such a multi-dimensional and multi-perspective integration process are crucial to the success of transitioning to circular economy 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 roadmap to circularity, based on a stakeholders' engagement approach, will support policymakers 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.

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 of **both Environmental** and **Economic account/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 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, Optimisation and Spatial Modelling	**Augmenting Spatial** and **Temporal Boundaries** of **LCA**, this integration **adds** the **Spatial Dimension**. Supporting methodological choices in LCA, **Simulation & Optimisation** techniques **Compliment LCIA** development & attribute **Significance** to **Impact Categories**. Also, **MCDM** methods can help **structuring multi-dimensional** assessment approaches.	This Integration Offers to **add the Spatial-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** playing 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.	By **Supplementing** the **Material Flow Account** with the **Spatial Dimension**, this integration **Helps** to **Analyse**, **Diagnose**, and **Model Spatial Dependence** of **Material and Stock Flows**. Also, **MCDM** methods can help **structuring multi-dimensional** assessment approaches.

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 **material flow analysis** process. 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 **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, Optimisation and Spatial Modelling	**Spatially specifying LCI data** for a successful integration **of Spatial Modelling** with **LCA** can be a **challenge.**	**Optimisation** results might be strongly **influenced** by the **initially selected value** yielded from the **LCC analysis**. **Spatially specifying costs** for a seamless integration of Spatial and Temporal Modelling with **LCC** can be a **challenge.**	**Social LCA outputs** as **objective functions** in a **multi-objective optimisation 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 optimisation**. **Spatial explicit modelling** due to lack of site-specific data can be an **obstacle** in **social databases**.	**Optimisation** 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 material flow analysis.

6. Underlying principles

In the previous sections, the existence of a rich and solid literature (part of which is contributed by the present project) about assessment methods suitable for Circular Economy as well as about possibilities and benefits of their integrated use has been pointed out and discussed. Many researchers have deepened the way these methods can be applied to specific production processes (micro-scale) as well as to larger, meso and macro, socio-economic scales (urban, regional, national and transnational), highlighting the usefulness, comprehensiveness, and limits of sequential or integrated use of specific methods as applied to CE. The scientific reliability of the investigated methods is of paramount importance to ensure transparent and successful planning and implementation of CE policies.

In particular, successful policymaking, planning, and implementation require that projects and suggested strategies are based on the following method-related characteristics:

- *Vision* - Clarifying goals and scope of the proposed and planned policy, pursued patterns, which benefits, which beneficiaries, for how long, which socio-economic and environmental costs;
- *Science* - Scientific strength and reliability (methods based on science; the existence of an expert team capable to deal with the different methods);
- *Transparency* - Transparent assessment of the project and policy characteristics (data and performance indicators open to all interested stakeholders);
- *Participation* - Stakeholders engagement (implementation involving all actors, based on assessment and participatory approaches);
- *Trust* - Trust among all actors (needed collaborative patterns, clear goals of each one expressed and verified);
- *Milestone* - Intermediate results assessment and comparison with goals jointly assumed (availability to implement process and strategical changes depending on milestones). Final results comparison with planned ones (discussion of the potential failures or successes with all stakeholders);
- *Well-being* - Achieved contribution to the well-being of local and larger-scale populations determined by the implemented policy.

All the above points can be applied to any strategy or policy (waste management, education, housing, mobility, etc.) and, of course, in our study specifically apply to Circular Economy policymaking. They require that a suitable roadmap is implemented to apply the existing methods, discuss their validity and results, share challenges and successes, and finally make successful patterns a scheme for the next CE steps and proposals.

6.1 Vision

Lack of clarity about the final goal and the context in which the proposed CE project should develop may generate uncertainty about the worth of abandoning the linear, business as usual pattern to be engaged in a maybe risky business, with unclear benefits, beneficiaries, and costs. The Circular Economy is a complex innovative model, and its global structure and organisation may

not necessarily be understood or easily accepted. For example, a common say is that most often steel scraps are more expensive than primary iron material, or purposefully cropped biomass is less expensive and more suitable than waste organic biomass from the municipal collection, and so on, due to several reasons that sometimes are true and sometimes are only lack of suitable information. Sometimes the benefits of a circular innovative pattern are not directly enjoyed by the specific business sector where the CE project develops, which means that the complexity of the system must be accompanied by a complexity of the narrative and the assessment tools, where the roles of each actor, the relations among them and the related benefits are well identified, including challenges and risks. Sharing a vision means that all actors have agreed upon not only the project and the direct benefits but also the social, psychological, organisational, and environmental aspects, including the fact that some benefits are enjoyed at a larger scale (e.g., the whole urban environment) which in turn will generate specific health and economic benefits to the business actor who accepts to move from the linear business-as-usual to the innovative circular model.

