H2020 MSCA-ITN-2018

ReTraCE Project

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

D2.1

Integrated Assessment of Sustainability Profiles in Circular Production Systems.

A Framework towards a comprehensive understanding

This project has received funding from the European Union's Horizon 2020 research and innovation proframme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE)

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Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation proframme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE)

Table of Figures

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List of acronyms

CE – Circular Economy

(e-)LCA – (environmental) Life Cycle Assessment

s- LCA – social Life Cycle Assessment

LCC – Life Cycle Costing

cLCC – conventional Life Cycle Costing

eLCC – environmental Life Cycle Costing

sLCC – social Life Cycle Costing

EMA – EMergy Accounting

(Sus-)VSM – (Sustainable) Value Stream Mapping

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Executive Summary

The Circular Economy (CE) paradigm has been framed as a pathway towards sustainability and has gained increasing attention from academia, the business community and policymakers. However, CE implementation is still in its infancy as its full potential for reshaping production and consumption systems has not yet been realised. Therefore, appropriate tools for assessing the environmental, economic and social implications of such a transition are needed to assist decision-making at different levels (i.e. micro, meso and macro).

This report introduces a framework for developing a robust and relevant procedure for monitoring and assessing the performance of circular production systems, mainly at a micro and meso level. The proposed framework consists of a set of existing methods, namely Life Cycle Assessment (LCA), social Life Cycle Assessment (s-LCA), environmental Life Cycle Costing (eLCC), EMergy Accounting (EMA) and Sustainable Value Stream Mapping (Sus-VSM). Currently, these methods are still optimised for linear production systems and have limitations when assessing circular systems and related feedback loops. These limitations can be overcome by improving each one of the methods (e.g. improvement of calculation methods), by providing guidance on the selection of methods in different contexts, and by integrating the methods further. All of these improvements are proposed in this report.

As part of the framework introduced here, a visual representation of a circular production system has been produced and the boundaries of each method illustrated. Furthermore, the framework has been developed to provide practical assistance to practitioners in choosing the methods to be applied according to the objectives and scale of the study. As a future step of this research, this framework will be tested and improved based on insights given by real case studies from the steel industry and related sectors, the electrical and electronic equipment sector, urban systems, and the agro-food industry. These are all key sectors for CE transition; the results will be reported in ReTraCE Deliverables D2.2 and D2.3.

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1. Introduction

In the last decades, production systems have operated within a 'take-make-use-dispose' paradigm, based on the extraction and often irresponsible use of finite natural resources. The current system has caused irreversible environmental impacts, as half of the total greenhouse gas emissions and more than 90% of biodiversity loss and water stress results from resource extraction and processing (European Commission, 2020).

In recent years, the concept of Circular Economy has emerged as a potential replacement of the current linear production model. The Ellen MacArthur Foundation (2012) defined CE as 'an industrial system that is restorative or regenerative by intention and design'. In such a system, the value of products, materials and resources is kept in the economy for as long as possible, while minimising the generation of waste (European Commission, 2015).

The European Union is committed to make CE the pillar of the EU Industrial Strategy, enabling circularity in new areas and sectors (European Commission, 2019). Within this context, the ReTraCE project aims to develop understanding about how the transition towards a CE can be successfully realised in the European context. The implementation of Circular Economy is still a challenging task due to the predominance of linear mindsets and structures in industry and society, and a lack of understanding about the environmental, economic and social implications of such a transition (Bocken et al., 2016; Lieder and Rashid, 2016). Therefore, appropriate tools for assessing the benefits and impacts of transitioning to a more Circular Economy are required to assist decision-making at different scales (i.e. the micro, meso and macro scale).

This study aims to develop a framework capable of assessing the performance of circular production systems (mainly at a micro and meso-level, although cross-scale evaluations will also be performed). Thus, various existing and widely used sustainability methods have been selected and reviewed, including Life Cycle Assessment (LCA), social Life Cycle Assessment (s-LCA), Life Cycle Costing (LCC) and Value Stream Mapping (VSM).

The report is divided in five sections. Chapter 2 provides a general overview of each method, followed by Chapter 3 which focus on the interactions between the methods and emerging issues related to their integration. In Chapter 4, a framework for methodological integration and selection is proposed and its potential application is discussed. Finally, Chapter 5 provides the conclusions as well as on-going and future research.

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2. Current Methods for Sustainability Assessment

This chapter gives an overview of current methods used to assess sustainability within production systems, namely Life Cycle Assessment, Social Life Cycle Assessment, Life Cycle Costing, EMergy Accounting and Value Stream Mapping.

2.1. Life Cycle Assessment

Life cycle assessment stems from the basic principle that to accurately assess the environmental impact of a system or product, all its productive stages must be included in the analysis, "from cradle to grave", i.e. from resource extraction to final disposal (Ulgiati et al., 2018). LCA is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts over the life cycle of a product, material or service. The main reasons for carrying out an LCA are:

- to identify hotspots across the life cycle of a product and provide improvement options;
- to analyse the contribution of the life cycle stages to the overall environmental load, usually with the objective of prioritizing improvements on products or processes and avoiding burden shifting;
- to compare products for internal or external communication, as a basis for certifying a product or producing environmental labels such as environmental product declarations;
- to support environmental policy making and stakeholders' involvement by governments, administrations, companies.

An LCA study consists of four main phases:

1. Defining the goal and scope of the study;
2. Making a model of the product life cycle with all the environmental inputs and outputs driving the process(es). This data collection and modelling is usually referred to as life cycle inventory (LCI) analysis;
3. Understanding the environmental relevance of all the inputs and outputs contained in the LCI. This is referred to as life cycle impact assessment (LCIA);
4. Interpretation of the study, its dynamics and options for mitigation and improvement.

2.1.1. Goal and scope definition

This step defines the reasons for the LCA study, namely the product, the intended use of the results, the functional unit (i.e. a quantified description of the performance requirements of a system under study), the necessary data and the type of sensitivity analysis. It also describes the system under investigation, its function

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and its boundaries (ISO, 2006a). Within the goal and scope framework, the most important (often subjective) aspects are described, such as:

- the reason for executing the LCA and the questions which need to be answered;
- a precise definition of the product, its life cycle and the function it fulfils;
- a definition of the functional unit (especially when products are to be compared);
- a description of the system boundaries and the way co-products, if any) are dealt with;
- data and data quality requirements, assumptions and limitations;
- the requirements regarding the LCIA procedure, and the subsequent interpretation to be used;
- the intended audience(s) and the way the results will be communicated;
- if applicable, the way peer review will be conducted;
- the type and format of the report required for the study.

The goal and scope definition help ensure that LCA is performed consistently. The goal and scope can be adjusted during the LCA study if the initial choices reveal themselves suboptimal or impractical.

2.1.2. Functional unit

The functional unit is a key element of LCA which must be clearly defined. The functional unit is a measure of the function of the system that is being studied and it provides a reference to which the inputs and outputs can be related, enabling the comparison of two different systems providing the same function/service. There are difficulties associated with defining a functional unit. Therefore, this definition should be precise and comparable so that the unit can be used throughout the study as a reference. For example, the functional unit for a paint system may be defined as the unit surface protected for 10 years. A comparison of the environmental impact of two different paint systems with the same functional unit is therefore possible. Another example is that of different light bulbs which can be compared in terms of lighting hours instead of their units.

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2.1.3. Defining the System Boundary

The system boundary is the interface between 1) the product system being analysed, and 2) either the environment or other product systems. When designing a system boundary, the flows of inputs and outputs should be clearly defined and separated. The system boundary defines which parts of the life cycle and which processes will be assessed. A clear definition of the boundary is important to ensure that all the relevant processes are included in the system, and that all potential environmental impacts are sufficiently addressed (Thomas, 2011). The most commonly used classifications to define the system boundary are illustrated in Figure 2.1.

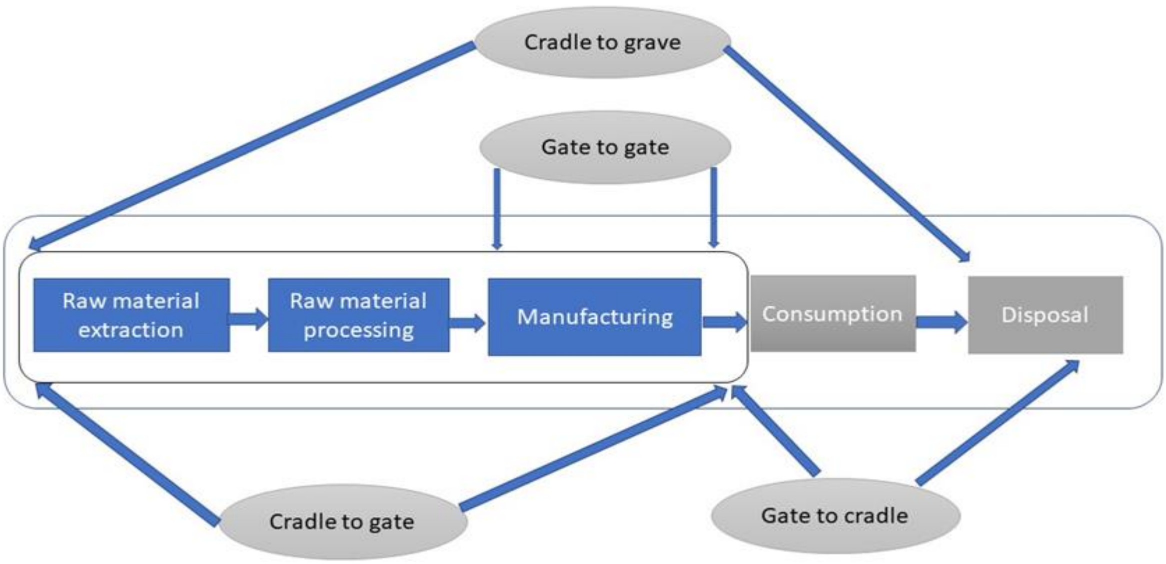

Figure 2.1 - Four common options for defining system boundaries in LCA.