6.2 Science

The recipients of this document will have to rely on appropriate and suitable scientific methods, applied and interpreted by a group of experts. It is important to avoid ideological or internet-based strategies or interpretations that are not based on the scientific method. Science is not infallible, and scientists and experts may have different opinions about the validity of processes or solutions (e.g., think of nuclear energy or the debate about energy from biomass competing for land with food production which leads to the definition of first- and second-generation biomass fuels). What characterizes science is its reproducibility, clarity of the method applied, acceptance of uncertainty and ways to deal with it, interaction and integration among researchers and procedures, and finally continuous evolution of solutions. In this Deliverable, we have clearly shown the solidity and the potential integration of monitoring, assessment, and modelling CE-oriented methods as well as the evolution of these methods over time and their systemic nature. We have also shown the still existing challenges and lack of sufficient testing of the same procedures, calling for uncertainty awareness, further research needs, and availability to change. Policies for a Circular Economy, like any kind of policymaking, will have to keep a continuous interaction with the Research Institutions, to make sure that the achievement of innovative research results translates into potential improvements of the CE planning in favour of all sectors of local or larger socio-economic systems.

6.3 Transparency

Transparency is a mandatory issue of any agreed-upon decision making, including CE policies. Most often differences among players in decision-making processes arise from different data about the situation and the process performance and more than that data sources are unknown or not easily available. Consider the cost and environmental impacts of primary materials, the efficiency of conversion processes, the potential advantages introduced by new technology, the new jobs associated with an innovative process, and the loss of jobs associated with the replaced one (e.g., the new jobs from electric cars introduction and the jobs lost in the sector of gasoline and diesel refining and distribution), the social and political costs of the transition from fossil powered to electricity-powered vehicles (e.g., mining of minerals for batteries and electric devices, determining local conflicts in areas which very unlikely will benefit from these innovations) (see Berman et al., 2017). In policy debates concerning innovative patterns, very seldom transparency of data is

ensured, and debates and decisions are based on generic statements and incomplete information. Although some uncertainty is unavoidable due to the very uncertainty of statistical and scientific data, most often data are kept hidden or confused to favour a decision or another. Consequently, reliance on transparent data (e.g., the inventory of a Life Cycle Assessment procedure) is a must and should be ensured for a debate and its conclusions to be acceptable. Furthermore, scientific information should also be "translated" into suitable concepts for those who do not have a scientific background but are still involved at some point in the effects of the decisions.

6.4 Participation

The stakeholders´ characteristics must be deeply analysed to make sure that the right players are involved in the process. Prevention of conflicts, but also a correct policy and strategy can be more easily carried out if stakeholders are involved in aspects where they see things that experts most often do not see. For example, if the process to be implemented is the reuse of construction and demolition waste, stakeholders must involve professional designers of the building sector, industrial in the recycling of construction materials, market economic experts, environmental experts, civil society organisations (e.g., neighbourhood associations), media operators, and perhaps many other categories. Stakeholders´ analysis generally follows four pillars:

- Identifying key players;
- Analysing stakeholders' interests;
- Mapping stakeholders influence and importance;
- Prioritising issues and stakeholders' engagement;

The identification step leads to the creation of a detailed list of stakeholders, continuously updated and depending on the process/policy dealt with, the stage of the action, the type of organisation, and the type of stakeholders' commitment. At this stage, it is crucial to analyse the legitimacy of the stakeholders, their willingness to engage in some action, and the influence that each individual or group may have on the project, to assign appropriate priorities to individuals, interests, and actions, even according to their usefulness to the proposal, intervention, activity or plan. Awareness of the influence and importance of the identified stakeholders is also crucial. Mapping stakeholders is an exercise of visual analysis tool that helps to further determine what are the characteristics and modes of action of the identified persons to be involved. This step also helps understand the relationships that are created between the different stakeholder groups. Finally, the prioritisation step designs a strategy of stakeholder participation, i.e., a plan to involve the stakeholders in the stages of the project, by also creating a scale of priorities for both issues and stakeholders. Of course, the priority list may change over time, according to the changing situations (Hornsby C. et al. 2014; Vassillo et al., 2019). No doubt, anyway, that lack of involvement of stakeholders may pave the way to the failure of any circular economy strategy.

However, it is also important to notice that the concept of stakeholder itself has often been used to identify collective or individual subjects that can actively affect or passively be affected by projects, productive processes, etc… with some specific interests. This comes from a perspective that is mainly economy-oriented and mainly creates rules for companies' profits to be "positive" for society as a whole. In a wider, policy-making-oriented perspective, participatory processes should also consider the involvement and empowerment of communities, individuals, social

movements and NGOs, civil society, labour unions, and consumer associations, without and beyond considering the dimension of their "interests".

6.5 Trust

Commonly, collaborative patterns fail due to a lack of reciprocal trust among actors. This is when civil society organisations have an a-priori lack of trust attitude against administrators or business operators or vice versa. In a like manner, sometimes there is a stable lack of collaboration between the Academy and the world of business, or the Academy and the policymakers. The reason for this lack of collaboration is most often lack of trust, indicating that each party is convinced that the other parties are only interested in fulfilling their own or somebody else's interests instead of the common interests. This a-priori lack-of-trust attitude should and can be removed by implementing a shared search of potential solutions. For example, the circular treatment of organic urban waste may be implemented by converting this waste into compost, transforming the waste into biogas via anaerobic digestion, separating the different organic components and converting at least a fraction into chemicals, and so on. Each alternative requires a plant, land use, and economic investment, and generates incomes and impacts, leading to potential interests and NIMBY attitudes, that might be prevented if decision making is carried out jointly. Sometimes, lack of trust is simply generated by insufficient expression and description of each party's needs and interests, which in the case of urban waste management can be economic (circular goals implementation may translate into a decrease of some urban taxes or an increase of some jobs), environmental (fewer emissions or achievement of aesthetic improvements of the urban territory) or social (making waste delivery easier by the individual inhabitant). Once again, appropriate expression of goals and appropriate use of ex-ante and ex-post simulation and monitoring tools may be of paramount importance for the achievement of collaboration habits and "circular trust" among all the system's interested players.

6.6 Milestones

The less productive and the most dangerous attitude for the successful implementation of an innovative policy when moving from linear to complex systems, is certainly the rigidity that prevents changes when intermediate results (milestones) require them. Strategies must be organised in a way that intermediate results are monitored and interpreted. For example, if the goal is to increase by a given percentage the circularity in the food supply chain, the final indicator may certainly be the total amount of organic waste generated and disposed of at the end of the year, while the intermediate indicators may be:

- The amount of fresh food trashed every month by wholesale markets and the amount of manufactured food trashed by urban supermarkets due to lack of careful storage and management of degradable items;
- The amount of last-minute food distributed to Institutions which take care of food poverty (e.g., the Last Minute Market initiative launched by the University of Bologna (Italy) (https://www.lastminutemarket.it);
- The amount of food and residues diverted to energy production, extraction of chemical and nutraceutical products, production of bio-colours and textiles from residues ('The

Italian Atlas of Circular Economy, https://www.hafactory.it/2017/12/11/italian-atlas-circulareconomy/; https://economiacircolare.com/atlante/).

When the monitoring and assessment methods (e.g., VSM, Value Stream Mapping method) indicate that the effectiveness of circular patterns is not consistent with the planned goals, the most appropriate behaviour is to stop the project or apply changes that ensure the planned goal to be reached. In short, comparing intermediate results with the planned final goal is a mandatory and scientifically sound behaviour to ensure that the implemented process is correctly managed. Otherwise, some operational steps need to be revised, in the interest of the final result. In a like manner, results should be compared to the expected ones, to identify the reasons for the failure and prevent new errors.

6.7 Well-being

Assuming the planned and implemented Circular Economy strategy has achieved its goals, still, a question arises if the result has been effective in increasing the well-being of the local or regional population. If, for instance, CE activities only translate into increased industrial activities and income, thanks to more products generated out of the residues, without providing a benefit to the local population in terms of jobs and income, this might indicate that the way circularity has been implemented is not the most appropriate use of new potential resources. In a very simple statement, not necessarily combustion for heat is the best use of straw from cereals' production, instead of being (partially) used for replacement of the nutrients in the soil or manure production in livestock farms. Therefore, accurate planning is needed to employ LCA, LCC, and EMA, among others, to make sure that the environmental benefits are not overwhelmed by the search for additional economic benefits from residues.

7.   Conclusion - a roadmap towards circular economy assessment

The research performed in this project and described in the Deliverables already completed as well as in a large number of papers published about Circular Economy conceptual models, methods, and case studies (agriculture, industry, urban structures, waste management, among others) supports the idea that CE business models are an interesting and innovative option for our society in the present state of development, awareness, and technology. Administrators and policymakers, all categories of stakeholders and social, professional, and cultural communities as well as business operators may successfully suggest new patterns for CE implementation in sectors of their common interest. The research carried out and described in this project provides conceptual and methodological tools as well as reference case studies to design, test, and implement innovative CE projects, in so benefiting themselves and society.

Considering that production systems in CE are often complex, stakeholders may often be interested in a variety of metrics to assess the performance as well as costs and benefits of the proposed new system/process. While most research often picks one assessment method only to study a system, this would rarely satisfy all stakeholders. Thus, it is very likely that multiple assessment methods need to be used, with appropriate sequence or integration. This deliverable has mainly dealt with how to integrate the different assessment methods typically used to assess the sustainability of a production system/product lifecycle. Once the assessment methods are

applied and properly integrated, the results need to be discussed with all the relevant stakeholders before the study is concluded. Figure 9 provides an overview and scheme of a suitable roadmap, to perform the different steps highlighted above and achieve the result of an agreed-upon goal, implementation, valuation, and decision making for further steps.

Following the above Chapters (systems thinking, circular economy, assessment methods, integration of tools, reliance on science, benefits, and limitations) it appears that random procedures and disorganised collaborative links do not lead anywhere and are unlikely to achieve the claimed results. Transition to Circular Economy means moving from linear to complex business models and requires awareness in planning and implementation. The roadmap in Figure 9, first of all, points out the need for a shared policy vision (light blue field in the Figure) where systems thinking, problems to be addressed, results and solutions to be achieved, assessment methods, and community empowerment patterns, stakeholders engagement are all integrated and become part of an agreed-upon strategy towards a quality-of-life improvement much beyond economic growth, but instead based on socio-economic, environmental and democracy results achievement.