2.1.4. Inventory analysis

The life cycle inventory is usually the most time consuming and complicated stage of an LCA. This includes data collection often involving interviews, surveys and other forms of personal communication, sourcing industry reports and grey literature, and accessing process data from LCI databases. The collected and compiled data lists and quantifies all the material and energy inputs (such as electricity, fertilizer and fuel consumption) and outputs (e.g. waste products and air emissions) for each activity or process in the product system. The data must be modelled and scaled by means of software tools, for example SimaPro, GaBi and OpenLCA among others.

2.1.5. Allocation between product systems

Allocation is defined as partitioning the input or output flows between the goods that are produced by the process under analysis (ISO, 2006b). The International Organization for Standardization (ISO) defines a specific procedure for allocation in ISO 14044/2006:

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- Wherever possible, allocation should be avoided by dividing the unit process to be allocated into two or more sub-processes.
- Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.
- Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. Input and output data might be allocated between coproducts in proportion to the exergy and economic value of these products (ISO, 2006b). Consider, for example, a sawmill that makes wooden planks, but in the process also produces sawdust. If sawdust generates 20% of the sawmill's revenue, 20% of the environmental load is allocated to this output and 80% to wooden planks.

2.1.6. Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is the stage in which the full inventory of inputs and outputs is translated into several aggregated metrics of environmental impact (Ulgiati et al., 2018). The impact assessment aims at a further interpretation of the LCI data. Several impacts are evaluated, and indicators developed to provide a clear picture of resource use and environmental damage generated within a process or an economy. The list of impact category indicators (for example, global warming potential, fossil resource scarcity, water consumption potential, among others) is called its environmental profile (Brentrup et al., 2004). For further interpretation of the environmental profile, a normalisation step relates the indicator values to reference values. The aim of normalisation of indicator results is to better understand the magnitude for each indicator result of the product system under study (ISO, 2006b).

2.1.7. Interpretation of results

Life cycle interpretation is the final stage, in which the results are discussed and compared to suitable benchmarks. The conclusions and recommendations are based on the outcomes of the LCA. In addition, limitations of the study are also identified at this stage, being highlighted according to their relevance to any conclusions and recommendations.

LCA attempts to model every environmental impact caused by a product throughout its life cycle (i.e. over time and space). In practice, this is impossible and certain simplifications to the system boundaries need to be introduced. A common practice is to exclude everything outside of the system boundaries from the analysis (i.e. "cut-off"). As this "cut-off" is often subjective, this leads to issues in comparing and repeating results. In order to minimise the biases, it can be useful to use Input-Output LCA (IOA). IOA is a framework in which

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the system boundary includes the entire economy. This framework is based on monetary transactions of resources flows and can be transformed into physical quantities and environmental externalities (Martinez et al., 2019).

2.2. Social Life Cycle Assessment

Social Life Cycle Assessment is a novel method that provides information about the social effects associated with the life cycle of a product. Its definition is, however, still incomplete and under development. The definition from Andrews et al. (2009) has been adopted, as it results from international voluntary guidance (i.e. collaboration between UNEP and SETAC) to assess social impacts along the life cycle of products in a global context. Andrews et al. (2009) defined s-LCA as an assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal. s-LCA defines social impacts as consequences of positive or negative pressures on social endpoints (i.e. well-being of stakeholders) (STAR-ProBio, 2019). These consequences arise from social relations (interactions) weaved in the context of an activity (production, consumption or disposal) and/or engendered by it and/or by preventive or reinforcing actions taken by stakeholders.

Many researchers have proposed different frameworks for s-LCA and all of them require comprehensive data. Moreover, social indicators (described in Appendix II) may be very subjective and vary in their interpretation in the literature. This subjectivity could bias the results especially when weighting factors to provide the relative importance of each impact category (STAR-ProBio, 2019). This problematic area may also limit the comparison of social indicators between studies. Only in 2013, UNEP and SETAC launched a specific guideline to standardise the knowledge and unify the evaluation method. Therefore, it is very important to be transparent when performing an s-LCA. The methodology to perform an s-LCA follows the same stages as for LCA, according to the ISO 14044 framework (ISO 14040, 2006; ISO 14044, 2006), as explained previously on section 2.1.

s-LCA accounts for aspects such as hierarchies in workplaces, production management and planning, unemployment, skills and know-how, demand for societal infrastructures, culture, child labour, poverty and trade fairness. To perform a social assessment, it is essential to identify all the stakeholders involved (e.g. workers, consumers, local community, society and value chain actors) and organise an inventory within subcategories to be able to assess the social, sociologic and socio-economic impacts of products throughout their life cycle. The evaluation requires heterogenic knowledge in sociology, anthropology, sociology, and management sciences (UNEP and SETAC, 2013; van Haaster et al., 2017; Zamagni et al., 2015).

2.3. Life Cycle Costing

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Conventional life cycle costing (cLCC) can be defined as the sum of all funds expended in support of an item from its conception and fabrication until the end of its useful economic life (White and Ostwald, 1976). Conventional LCC was first used in 1933 by the General Accounting Office in the United States. However, the cLCC concept and method were only formally developed and implemented in the 1960s by the U.S. Department of Defence to assess the acquisition of high-cost equipment, such as airplanes and tanks (Hoogmartens et al., 2014). During the 1970s, this method started to be implemented in Europe to support policy and business decisions (UNEP, 2011). Several LCC approaches have been conceptualised over the years. Nevertheless, only two other approaches, in addition to cLCC, have been widely accepted in the scientific literature, namely: environmental and social LCC (eLCC and sLCC, respectively). Both approaches are built-on and expand the scope and boundaries of conventional LCC, as shown in Figure 2.2.

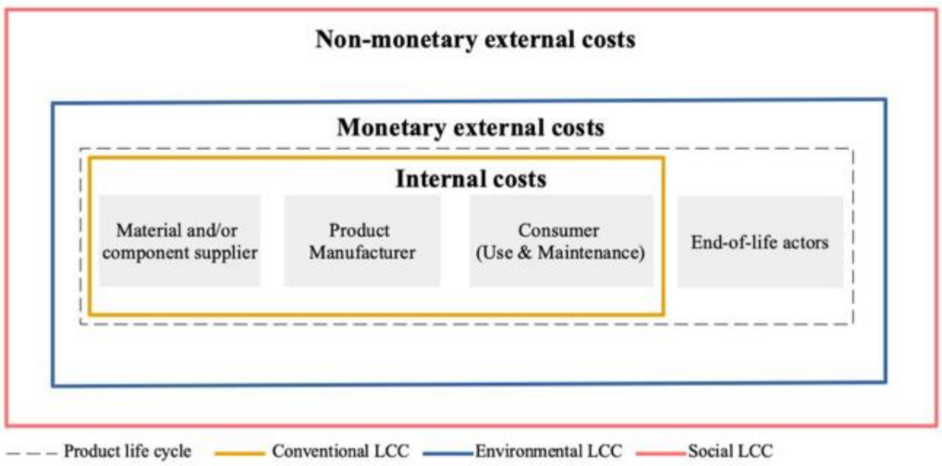

Figure 2.2 - Conventional, environmental and social LCC scopes (adapted from Hunkeler et al., 2008).

Environmental LCC assesses all costs, which are directly met by one or more stakeholders during the life cycle of a product or service (i.e. supplier, producer, user or consumer and/or end-of-life actor) (Hunkeler et al., 2008; Swarr et al., 2011). This approach expands conventional LCC by including end-of-life and monetary external costs (e.g. carbon emission costs) (Bierer et al., 2015; Norris, 2001). In addition, eLCC also considers the 'physical' life cycle of a product instead of the marketing life cycle commonly considered in cLCC.

Regarding social LCC, this approach is rooted in cost-benefit analysis (CBA) and includes third party costs, normally not covered by transaction costs (e.g. taxes associated with buying a product) (Ciroth et al., 2011). sLCC assesses all costs associated with the life cycle of a product or service that are met by anyone in the society (i.e. macro-economic level), whether today or in the future (Hunkeler et al., 2008). Even though eLCC already includes the monetisation of externalities, sLCC expands the scope to incorporate non-monetary externalities (e.g. societal costs associated with loss of biodiversity).

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Environmental LCC was developed to provide a comprehensive combination of both the environmental and economic performance of a product or service, in order to support technological and managerial decisions. In general, the eLCC method aims at estimating and comparing eLCC of alternative products. For example, Iraldo et al. (2017) compared two alternative options (i.e. standard and durable) of two energy-intensive products (e.g. domestic refrigerator and oven) by estimating their life cycle costs.

The eLCC approach will be described in detail in this chapter and included in the proposed framework, considering eLCC objectives, rationale and the industrial system focus of this report. The eLCC does not take into consideration time, assuming all cost variables will remain constant. According to Hunkeler et al. (2008), the following steps are commonly implemented while performing an eLCC: (i) Goal and Scope definition; (ii) Information gathering; (iii) Interpretation and identification of hotspots and, (iv) Sensitivity analysis and discussion. These steps will be elaborated on in the following sub-sections.

2.3.1. eLCC Scope and System Boundaries

The scope, goal and system boundaries need to be defined before the study starts, which need to be in accordance with the functional unit. In addition, the perspective of the analysis (e.g. producer, consumer) should be defined in order to identify all relevant costs for the stakeholder(s). The costs are classified in two ways:

- Internal costs – refers to costs along the life cycle of a product or service which are borne by a stakeholder (e.g. supplier, EoL manager). These costs are normally related to production, use, or end-of-life expenses, and can be connected to a business cost.
- External costs (also known as externalities) – indicates impacts that have been priced in monetary units but aren't directly met by any actor within the life cycle. However, due to their relevance for decision-making they should be considered in the study. These costs can refer environmental and social externalities, such as carbon emissions, effects of air pollution on human health and poverty.

2.3.2. eLCC Information Gathering

The data requirements for eLCC depend on the scope and goal of the study. Generally, eLCC requires an intensive data gathering process to collect cost information. This cost information is more variable over time and is not readily available in databases. When data is not available, other techniques are needed such as scenario development, forecasting or estimation methods. The latter is the most common in the field of life cycle costing. Asiedu and Gu (1998) have classified cost estimation techniques into three different categories:

- Parametric – Requires the application of equations that describe relations between cost and the attributes of a product, service or process. This technique uses several statistical procedures and

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requires a continuous collection of data and process revision to keep the cost estimation relationships updated (Korpi and Ala-Risku, 2008).

- By analogy – Normally used to perform cost estimations of new products and services. This approach identifies similar existing products and adjusts their costs to the new product. It requires a high degree of judgment and generally experts with in-depth knowledge are needed (Asiedu and Gu, 1998; Korpi and Ala-Risku, 2008).
- By engineering standards/detailed model – Commonly uses labour time, rates, material quantities and prices to estimate the direct costs of a product or activity. In addition, an allocation rate is used to account for indirect costs. This approach provides the most accurate estimates, nonetheless, it requires a large amount of detailed data and effort to perform calculations (Asiedu and Gu, 1998; Korpi and Ala-Risku, 2008).

The allocation of costs in eLCC is particularly important for indirect costs and the costs associated with different components within a single product. eLCC can minimise indirect costs, such as overhead costs (i.e. ongoing expenses of operating a business, for example, building rent and insurance fees) by using a system view and converting these costs into direct costs associated with a process or product (Hunkeler et al., 2008). In addition, the Activity-Based Costing (ABC) method which deals with the allocation of overhead costs can be integrated within eLCC to overcome this barrier. On the other hand, the allocation of different components or materials of a product to costs that can be only associated with the entire product needs to be solved using a case-by-case approach, following the LCA economic or physical allocations.

2.3.3. eLCC Interpretation and identification of hotspots

One of the key outcomes of an eLCC is the identification of hotspots and trade-offs. The interpretation of such hotspots can be performed by using classical methods of investment appraisal, such as: net present value (NPV), break-even point, internal rate of return and pay-back period.

2.3.4. eLCC Sensitivity analysis and discussion

Sensitivity analysis identifies how sensitive the calculated outputs (e.g. NPV) are to changes in the parameters used in the analysis (e.g. estimated lifetime, revenues and life cycle costs, sales volumes). However, in a sensitivity analysis only one input can only vary at a time. Therefore, Monte Carlo simulations are often used to estimate this relationship, even though it is more complex and less transparent. This should be the final step before discussion of results and development of recommendations for decision-making (Hunkeler et al., 2008).

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2.3.5. LCC limitations

Currently, there still are some challenges associated with LCC, such as the lack of a standardised procedure, data availability, the use of different currencies, the definition and choice of discount rates, the relevance of life cycle costs for different actors and the lack of robustness of valuation methods for externalities (Costa et al., 2019; Swarr et al., 2011). In addition, there is still a lack of widely used and dedicated software to perform life cycle costing, even though GaBi and SIMA pro have included extensions to conduct eLCC in parallel to LCA.

2.4. EMergy Accounting

EMergy Accounting is a powerful thermodynamics-based and systems-oriented method, which provides an evaluation of processes from an environmental perspective (Odum, 1994; Raugei et al., 2014). EMergy (spelled with a capital M) is defined as all available energy (exergy) directly and indirectly used to produce a resource in the biosphere, as well as, to generate a product or a service in the economy. Therefore, to calculate the eMergy value of a resource, it is necessary to know all the thermodynamic work required to produce it over time. LCA begins from cradle (mining), while EMA starts from the resource generation within environmental domains (e.g. earth crust, atmosphere and oceans) over time (as illustrated in Figure 2.3). Therefore, fossil fuels are not evaluated starting from extraction (as in LCA) but starting from phytoplankton sequestration over millions of years. Solar energy is used as a common denominator to express all flows in a standard unit, as it is the basis of the development of every system in the biosphere (Odum, 1996).

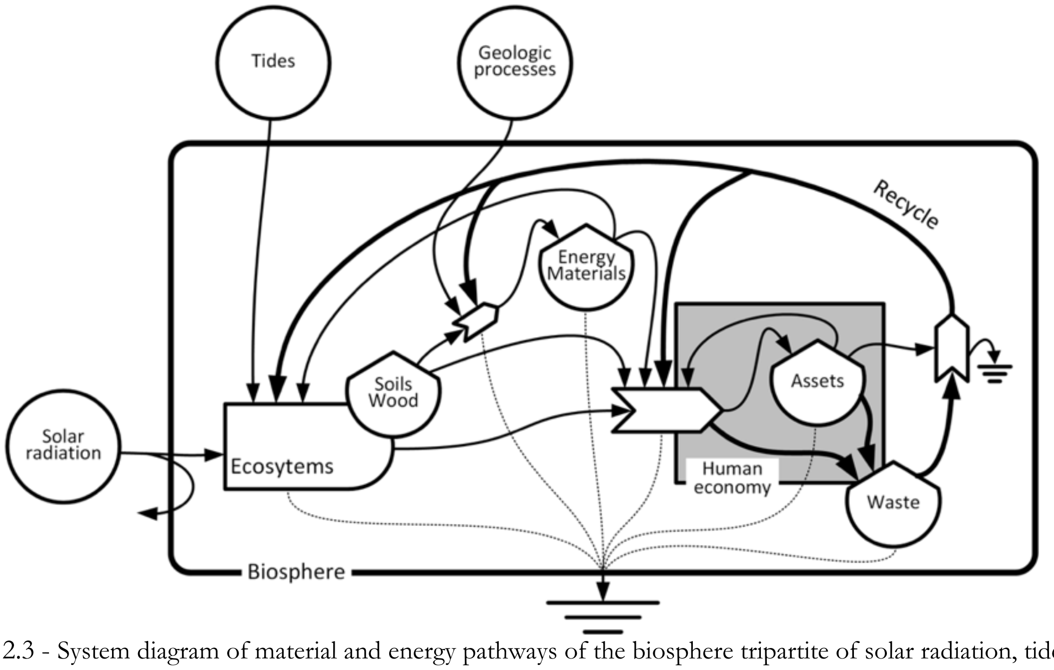

Figure 2.3 - System diagram of material and energy pathways of the biosphere tripartite of solar radiation, tides and geologic processes (adapted from Brown and Buranakarn, 2003).

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EMA allows the numerical measurement of stocks and flows in different units thus overcoming the limitations of other approaches (Brown and Ulgiati, 2004; Odum, 1996). EMA uses equivalence factors to convert inputs values to a standard unit. These factors express the work done by nature to produce them, are the eMergy required per unit of product or service and they are defined as:

- Solar Equivalent exergy per unit of exergy (SER), measured in seJ J^{-1}: used for the geo-biosphere tripartite of solar, tidal and geothermal flows;
- Transformities (Tr), measured in sej J-1: used to all the other measured flows (Brown and Ulgiati, 2016a).

The starting point of EMA calculations is the definition of the system boundaries to draw a diagram considering: space or territory, infrastructure, socio-cultural, economic, and market aspects. Based on this diagram, components, interactions, upstream (inputs), downstream (outputs) and internal assets (used goods) relationships are collected (Becht, 1974; Odum, 1996). The total eMergy (U) of an evaluated process is the sum of all inflows already converted in solar equivalent joules (see Appendix I for EMA evaluation procedure and calculation of indicators).

EMA accounts for the resource cost of know-how, information, and infrastructure, missing in other methods. The total eMergy value considers, among other input data categories such as renewable and non-renewable resources and materials, the value of labour and services (L&S) that support the processes. The necessity of appropriate policy decisions will drive the use of L&S. An evaluation that considers L&S helps to understand the process on a local level (i.e. know-how, infrastructure, and information are not comparable among different cultures, countries or even regions). Instead, when the methods do not account for L&S, it is difficult to compare results to other studies beyond local boundaries (Santagata et al., 2019).

2.4.1. EMA applied to Industrial Processes

EMA is a method that sits at the interface between human and natural systems (Ridolfi et al., 2018), being able to evaluate energy use efficiency (Ghisellini et al., 2014). EMA also supports policy decisions by highlighting the overall environmental loading of the considered system, and by evaluating the evolution of environmental and economic losses of natural capital and ecological functions (Santagata et al., 2020b). Indeed, EMA brings the donor side perspective (nature) to the evaluation of the system instead of only the consumer side (industry) (Raugei et al., 2014).

2.5. Value Stream Mapping

Value Stream Mapping (VSM), also called material and information flow identification or stream analysis, finds its origin in lean management. VSM aims to identify waste in production processes and eliminate it in an

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efficient method suitable for being performed by small teams/companies (Hines and Rich, 1997). Initially, waste was defined from an economic perspective, focusing more on wasted time and inventory as indicators of inefficient production systems. Over the last decade, VSM has been adapted to include more environmental (waste) indicators as part of a growing understanding of the strong synergies between lean and green manufacturing.

There is no single source of the VSM method; it has evolved over the last 100 years from basic flow chart diagrams first found in the work of Knoeppel (1915). VSM in its current form became recognisable in the 1990s, as part of the lean manufacturing paradigm. VSM was originally used to minimise the seven wastes as defined by the lean manufacturing paradigm (transport, inventory, motion, waiting, over-processing, overproduction, and defects) (Hines and Rich, 1997). Over-processing and overproduction metrics are useful for transitioning to a circular production process (i.e. they have a strong focus on excess material use). Furthermore, VSM has a strong focus on the prevention of waste generation in general.