The leaders of any kind of system (be it a city, a social community, a cultural or professional organisation, or a business-oriented company) may be in the position to identify a problem (excess of waste production, excess of energy consumption, lack of sufficient food or resources, environmental or social degradation due to ongoing economic processes, etc.) and suggest a new goal to be achieved to overcome the problem itself (more efficient waste management, increased resource circularity, innovative production technologies and patterns, renewable resources use, among others). Identifying a new goal (e.g., increased circularity) does not mean implementing a new way to solve the problem itself. The past and present ways to address problems and goals have most often been top-down models and strategies, with leaders and their experts indicating the "new way" (the new energy source - be it nuclear or solar; the new industrial chain – be it increasing imports or implementing eco-industrial parks; the new waste treatment plant - be it a waste-to-energy plant or a new anaerobic digester). This has been sometimes economically profitable for some companies and systems but has not built any systemic pattern to involve communities and scientists in the search for agreed-upon solutions to motivate larger fractions of the population and operators in pursuing radical changes and being engaged in choices and search for shared and systemic solutions (bottom-up approach to complement top-down models).

The demonstrated existence (concepts and papers mentioned in Sections 4 and 5) of science-based, comprehensive, and multidimensional integrated methods to model, test and improve innovative proposals such as circularity processes in all sectors push local, national, and trans-national economies to go beyond top-down decision-making models and strongly rely on science to design and implement new strategies, in particular the transition from linear Business As Usual to complex CE.

Reliance on Science (orange coloured field in Figure 9) not only provides the ability to select the appropriate methods and perform ex-ante planning and assessment of the proposed innovation but allows the growth of transparency and trust among leaders and the community, favouring stakeholders' engagement and – even more important - community empowerment (light green field in Figure 9). This leads to Results (i.e., science-based quantitative and qualitative figures and indicators) and potential solutions (i.e., proposals that may be the basis for a deep debate at all levels of the societal system) that in turn may lead to agreement or disagreement feedback choices

as well as reinforcement of Community´s ability to be involved in the present and future debates (pink field in Figure 9). Whoever has started the process by identifying a problem should be finally happy and rewarded with the final result of achieved well-being in the local or larger scale community.
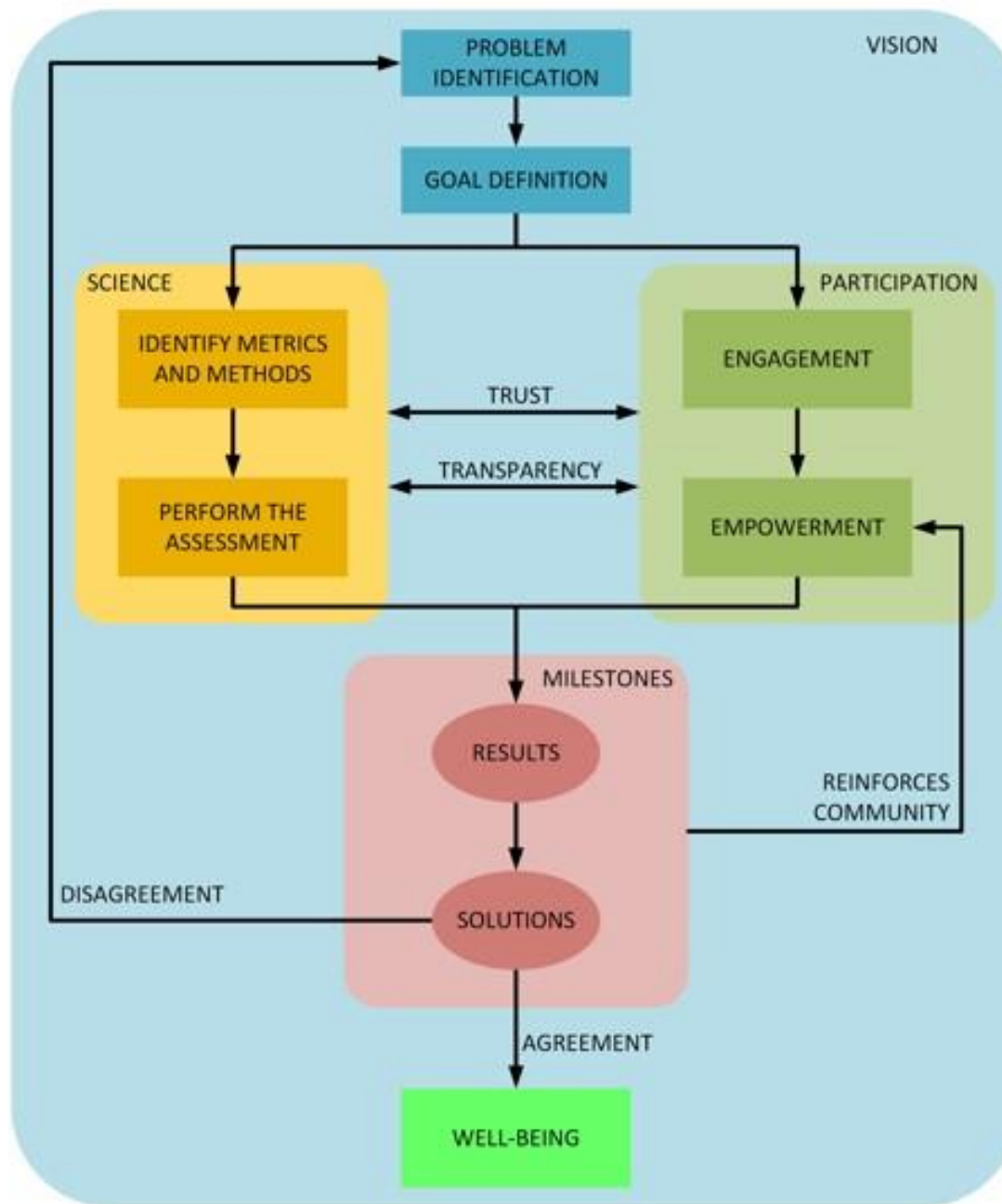