VSM can study inputs, outputs, waste and by-products on a process level. In so doing, VSM identifies in which exact step of a process waste is generated and that allows for comparing (planned) improvements to the current state in efforts to minimise waste. While VSM is normally used on a micro level, variations of VSM that look at the meso level exist, often focusing on a supply chain (e.g. analysing the transport process in a similar way to the production process). The output is visualised in a diagram. Although there are no official standards for reporting the results, most reports use a similar representation which can be considered the *de-facto* standard. The different variations of VSM mostly vary according to the types of waste measured or the scope under study.

Sustainable Value Stream Mapping (Sus-VSM) adds dedicated environmental and social indicators to VSM, indicators related to resource and energy use as well indicators regarding labour conditions (other variations of VSM tend to focus on only adding a single metric) (Faulkner and Badurdeen, 2014). A full list of indicators can be found in Appendix II. Sus-VSM is built on the work of earlier attempts to include environmental metrics in VSM. The modular nature of Sus-VSM (extended from VSM) allows practitioners to focus on a single metric for an incremental improvement if preferred (e.g. energy or water usage), while also allowing for the holistic approach that characterises Sus-VSM. For this reason, Sus-VSM is the preferred VSM variation in the next sections of this report.

2.5.1. Critiques of Sus-VSM

The Sus-VSM as imagined by Faulkner and Badurdeen (2014) is missing a direct representation in monetary value for its indicators. Thus, by adding a financial component to the indicators, this could be a more complete "Triple Bottom Line" framework allowing for better cost-benefit analyses of any proposed improvements to the production process. In addition, Sus-VSM is useful to improve circularity in production processes, as the

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main objective is to eliminate waste and identify sources for reuse, but it is not optimised for circular production processes that include repairing or remanufacturing operations. Another problem is that there is only limited research on how VSM can be integrated with other (environmental) assessment tools, which brings us to the next section of this report.

3. Interaction between methods

Figure 3.1 shows the interactions between the different methods analysed in this report, considering sustainability dimensions and across different scales of interest (micro, meso and macro). As shown, the methods focus on the micro and meso levels, which indicates that different methods could be integrated to assess the same system. Therefore, this would provide more comprehensive support for decision making, as the methods consider different sustainability dimensions. Regarding the sustainability dimensions:

- LCA and EMA are mainly concerned with environmental aspects. Nonetheless, these methods also consider some social and economic aspects (e.g. effects on human health of NOx pollutants and direct and indirect human labour, respectively);
- eLCC and Sus-VSM are mainly based on the economic pillar, however, these methods also consider environmental and social dimensions. For example, eLCC monetises the environmental impacts (external costs), while Sus-VSM considers human labour conditions and excess material/energy use;
- s-LCA is the only method designed to address social aspects, also having some economic considerations, such as fair salary and effects on local employment.

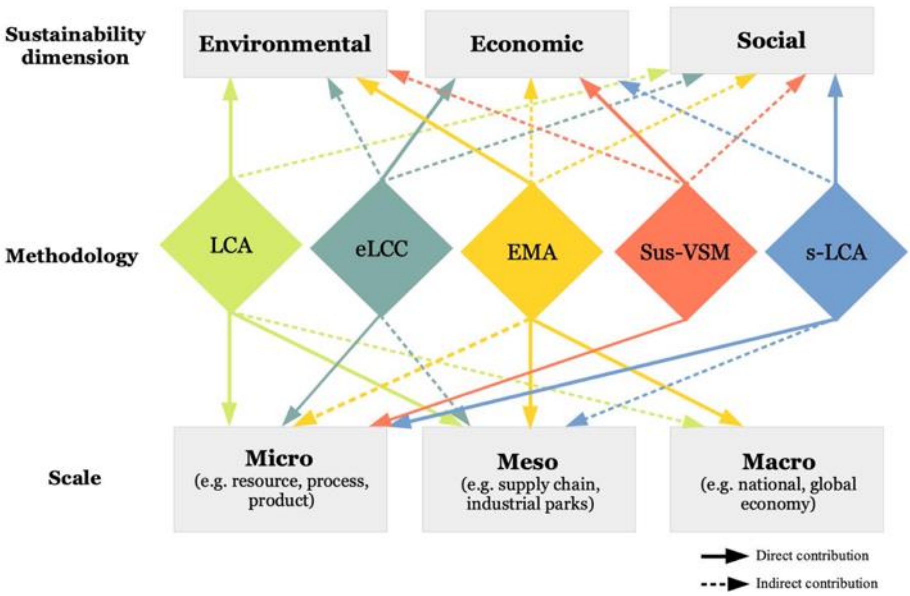

Figure 3.1 - Interactions between selected methods considering sustainability dimensions and scale of interest.

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3.1. Overview of previous integrations: strengths and limitations

LCA has been integrated, separately, with LCC, s-LCA, EMA and VSM. Currently, there is not any relevant scientific literature on the integration of the Sus-VSM, LCC and EMA methods with each other. This signals the need to foster discussion on the strengths and the limitations this may entail.

3.1.1. LCA, LCC and s-LCA integration

Initially, the first conceptual idea of integrating the economic dimension of sustainability into LCA emerged in 1987 (Finkbeiner et al., 2010); this was followed by the work of Norris (2001) who suggested the integration of cLCC and LCA. Around the same time, O'Brien et al. (1996) proposed the first integration of social aspects in environmental LCA, through the conceptualisation of the Social and Environmental Life Cycle Assessment (SELCA) tool.

The integration of the economic and social pillars into LCA has been debated in the scientific literature since the beginning of the 21st century (Costa et al., 2019). According to Sala et al. (2013), LCA, eLCC and s- LCA work in isolation as they are applied separately, however, they keep the same system boundaries without taking mutual relations into account. The integration debate culminated in the introduction of the Life Cycle Sustainability Assessment (LCSA) framework by Kloepffer (2008), which includes LCA, eLCC and s-LCA. One of the main advantages of this framework is the possibility of jointly evaluating the results of the three assessments. Nonetheless, the LCSA framework faces several challenges. These include the lack of harmonisation between the methods considered, the absence of databases that allow a life cycle perspective in the economic and social pillars and obstacles to the development of impact assessment methods and methods to perform sensitivity and uncertainty analysis (Costa et al., 2019).

In recent years, the scientific community has focused on improving and developing s-LCA (i.e. methodology and indicators) (Costa et al., 2019; Petti et al., 2018), while continuing to propose new conceptual integrations of LCA and LCC. For example, Heijungs et al. (2013) proposed a computational integration of LCA and LCC by providing an explicit and transparent account of how to calculate life cycle costs, which are fed into eco-efficiency indicators aggregating economic and environmental information. On the other hand, Bierer et al. (2015) proposed linking eLCC and LCA through an extended Material Flow Cost Analysis (MFCA). This could help overcoming problems with harmonisation of system models between the two methods, providing a consistent basis for joint evaluation of monetary and non-monetary figures. Despite the efforts in integrating LCA, eLCC and s-LCA, there are still aspects that need to be considered, namely:

- Functional unit – One of the limitations of integrating s-LCA with other LCT methods is the difficulty in specifying a functional unit (FU) and presenting qualitative data in relation to FU (Petti et al., 2018);
- System boundaries – Defining the same system boundaries is an important step to integrate these methods, however, for s-LCA there is still a lack of scientific evidence in defining system boundaries (Benoît et al., 2010; Petti et al., 2018);

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- Metric system – eLCC expresses all units in monetary terms, whereas LCA focuses on flows characterised by physical quantities (Hoogmartens et al., 2014); In addition, s-LCA considers both qualitative and quantitative data, while eLCC and LCA only require quantitative information (Petti et al., 2018);
- Data requirements – In LCA, the environmental impacts of upstream processes need to be gathered to calculate the total environmental impacts of a particular product, while in eLCC assessments the upstream processes are measured by the price (e.g. price of raw material accounts for costs associated with extraction and processing) (Hunkeler et al., 2008).
- Normalisation and weighting methods – These methods reduce the transparency of the study, making results uncertain and subjective, preventing comparison of results.

3.1.2. LCA and Sus-VSM integration

Some attempts have been made to integrate LCA and Sus-VSM into a new method (Paju et al., 2010; Thiede, Li, Kara, & Herrmann, 2016). However, only two papers have tried to directly use Sus-VSM with LCA (Djatna and Prasetyo, 2019; Vinodh et al., 2016). Djatna and Prasetyo (2019) performed a Sus-VSM first and the estimated values were used in a gate-to-gate LCA of the production process. The results of the gate-to-gate LCA can then be integrated in an LCA with a broader scope (e.g. cradle-to-cradle or cradle-to-gate). Moreover, the LCA results can also be used again in Sus-VSM in order to decide the best way to improve the current production process from an environmental perspective (Djatna and Prasetyo, 2019). While Vinodh et al. (2016) took a similar approach but did not include the LCA results in deciding on which improvement to prioritise, instead they compared the current state Sus-VSM with the future state of Sus-VSM to decide on disposal strategies.

3.1.3. LCA and EMA integration

Ghisellini et al. (2014) applied LCA and EMA to evaluate different scenarios of dairy farms in Italy and Poland. For example, they looked at the substitution of electricity for solar panels and the use of manure as fertilizer and to generate biogas. LCA showed the reduction of environmental impacts, and EMA was able to show that self-sufficiency is a way towards better performance in terms of resource efficiency. This study also highlighted that energy was not the most important aspect on dairy farms from an environmental perspective.