Figure 9. Decision making roadmap for CE sustainability assessment

If we now think of CE debates and proposals that are growing locally and at larger EU scales, the only way to prevent and fight greenwashing and instead achieve actual and effective CE patterns and results is to make sure that a roadmap involving all the steps and all the actors indicated in Section 6 as well as in Figure 9 is implemented and becomes the rule in decision-making processes.

This Deliverable, and the scientific research underlying it, proves that CE can be supported by science and democracy at the same time as well as that random and dis-organised projects can be avoided, to implement high-quality and systemic discussion and research.

References

Alejandrino, C., Mercante, I., & Bovea, M. D. (2021). Life cycle sustainability assessment: Lessons learned from case studies. *Environmental Impact Assessment Review*, *87*, 106517.

Alejandrino, C., Mercante, I. T., & Bovea, M. D. (2022). Combining O-LCA and O-LCC to support circular economy strategies in organizations: Methodology and case study. *Journal of Cleaner Production*, 130365.

Andrews, K.R. (1971). The Concept of Corporate Strategy. Irwin, Homewood, IL.

Andrews, K.R. (1980). The Concept of Corporate Strategy, second ed. Irwin, Homewood, IL.

Angulo-Mosquera, L. S., Alvarado-Alvarado, A. A., Rivas-Arrieta, M. J., Cattaneo, C. R., Rene, E. R., & García-Depraect, O. (2021). Production of solid biofuels from organic waste in developing countries: A review from sustainability and economic feasibility perspectives. *Science of The Total Environment*, *795*, 148816.

Arsova, S., Genovese, A., Ketikidis, P. H., Alberich, J. P., & Solomon, A. (2021). Implementing regional circular economy policies: a proposed living constellation of stakeholders. *Sustainability*, *13*(9), 4916.

Bargigli, S., Raugei, M. & Ulgiati, S. (2004). Comparison of thermodynamic and environmental indexes of natural gas, syngas and hydrogen production processes. Energy - The International Journal, 29(12-15): 2145–2159.

Berman, N., Couttenier, M., Rohner , D. & Thoenig, M. (2017). This Mine is Mine! How Minerals Fuel Conflicts in Africa. *American Economic Review*, 107(6): 1564–1610.

Bonnafous-Boucher, M., & Rendtorff, J. D. (2016). Stakeholder theory and ethics. In *Stakeholder Theory* (pp. 67-78). Springer, Cham.

Brown, M.T., 2004. A picture is worth a thousand words: energy systems language and simulation. *Ecological Modelling*, 178, 83–100.

Byrne, J., Zhou, A., Shen, B., & Hughes, K. (2007). Evaluating the potential of small-scale renewable energy options to meet rural livelihoods needs: A GIS-and lifecycle cost-based assessment of Western China's options. *Energy policy*, *35*(8), 4391-4401.

Capra, F. (1997). *The web of life: A new scientific understanding of living systems*. Anchor, New York.

Calzolari, T., Genovese, A., & Brint, A. (2022). Circular Economy indicators for supply chains: A systematic literature review. *Environmental and Sustainability Indicators*, *13*, 100160.

Cobo, S., Levis, J. W., Dominguez-Ramos, A., & Irabien, A. (2019). Economics of enhancing nutrient circularity in an organic waste valorization system. *Environmental science & technology*, *53*(11), 6123-6132.

Cristiano, S., Ghisellini, P., D'Ambrosio, G., Xue, J., Nesticò, A., Gonella, F. & Ulgiati, S. (2021). Construction and demolition waste in the Metropolitan City of Naples, Italy: State of the art, circular design, and sustainable planning opportunities. *Journal of Cleaner Production* 293, 125856.

D'Eusanio, M., Arzoumanidis, I., Raggi, A. & Petti, L. (2018). Definizione dei criteri della functional unit nell'LCA e nella Social LCA: spunti di discussione. *Atti XVIII Congresso Nazionale di Scienze Merceologiche*, Firenze 21-23 febbraio 2018, Università degli Studi di Firenze, PIN Polo Universitario Città di Prato, Italy.

Djatna, T., & Prasetyo, D., 2019. Integration of sustainable value stream mapping (sus. VSM) and life-cycle assessment (LCA) to improve sustainability performance. *International Journal on Advanced Science Engineering Information Technology*, 9 (4), 1343–1997.

Di Maria, A., Eyckmans, J., & Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste management*, *75*, 3-21.

Delli Gatti, D., & Gallegati, M., 2001. *Macroeconomia: fatti, teorie, politiche*. Giappichelli, Torino (in Italian).

Diaz, F., Vignati, J. A., Marchi, B., Paoli, R., Zanoni, S., & Romagnoli, F. (2021). Effects of Energy Efficiency Measures in the Beef Cold Chain: A Life Cycle-based Study. *Rigas Tehniskas Universitates Zinatniskie Raksti*, *25*(1), 343-355.

Eisenhardt, K. M., & Graebner, M. E. (1989). Theory building from case study research. *Academy of Management Review*, *14*(4), 532-550.

European Commission (2022). First Circular Economy Action Plan. Available online at: https://ec.europa.eu/environment/topics/circular-economy/first-circular-economyaction-plan_en. Last accessed: 07/04/2022.

European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A new Circular Economy Action Plan For a cleaner and more competitive Europe COM/2020/98 final. Available online at: https://eur-lex.europa.eu/legalcontent/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN. Last accessed: 11/05/2022.

European Union, 2022. Next Generation EU. Available online at: https://europa.eu/nextgeneration-eu/index_en. Last accessed: 07/04/2022.

European Union, 2017. SWOT analysis. Available online at: https://europa.eu/capacity4dev/evaluation_guidelines/wiki/swot-strenghts-weaknessopportunities-threats-0. Last accessed: 10/04/2022.

Freeman, R. E. (2010). Managing for stakeholders: Trade-offs or value creation. Journal of Business Ethics, 96(S1), 7–9.

Garcia-Muiña, F. E., González-Sánchez, R., Ferrari, A. M., & Settembre-Blundo, D. (2018). The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company. *Social Sciences*, *7*(12), 255.

Georgescu-Roegen, N. (1971). *The Entropy Low and the Economic Process*. Cambridge Mass. Harward University Press.

Ghisellini, P., Cialani, C., Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production,* 114, 11-32.

Giannantoni, C., Lazzaretto, A., Macor, A., Mirandola, A., Stoppato, A., Tonon, S., Ulgiati, S. (2005). Multicriteria Approach for the Improvement of Energy Systems Design. *Energy - The International Journal*, 30(10): 1989–2016.

Hosseinijou, S. A., Mansour, S., & Shirazi, M. A. (2014). Social life cycle assessment for material selection: a case study of building materials. *The International Journal of Life Cycle Assessment*, *19*(3), 620-645.

Hill, T., Westbrook, R., 1997. SWOT Analysis: it's time for a product recall. *Long Range Planning*, 30 (1), 46-52.

Hornsby, C., Ripa, M., Vassillo, C., & Ulgiati, S. (2014). Conversion of municipal solid waste into biomass fuel, by means of the MARSS concept. An integrated sustainability assessment. *Proceedings of the Symbiosis Conference*, 19-21 June 2014, Athens, Greece.

Jackson, M.C. (2003). *Systems Thinking: Creative Holism for Managers*. Wiley. ISBN 0-47084522-8.

Jiang, Q., Liu, Z., Li, T., Cong, W., & Zhang, H. C. (2019). Emergy-based life-cycle assessment (Em-LCA) for sustainability assessment: a case study of laser additive manufacturing versus CNC machining. *The International Journal of Advanced Manufacturing Technology*, *102*(9), 4109-4120.

Kaiser, S., Oliveira, M., Vassillo, C., Orlandini, G., & Zucaro, A. (2022). Social and Environmental Assessment of a Solidarity Oriented Energy Community: A Case-Study in San Giovanni a Teduccio, Napoli (IT). *Energies*, 15, 1557.

Kocjančič, T., Debeljak, M., Žgajnar, J., & Juvančič, L. (2018). Incorporation of emergy into multiplecriteria decision analysis for sustainable and resilient structure of dairy farms in Slovenia. *Agricultural Systems*, 164, 71-83.

Lambrecht, H., & Thißen, N. (2015). Enhancing sustainable production by the combined use of material flow analysis and mathematical programming. *Journal of Cleaner Production*, *105*, 263-274.

Liu, Y.X., Chen, W., Liu, X.Y., Shi, J.G., Liu, N., Ren, H.J., Li, H.J., and Ulgiati, S. (2022). Multiobjective coordinated development paths for China's steel industry chain based on "water-energy-economy" dependence. Working Paper.