Recently, a mixed EMA-LCA evaluation was consolidated in a framework called LEAF; within this framework, the two methods were integrated in order to provide new insights into sustainable process improvements (Santagata et al., 2019 and 2020a). LEAF compares LCA and EMA results from different scenarios (Figure 3.2), as described in the steps that are needed to perform this evaluation:

1. Ex-Ante LCA analysis - identification of the hot-spots;

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2. EMA Scenario analysis, divided into:
    a. Business as usual - evaluating the system as it is;
    b. Technology-based Efficiency Improvement - to suggest improvements of the investigated hotspot of studied process, through energy and material technological efficiency;
    c. Eco-Efficiency Implementation - achievable improvements of the environmental sustainability by substituting energy and material hotspots with renewable or less environmental costly input flows;
3. Ex-Post LCA is performed for each EMA scenario to detect their environmental burdens. It is possible to conclude that the presented framework can provide a multi-perspective set of indicators able to guide decision-making and management. The alternate application of LCA and EMA provides insights from the donor side (EMA) and from the consumer side (LCA).

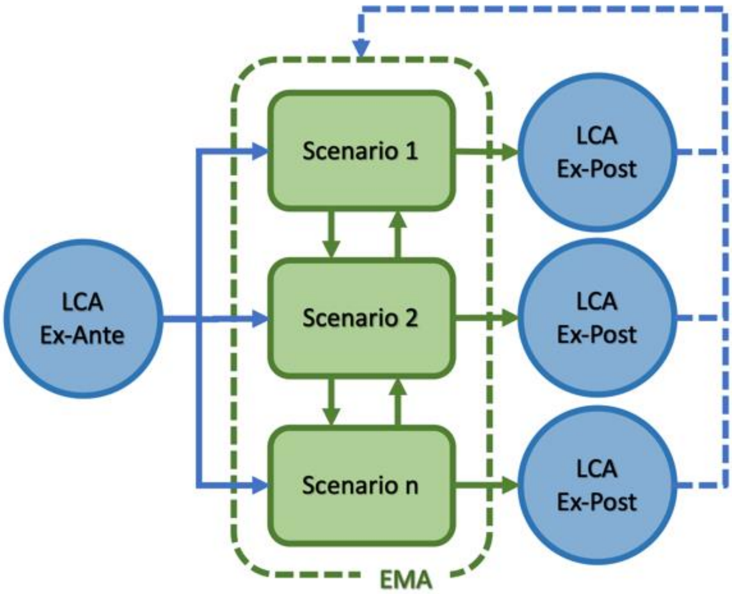

Figure 3.2 - The integrated LCA and EMA framework (LEAF) – a multi-perspective set of indicators by the simultaneous calculation of both indicators (adapted from Santagata et al., 2020a).

LEAF provides a holistic evaluation that brings both the environmental (donor side) and the technosphere (consumer side) perspectives (Santagata et al., 2020a). Furthermore, the development of the innovative SCALEM software tool (Marvuglia et al., 2018) has contributed to extend the application of EMA by using Life Cycle Inventory (LCI) data to provide detailed input data in an accurate and replicable manner.

4. Assessing Circular Economy at the micro and meso scales

The Circular Economy is based on three pillars: preventive design of systems by increasing systems efficiency, substitution of non-renewable resources with renewable ones, and feedback of (by-)products and waste based

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on circular strategies and reverse logistics. While there is a lot of research on improving system efficiency and material substitution, companies find it more difficult to understand the economic, environmental, and social benefits of using (by)products and waste through a feedback loop in a production system (Lieder and Rashid, 2016).

In addition, the debate on the identification of the most suitable methods for assessing CE has not yet reached any consensus, leading to the creation of multiple methodological frameworks for assessing circular systems (Niero and Kalbar, 2019). Currently, most of the available indicators measuring CE strategies refer either to macro or meso levels, ignoring micro scale (Linder et al., 2017). Furthermore, there are contrasting opinions within the scientific community on how and what should measure CE strategies (Niero and Kalbar, 2019). For example, Linder et al. (2017) proposes that circularity metrics at product level should only focus on measuring circularity, ignoring environmental performance. On the other hand, Pauliuk (2018) conceptualised a dashboard with new and established indicators for a quantitative assessment of product systems, considering circularity, environmental and economic aspects.

The links between the CE concept and sustainability (Geissdoerfer et al., 2017) have suggested that it is fundamental to assess CE measures through indicators that address several aspects (Niero and Kalbar, 2019). Recent work has proposed coupling circularity indicators with sustainability assessment methods. For example, Niero and Kalbar (2019) proposed coupling circularity indicators with LCA through Multi Criteria Decision Analysis (MCDA). Moreover, eMergy-based indicators bring benefits to evaluate circular strategies, because they are systemic and include global aspects of the system's performance and planetary boundaries. These indicators are also able to enhance the appropriate use of natural capital and assess ecosystem's functions (Santagata et al., 2018).

4.1. Framework for method selection and integration

Considering the current debate around the concept of CE and the lack of approaches to assess the environmental, economic and social benefits and impacts of such a transition at micro and meso level, we propose a framework for method selection and integration. This framework is based on a representation of a local economy in a Circular Economy context. Figure 4.1 uses the systems diagram language developed by Odum (1996).

The diagram sets the boundaries to those of a local economy, receiving environmental support from renewable sources (i.e. sunlight, deep heat, rain, wind) which enables the environmental production of raw materials as an evaluated input flow. Raw materials are extracted from different compartments within the ecosphere (i.e. earth crust, hydrosphere, forests, etc.) and then processed, making them ready for industrial production and distribution to final consumers (both within and outside the considered boundaries). Used products, together with scrap materials from the different steps, are collected in different ways in order to be directed to repair,

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recycle and remanufacture, or to disposal processes. The entire network of processes is made possible by a virtual storage of assets, sustained by goods, machinery, energy and fuels coming from outside the local economy boundaries. These virtual storages represent the energy filled and restored within the analyses period of time, regulating and equalising the flows. Repaired, recycled and remanufactured goods and materials also contribute to the storage of assets, in a Circular Economy perspective. Emissions and discharges from final disposal go back to the ecosphere both inside and outside the considered boundaries. The network functioning is maintained by labour, both direct and indirect. The economic sustenance to labour and services, and to the entire system, comes from a virtual storage of money, supported by an inflow from the outside economy in exchange for assets from the system. All transformations generate a certain loss of energy, expressed as a heat sink, according to the second principle of thermodynamics.

To accurately understand the environmental, economic, and social aspects and impacts of the different interactions and processes found in a local economy, different methods must be employed, and their outcomes should be integrated where possible. So far, only LCA has been integrated with the other methods considered in this report (as mentioned in Chapter 3). As illustrated in Figure 4.1, Sus-VSM mainly assesses production and material recovery processes, identifying inputs and outputs during each process and improving knowledge about different processes which can be compiled into inventories. These inventories are the starting point of LCA, eLCC and EMA assessments.

LCA analyses physical flows occurring under human control, delivering information about the resource and environmental impacts of given products and/or processes, while eLCC adds the costs and the economic transactions, calculating costs and revenues during the life cycle of products and/or processes. Furthermore, EMA provides not only the donor side perspective of nature (e.g. consumption and use of natural resources, and their renewability) but also information on to what extent the process is based on a local or larger scale by considering labour and service costs. A flow chart illustrated by Figure 4.2 was developed, in order to aid the selection process of which method is more suitable for practitioners to apply according to their objectives and scale of the assessment.

We propose that the assessment methods can be further integrated with one another to better capture the benefits and impacts of circular systems. Moreover, the methods can also be used to complement each other, for example by giving specific information which can be used as an input to another method. Thus, a detailed table correlating the output indicators and sustainability dimensions for each method has been developed (see Appendix II). Another aspect of this framework is the fact that different levels of circularity are considered, not only circularity within a production system but within different production systems at a local economy scale. Conventional Economics Assessment (CEA) boundaries were also represented in Figure 4.1 to illustrate the inadequacy of current indicators (e.g. company's turnover or GDP, at national level) in capturing the complexity and evaluating the impacts and benefits of Circular Economy.

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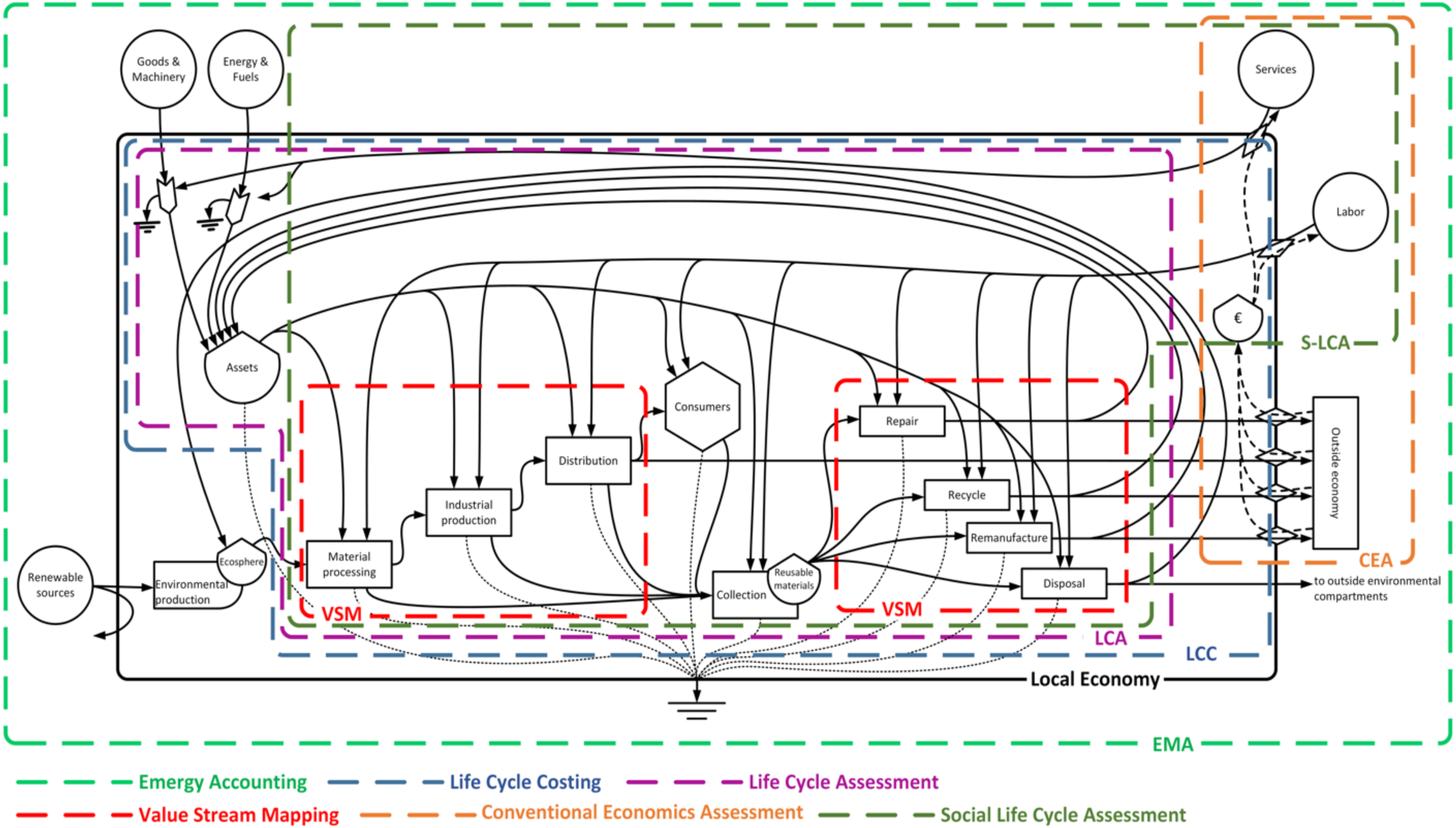

Figure 4.1 - Systems diagram representing a circular production system within a local economy, indicating overlaps and how each method complements the other.

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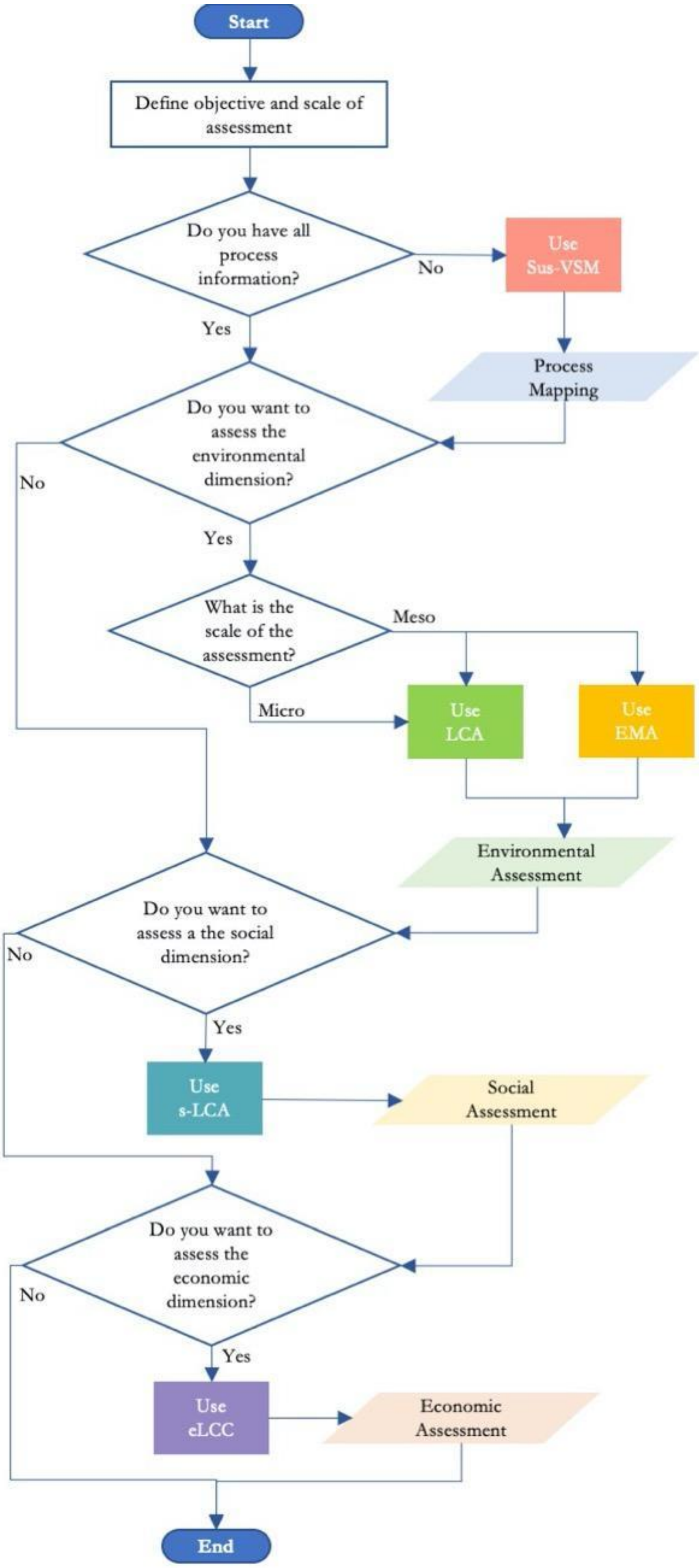

Figure 4.2 – Flow chart to aid method selection process by practitioners.

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To better understand how the framework can be used practically, two scenarios have been conceptualised:

1. Taking the example of the automotive industry, where repair, remanufacturing, and recycling levels are relatively high compared to most industrial sectors, and where a lot of research has been done on production process optimisation and separately on remanufacturing processes. Nonetheless, if a product's design is conceptualised for optimising the production process, it might be harder to remanufacture. While if design is heavily focused on remanufacturing, it might be harder to produce initially. In such a situation, EMA could be used to account for the non-renewable and renewable resources required and to ascertain if a given economy can afford such resource expenditure (precautionary principle) or if a production pattern should simply be abandoned and replaced. This information could be used as input to LCA and eLCC assessments, which can be run in parallel to evaluate the environmental and economic implications of different alternatives for production. Finally, the LCA and eLCC outcomes can be integrated into VSM to better compare manufacturing and remanufacturing options and to decide further optimisation techniques for each;
2. Considering the consumer electronics sector, usually manufacturers try to minimise material use to improve their environmental performance, however, this makes products harder to repair. On the other hand, repairing increases lifetime which also improves the environmental score of many electronics products. This dilemma has been identified in an LCA previously performed for the Fairphone 2 (Proske et al., 2017): an increase in material use would only pay off if people repaired their products instead of disposing of them when they broke. Nevertheless, many companies fear an easy to repair phone might cannibalise their sales and are thus hesitant to make their phones easy to repair. To better understand the sustainability of repairable phones, LCA can be performed covering both changes in the production and repair process. eLCC will be performed after LCA in order to monetise the environmental impacts previously identified. In this scenario, VSM can be used as supporting tool by providing reliable input data to LCA and eLCC, as currently repairs are very diverse and there is a lack of available data.

4.1.1. Perspectives and Limitations

As shown in the previous section, multiple assessment methods can be used simultaneously to assess the same (circular) production system as they answer to different questions regarding sustainability. The proposed framework helps to identify and overcome inconsistencies and missed links between the selected methods by raising awareness about each method. For example, in terms of the type of information that can be obtained by implementing each one of them and when a method should be preferred over another.

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Nonetheless, the selected methods are still optimised for a linear economy paradigm. Thus, further research to develop suitable indicators and calculation models to assess the benefits and impacts of CE measures adoption is needed. The proposed diagram covers most aspects of a full circular production system. However, there are still some aspects that are not covered, for example resale, which is a clear limitation of this framework.

5. Conclusion

LCA, s-LCA, LCC, EMA and VSM play different roles in assessing the sustainability of a production system as each one of these methods addresses different sustainability indicators. Currently, these methods are optimised for linear production systems and have limitations when assessing circular systems and related feedback loops. These limitations can be overcome by providing a guide on method selection for different production scenarios or by further integration of these methods (e.g. use outputs of VSM as input to LCA) in order to get more comprehensive outcomes.

In summary, VSM identifies inputs and outputs related to different process phases, while LCA, s-LCA, and LCC account for environmental impacts, social impacts, and costs (respectively) associated with a product's life cycle (i.e. from extraction of resources to end-of-life phase). Finally, EMA has a wider scope adding the amount of natural resources consumed, providing the donor side perspective, the efficiency of natural resources uses and renewability.

Therefore, a framework for method selection and integration, focused on a circular product system is proposed. Further research is needed to develop indicators and calculation models within the selected methods to assess the environmental, social and economic implications of circular production systems, as these methods are still optimised for a linear economy. Moreover, the proposed framework does not cover some aspects of a circular paradigm, such as resale. Thus, the authors recommend further research in understanding how a resale system would work in a CE context.

5.1. On-going & Future research

This framework will be tested throughout its implementation in different industrial systems. For Sus-VSM, a study in the electrical and electronic equipment industry has started that will look to integrate primary production, remanufacturing, and repairs in a dynamic process for which Sus-VSM will be adapted to better work with such integrated circular production systems. Ideally, this will result in a new VSM variant that can not only cover interconnected production processes but may also provide data on resource/material substitution by different levels of repairs/remanufacturing. Furthermore, case studies considering the construction, automotive, and steel sectors will be conceptualised and Sus-VSM will be used to map production processes, after which an eLCC will be performed using the data provided by Sus-VSM.