Loiseau, E., Aissani, L., Le Féon, S., Laurent, F., Cerceau, J., Sala, S., & Roux, P. (2018). Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. *Journal of Cleaner Production*, *176*, 474-485.

Lotka, A. J. (1922). Natural selection as a physical principle. *Proceedings of the National Academy of Sciences of the United States of America*, *8*(6), 151.

Lyu, Y., Raugei, M., Zhang, X., Mellino, S., & Ulgiati, S. (2021). Environmental cost and impacts of chemicals used in agriculture: An integration of emergy and Life Cycle Assessment. *Renewable and Sustainable Energy Reviews*, *151*, 111604.

Martínez-Blanco, J., Lehmann, A., Chang, Y. J., & Finkbeiner, M. (2015). Social organizational LCA (SOLCA)—a new approach for implementing social LCA. *The International Journal of Life Cycle Assessment*, *20*(11), 1586-1599.

Meglin, R., Kytzia, S., & Habert, G. (2022a). Uncertainty, variability, price changes and their implications on a regional building materials industry: The case of Swiss canton Argovia. *Journal of Cleaner Production*, *330*, 129944.

Meglin, R., Kytzia, S., & Habert, G. (2022b). Regional circular economy of building materials: environmental and economic assessment combining material flow analysis, input-output analyses, and life cycle assessment. *Journal of Industrial Ecology*, *26*(2), 562-576.

Mellino, S., Ripa, M., Zucaro, A., & Ulgiati, S. (2014). An emergy–GIS approach to the evaluation of renewable resource flows: a case study of Campania Region, Italy. *Ecological Modelling*, *271*, 103-112.

Miah, J. H., Koh, S. C. L., & Stone, D. (2017). A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing. *Journal of cleaner production*, *168*, 846-866.

Millward-Hopkins, J., Busch, J., Purnell, P., Zwirner, O., Velis, C. A., Brown, A., ... & Iacovidou, E. (2018). Fully integrated modelling for sustainability assessment of resource recovery from waste. *Science of the Total Environment*, *612*, 613-624.

Motuzienė, V., Rogoža, A., Lapinskienė, V., & Vilutienė, T. (2016). Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study. *Journal of Cleaner production*, *112*, 532-541.

Mousavi, S., Thiede, S., Li, W., Kara, S., & Herrmann, C. (2016). An integrated approach for improving energy efficiency of manufacturing process chains. *International Journal of Sustainable Engineering*, *9*(1), 11-24.

Nakamura, S., & Kondo, Y. (2018). Toward an integrated model of the circular economy: Dynamic waste input–output. *Resources, Conservation and Recycling*, *139*, 326-332.

Odum, H. T. (2002). Explanations of ecological relationships with energy systems concepts. *Ecological Modelling*, *158*(3), 201-211.

Odum, H. T. (1988). Self-organization, transformity, and information. *Science*, *242*(4882), 1132-1139.

Odum,, H.T. 1994. Ecological and General Systems: An Introduction to Systems Ecology. (Revised edition of: Systems Ecology, 1983, John Wiley, 644 pp.) University Press of Colorado.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York, p. 370.

Oliveira, M., Miguel, M., van Langen, S. K., Ncube, A., Zucaro, A., Fiorentino, G., ... & Genovese, A. (2021). Circular economy and the transition to a sustainable society: integrated assessment methods for a new paradigm. *Circular Economy and Sustainability*, *1*(1), 99-113.

Oliveira, M., Cocozza, A., Zucaro, A., Santagata, R., & Ulgiati, S. (2021). Circular economy in the agro-industry: Integrated environmental assessment of dairy products. *Renewable and Sustainable Energy Reviews*, *148*, 111314.

Paju, M., Heilala, J., Hentula, M., Heikkilä, A., Johansson, B., Leong, S., & Lyons, K. (2010). Framework and indicators for a sustainable manufacturing mapping methodology. In *Proceedings of the 2010 winter simulation conference* (pp. 3411-3422). IEEE.

Perosa, A., Gonella, F., & Spagnolo, S. (2019). Systems thinking: adopting an emergy perspective as a tool for teaching green chemistry. *Journal of Chemical Education*, *96*(12), 2784-2793.

Prendeville, S., Cherim, E., & Bocken, N. (2018). Circular cities: mapping six cities in transition. *Environmental innovation and societal transitions*, *26*, 171-194.

Provasnek, A. K., Sentic, A., & Schmid, E. (2017). Integrating eco-innovations and stakeholder engagement for sustainable development and a social license to operate. *Corporate Social Responsibility and Environmental Management*, *24*(3), 173-185.

Salvador, R., Barros, M. V., dos Santos, G. E. T., van Mierlo, K. G., Piekarski, C. M., & de Francisco, A. C. (2021). Towards a green and fast production system: Integrating life cycle assessment and value stream mapping for decision making. *Environmental Impact Assessment Review*, *87*, 106519.

Santagata, R., Zucaro, A., Fiorentino, G., Lucagnano, E., & Ulgiati, S. (2020). Developing a procedure for the integration of Life Cycle Assessment and Emergy Accounting approaches. The Amalfi paper case study. *Ecological Indicators*, *117*, 106676.

Santillán-Saldivar, J., Cimprich, A., Shaikh, N., Laratte, B., Young, S. B., & Sonnemann, G. (2021). How recycling mitigates supply risks of critical raw materials: Extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. *Resources, Conservation and Recycling, 164*, 105108.

Schaubroeck, T., Gibon, T., Igos, E., & Benetto, E. (2021). Sustainability assessment of circular economy over time: Modelling of finite and variable loops & impact distribution among related products. *Resources, Conservation and Recycling, 168*, 105319.

Senán-Salinas, J., Blanco, A., García-Pacheco, R., Landaburu-Aguirre, J., & García-Calvo, E. (2021). Prospective Life Cycle Assessment and economic analysis of direct recycling of end-of-life reverse osmosis membranes based on Geographic Information Systems. *Journal of Cleaner Production, 282*, 124400.

Smith, B., Kruschwitz, N., Laur, J., & Schley, S. (2010). *The necessary revolution: Working together to create a sustainable world*. Crown Business.

Solis, C. M. A., San Juan, J. L. G., Mayol, A. P., Sy, C. L., Ubando, A. T., & Culaba, A. B. (2021). A multi-objective life cycle optimization model of an integrated algal biorefinery toward a sustainable circular bioeconomy considering resource recirculation. *Energies, 14*(5), 1416.

Subramanian, K., Chau, C. K., & Yung, W. K. (2018). Relevance and feasibility of the existing social LCA methods and case studies from a decision-making perspective. *Journal of Cleaner Production, 171*, 690-703.

Sun, L., Li, H., Dong, L., Fang, K., Ren, J., Geng, Y., ... & Liu, Z. (2017). Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China. *Resources, Conservation and Recycling, 119*, 78-88.

Swanson, R.A., 2001. Assessing the Financial Benefits of Human Resource Development. Basic Books, Perseus Books Group, Cambridge, ISBN 978-0-738-20457-4, p. 198. www.basicbooks.com.

Taskhiri, M. S., Tan, R. R., & Chiu, A. S. (2011). MILP model for emergy optimization in EIP water networks. *Clean Technologies and Environmental Policy, 13*(5), 703-712.

Taskhiri, M. S., Jeswani, H., Geldermann, J., & Azapagic, A. (2019). Optimising cascaded utilisation of wood resources considering economic and environmental aspects. *Computers & Chemical Engineering, 124*, 302-316.

Thakker, V., & Bakshi, B. R. (2021). Toward sustainable circular economies: A computational framework for assessment and design. *Journal of Cleaner Production, 295*, 126353.

Tirado, R., Aublet, A., Laurenceau, S., Thorel, M., Louërat, M., & Habert, G. (2021). ComponentBased Model for Building Material Stock and Waste-Flow Characterization: A Case in the Île-de-France Region. *Sustainability, 13*(23), 13159.

Tsalis, T., Stefanakis, A. I., & Nikolaou, I. (2022). A Framework to Evaluate the Social Life Cycle Impact of Products under the Circular Economy Thinking. *Sustainability, 14*(4), 2196.

Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., Zucaro, A. (2011). Material, Energy and Environmental Performance of Technological and Social Systems under a Life Cycle Assessment Perspective. *Ecological Modelling*, 222(1), 176189.

UNEP (2015) Guidance on Organizational Life Cycle Assessment. Life-Cycle Initiative, United Nations Environment Programme and Society for Environmental Toxicology and Chemistry, Paris, France. Available online at:

http://www.lifecycleinitiative.org/wpcontent/uploads/2015/04/o-lca_24.4.15-web.pdf. Last accessed: 11/05/2022.

Vassillo C., Restaino D., Santagata D., Viglia S, Vehmas J. & Ulgiati S. (2019). Barriers and Solutions to the Implementation of Energy Efficiency. A Survey about Stakeholders' Diversity, Motivations and Engagement in Naples (Italy), *Journal of Environmental Accounting and Management*, 7(2): 229-251.

Wang, J., Shou, W., Wang, X., & Wu, P. (2016). Developing and evaluating a framework of total constraint management for improving workflow in liquefied natural gas construction. *Construction Management and Economics*, *34*(12), 859-874.

Von Bertalanffy, L. (1969). *General System Theory, Foundations, Development, Applications*. George Braziller, New York.

Voukkali, I., & Zorpas, A. A. (2022). Evaluation of urban metabolism assessment methods through SWOT analysis and analytical hierarchy process. *Science of the Total Environment*, 807, 150700.

Wallsten, B., 2015. Towards social material flow analysis: on the usefulness of boundary objects in urban mining research. Journal of Industrial Ecology 19 (5): 742-752.

Wang, Q., Zhang, Y., Tian, S., Yuan, X., Ma, Q., Liu, M., ... & Liu, J. (2021). Evaluation and optimization of a circular economy model integrating planting and breeding based on the coupling of emergy analysis and life cycle assessment. *Environmental Science and Pollution Research*, *28*(44), 62407-62420.