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There are ongoing studies relating to the assessment of circularity in the agro-food industry using LCA. The issue of allocation is still problematic, and it is even more subjective when considering biorefineries. LCA alone does not give a comprehensive analysis of an entire system by not considering other factors such as labour, biotic resources, cost of raw materials, investment potential and the renewability of the products. By merging LCA with EMA, we can expand the focus of LCA to encompass resource generation time and environmental quality, whereas with eLCC we can provide the information needed to support technological and managerial businesses decisions. There will also be the opportunity to test the integration of EMA and Geographical Information System (GIS) software as part of a study supported by the Metropolitan City of Naples under the Project Ossigeno Bene Comune.

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References

Andrews, Evan Stuart, S., Barthel, Leif-Patrick, L.-U.S., Beck Tabea, L.-U.S., Benoît, Catherine, UQAM/CIRAIG, S., Ciroth, Andreas, G.D., Cucuzzella, Carmela, UDM, L., Gensch, Carl-Otto, O.I., Hébert, Julie, F. d'Investissement, Durable, en D., Lesage, Pascal, S., Manhart, Andreas, O.I., Mazeau, Pierre, E. de F., 2009. Guidelines for social life cycle assessment of products. UNEP/SETAC Life Cycle Initiative at UNEP, CIRAIG, FAQDD and the Belgium Federal Public Planning Service Sustainable Development.

Asiedu, Y., Gu, P., 1998. Product life cycle cost analysis: State of the art review. Int. J. Prod. Res. https://doi.org/10.1080/002075498193444

Becht, G., 1974. Systems Theory, The Key to Holism and Reductionism. Bioscience 24, 569–579. https://doi.org/10.2307/1296630

Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T., 2010. The guidelines for social life cycle assessment of products: Just in time! Int. J. Life Cycle Assess. 15, 156–163. https://doi.org/10.1007/s11367-009-0147-8

Bierer, A., Götze, U., Meynerts, L., Sygulla, R., 2015. Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. J. Clean. Prod. 108, 1289–1301. https://doi.org/10.1016/j.jclepro.2014.08.036

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology I . Theoretical concept of a LCA method tailored to crop production 20, 247–264. https://doi.org/10.1016/S1161-0301(03)00024-8

Brown, M.T., 2018. ICEAM - 9 EMERGY and Environmental Accounting.

Brown, M.T., 2015. Emergy and Form: Accounting Principles for Recycle Pathways. J. Environ. Account. Manag. 3, 259–274. https://doi.org/10.5890/jeam.2015.09.005

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour. Conserv. Recycl. 38, 1–22. https://doi.org/10.1016/S0921-3449(02)00093-9

Brown, M.T., Ulgiati, S., 2016a. Assessing the global environmental sources driving the geobiosphere: A revised emergy baseline. Ecol. Modell. 339, 126–132. https://doi.org/10.1016/J.ECOLMODEL.2016.03.017

Brown, M.T., Ulgiati, S., 2016b. Emergy assessment of global renewable sources. Ecol. Modell. 339, 148–156. https://doi.org/10.1016/j.ecolmodel.2016.03.010

Brown, M.T., Ulgiati, S., 2004. Emergy Analysis and Environmental Accounting. Encycl. Energy 2, 329–354. https://doi.org/10.1016/B0-12-176480-X/00242-4

Ciroth, A., Hildenbrand, J., Steen, B., 2011. Life Cycle Costing, in: De Meester, S., Alvarenga, R. (Eds.), Sustainability Assessment of Renewables-Based Products: Methods and Case Studies. John Wiley & Sons. https://doi.org/10.1111/j.1559-3584.1969.tb05481.x

Costa, D., Quinteiro, P., Dias, A.C., 2019. A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues. Sci. Total Environ. 686, 774–787. https://doi.org/10.1016/j.scitotenv.2019.05.435

This project has received funding from the European Union's Horizon 2020 research and innovation proframme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE)

Djatna, T., Prasetyo, D., 2019. Integration of sustainable value stream mapping (Sus. VSM) and life-cycle assessment (LCA) to improve sustainability performance. Int. J. Adv. Sci. Eng. Inf. Technol. 9, 1337–1343. https://doi.org/10.18517/ijaseit.9.4.9302

Ellen MacArthur Foundation, 2012. Towards the Circular Economy Vol. 1: an economic and business rationale for an accelerated transition 1.

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). Brussels, Belgium.

European Commission, 2019. Sustainable Products in a Circular Economy - Towards an EU Product Policy Framework contributing to the Circular Economy.

European Commission, 2015. Closing the loop - An EU action plan for the Circular Economy.

Faulkner, W., Badurdeen, F., 2014. Sustainable Value Stream Mapping (Sus-VSM): Methodology to visualize and assess manufacturing sustainability performance. J. Clean. Prod. 85, 8–18. https://doi.org/10.1016/j.jclepro.2014.05.042

Finkbeiner, M., Schau, E.M., Lehmann, A., Traverso, M., 2010. Towards life cycle sustainability assessment. Sustainability 2, 3309–3322. https://doi.org/10.3390/su2103309

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghisellini, P., Protano, G., Viglia, S., Gaworski, M., Setti, M., Ulgiati, S., 2014. Integrated agricultural and dairy production within a circular economy framework. A comparison of Italian and Polish farming systems. J. Environ. Account. Manag. 2, 367–384. https://doi.org/10.5890/JEAM.2014.12.007

Heijungs, R., Settanni, E., Guinée, J., 2013. Toward a computational structure for life cycle sustainability analysis: Unifying LCA and LCC. Int. J. Life Cycle Assess. 18, 1722–1733. https://doi.org/10.1007/s11367-012-0461-4

Hines, P., Rich, N., 1997. The seven value stream mapping tools. Int. J. Oper. Prod. Manag. 17, 46–64. https://doi.org/10.1108/01443579710157989

Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M., 2014. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ. Impact Assess. Rev. 48, 27–33. https://doi.org/10.1016/j.eiar.2014.05.001

Hunkeler, D., Lichtenvort, K., Rebitzer, G., 2008. Environmental Life Cycle Costing. SETAC Press.

Iraldo, F., Facheris, C., Nucci, B., 2017. Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. J. Clean. Prod. 140, 1353–1364. https://doi.org/10.1016/j.jclepro.2016.10.017

ISO, 2006a. 14040: Environmental management–life cycle assessment—Principles and framework. Int. Organ. Stand.

ISO, 2006b. ISO 14044:2006. Environ. Manag. - Life cycle assessement - Requir. Guidel. ISO 14044, Int. Organ. Stand. https://doi.org/10.1007/s11367-011-0297-3

Kloepffer, W., 2008. Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95). Int. J. Life Cycle Assess. 13, 89–94. https://doi.org/10.1065/lca2008.02.376

This project has received funding from the European Union's Horizon 2020 research and innovation proframme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE)

Knoeppel, C.E., 1915. Installing Efficiency Methods. The Engineering Magazine, New York.

Korpi, E., Ala-Risku, T., 2008. Life cycle costing: A review of published case studies. Manag. Audit. J. 23, 240–261. https://doi.org/10.1108/02686900810857703

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Linder, M., Sarasini, S., van Loon, P., 2017. A Metric for Quantifying Product-Level Circularity. J. Ind. Ecol. 21, 545–558. https://doi.org/10.1111/jiec.12552

Martinez, S., Delgado, M. del M., Martinez Marin, R., Alvarez, S., 2019. Organization Environmental Footprint through Input-Output Analysis: A Case Study in the Construction Sector. J. Ind. Ecol. https://doi.org/10.1111/jiec.12827

Marvuglia, A., Santagata, R., Rugani, B., Benetto, E., 2018. Emergy-based indicators to measure circularity : promises and problems Emergy-based indicators to measure circularity : promises and problems. ENERGY POLICY J. 21, 176–196. https://doi.org/10.24425/124510

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2018.10.002

Norris, G.A., 2001. Integrating life cycle cost analysis and LCA. Int. J. Life Cycle Assess. 6, 118–120. https://doi.org/10.1007/BF02977849

O'Brien, M., Doig, A., Clift, R., 1996. Social and environmental life cycle assessment (SELCA): Approach and methodological development. Int. J. Life Cycle Assess. 1, 231–237. https://doi.org/10.1007/BF02978703

Odum, H.T., 1996. Environmental accounting. Emergy and Environmental Decision Making. John Wiley Sons, INC 370. https://doi.org/10.1017/CBO9781107415324.004

Odum, H.T., 1994. Ecological and general systems : an introduction to systems ecology.

Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Petti, L., Serreli, M., Di Cesare, S., 2018. Systematic literature review in social life cycle assessment. Int. J. Life Cycle Assess. 23, 422–431. https://doi.org/10.1007/s11367-016-1135-4

Proske, M., Winzer, J., Marwede, M., Nissen, N.F., Lang, K.D., 2017. Obsolescence of electronics-the example of smartphones. 2016 Electron. Goes Green 2016+, EGG 2016 1–8. https://doi.org/10.1109/EGG.2016.7829852

Raugei, M., Rugani, B., Benetto, E., Ingwersen, W.W., 2014. Integrating emergy into LCA: Potential added value and lingering obstacles. Ecol. Modell. 271, 4–9. https://doi.org/10.1016/j.ecolmodel.2012.11.025

Ridolfi, R., Pulselli, F.M., Morandi, F., Oliveira, M., Bastianoni, S., 2018. Emergy and Sustainability ☆, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.00590-X

Sala, S., Farioli, F., Zamagni, A., 2013. Life cycle sustainability assessment in the context of sustainability science progress (part 2). Int. J. Life Cycle Assess. 18, 1686–1697. https://doi.org/10.1007/s11367-012-0509-5

This project has received funding from the European Union's Horizon 2020 research and innovation proframme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE)

Santagata, R., Fiorentino, G., Zucaro, A., Ripa, M., 2018. Implementing a Circular Economy Framework in Campania Region (Italy) within an emergy perspective ., in: - (Ed.), Proceedings of the 10th Biennal Emergy Conference. Gainesville (Florida/USA).

Santagata, R., Viglia, S., Fiorentino, G., Liu, G., Ripa, M., 2019. Power generation from slaughterhouse waste materials. An Emergy Accounting assessment. J. Clean. Prod. 223, 536–552. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.148

Santagata, R., Zucaro, A., Fiorentino, G., Lucagnano, E., Ulgiati, S., 2020a. Developing a procedural method for the integration of Life Cycle Assessment and Emergy Analysis. The Amalfi paper case study. Ecol. Indic.

Santagata, R., Zucaro, A., Viglia, S., Ripa, M., Tian, X., Ulgiati, S., 2020b. Assessing the sustainability of urban eco-systems through Emergy-based circular economy indicators. Ecol. Indic. 109, 105859. https://doi.org/10.1016/j.ecolind.2019.105859

STAR-ProBio, 2019. STAR-ProBio Deliverable D6.3, Criteria and indicators developed for conducting S-LCA impact assessment.

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: A code of practice. Int. J. Life Cycle Assess. 16, 389–391. https://doi.org/10.1007/s11367-011-0287-5

Thomas, M., n.d. Life Cycle Assessment and the New Zealand Wine Industry : A tool to support continuous environmental improvement.

Ulgiati, S., Franzese, P.P., Zucaro, A., Fiorentino, G., Santagata, R., Corcelli, F., Rallo, R.F., Casazza, M., 2018. Report. Standardization and integration of assessment methods focused on energy efficiency. Deliverable 3.4. European Futures of Energy Efficiency (EUFORIE). http://www.euforie-h2020.eu.

UNEP, SETAC, 2013. The Methodological Sheets for Sub-categories in Social Life Cycle Assessment (S-LCA).

van Haaster, B., Ciroth, A., Fontes, J., Wood, R., Ramirez, A., 2017. Development of a methodological framework for social life-cycle assessment of novel technologies. Int. J. Life Cycle Assess. 22, 423–440. https://doi.org/10.1007/s11367-016-1162-1

Vinodh, S., Ben Ruben, R., Asokan, P., 2016. Life cycle assessment integrated value stream mapping framework to ensure sustainable manufacturing: A case study. Clean Technol. Environ. Policy 18, 279–295. https://doi.org/10.1007/s10098-015-1016-8

White, G.E., Ostwald, P.F., 1976. Life cycle costing. Manag. Account. 15, 335–44.

Zamagni, A., Feschet, P., De Luca, A.I., Iofrida, N., Buttol, P., 2015. Social Life Cycle Assessment. Sustain. Assess. Renewables-Based Prod. 229–240. https://doi.org/10.1002/9781118933916.ch15

Zucaro, A., Santagata, R., 2019. Case Studies, in: Gonela, F., Liu, G. (Eds.), 3rd International School on Emergy Accounting Proceedings. CLEUP, Venezia (Italia), pp. 89–111.

This project has received funding from the European Union's Horizon 2020 research and innovation proframme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE)

Appendix I

EMergy Accounting Evaluation Procedure

The first step is the elaboration of the conceptual model of the system under study, which is represented by energy flow diagrams using the symbolic language proposed by Odum (1996). According to Brown (2018), the purposes of the diagrams are: to convey system boundaries, the structure and functions of the system under study, and to conduct a critical inventory of processes, storages and flows that are important to the system under consideration.

The diagrams use system language symbols (Odum, 1996, 1994) to put into perspective the system of interest, integrate information, organise data collection, data processing and results (Figure A.1).

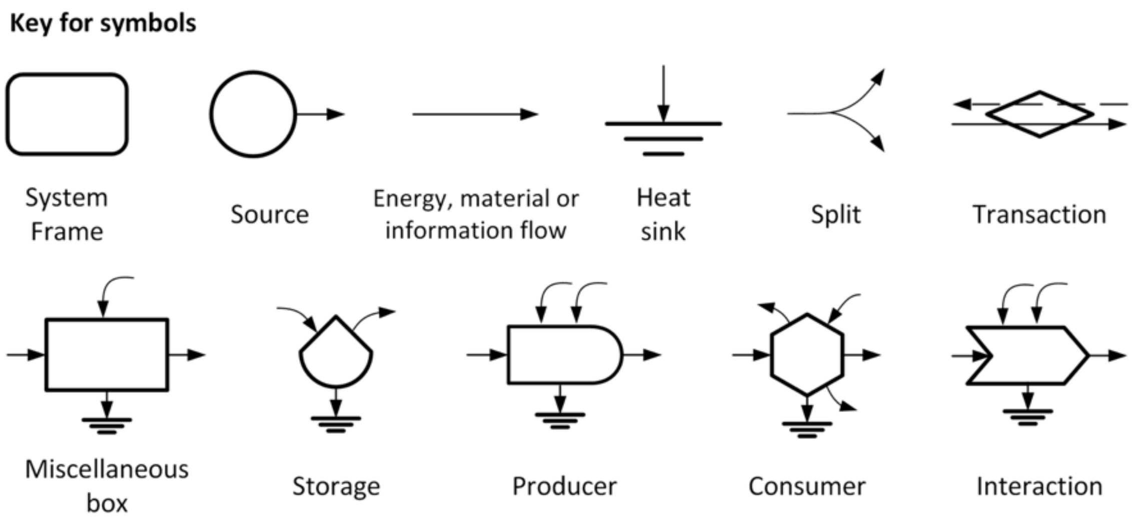

Figure A.1 - Systems Diagram Symbols (adapted from Odum, 1996).

The systems diagram should express how available energies are transformed to generate internal inventories, useful resources coming out of the system, as well as the degraded energy and materials that the system exports. Figures A.2 and A.3 show examples of system diagrams, illustrating the materials and energy flows of the whole biosphere.

Preparation of an EMA Table

As described by Odum (1996), the calculations of eMergy are made with an evaluation table (Table A.1). The first column has a number for the footnote with details of data and calculations sources. The second column has labels of the input items. The third column has the numerical value of the input in its usual units (e.g. joules, grams, dollars, individuals, bits), while column 4 has the unit of the data. Column 5 has the eMergy values, transformities or UEV (Unit eMergy value). Finally, column 6 has the eMergy of each line item, which is

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calculated by multiplying column 3 (Data) and column 5 (eMergy per unit input). The total eMergy (U) of the studied system is given by the sum of all lines of column 6.

Table A.1 - EMergy evaluation table template.

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Note	Item	Data	Unit	Transformity (sej unit-1)	EMergy (sej)
Input Category					
1					
2					
…					

The Input categories are shown in Figure A.2. The eMergy (U) is the total sum of aggregated inflows to a process or system, divided in Renewable (R) and Non-Renewable (N) natural resources and Imported Resources (F, indicating the feedback role of imported resources), categorized as Purchased Resources (M) and Labour and Services (L&S):

$$U = L + F = (R + N) + (M + L\&S) \qquad \textit{Eq. 1}$$

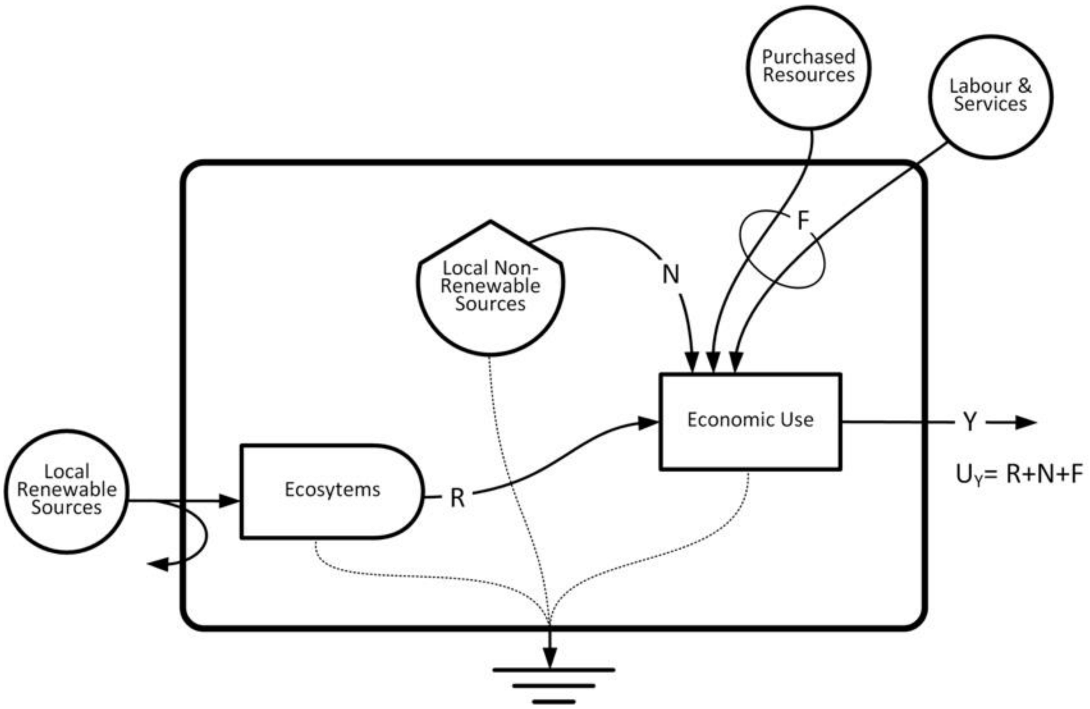

Figure A.2 - Generic System Diagram showing the Emergy input categories, their connections and energy pathways (adapted from Brown, 2018).

The Figure A.3 details driving inputs forces of the R input category, divided in geo-biosphere tripartite (solar radiation, tides and deep heat (geothermal flows) and secondary and tertiary sources (wind, waves, and rain). An important consideration should be made regarding the calculation of Renewable Resources. To avoid input

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double counting, the R final value is the largest number between the sum of tripartite primary sources and the largest value of the secondary and tertiary sources (Brown and Ulgiati, 2016b).

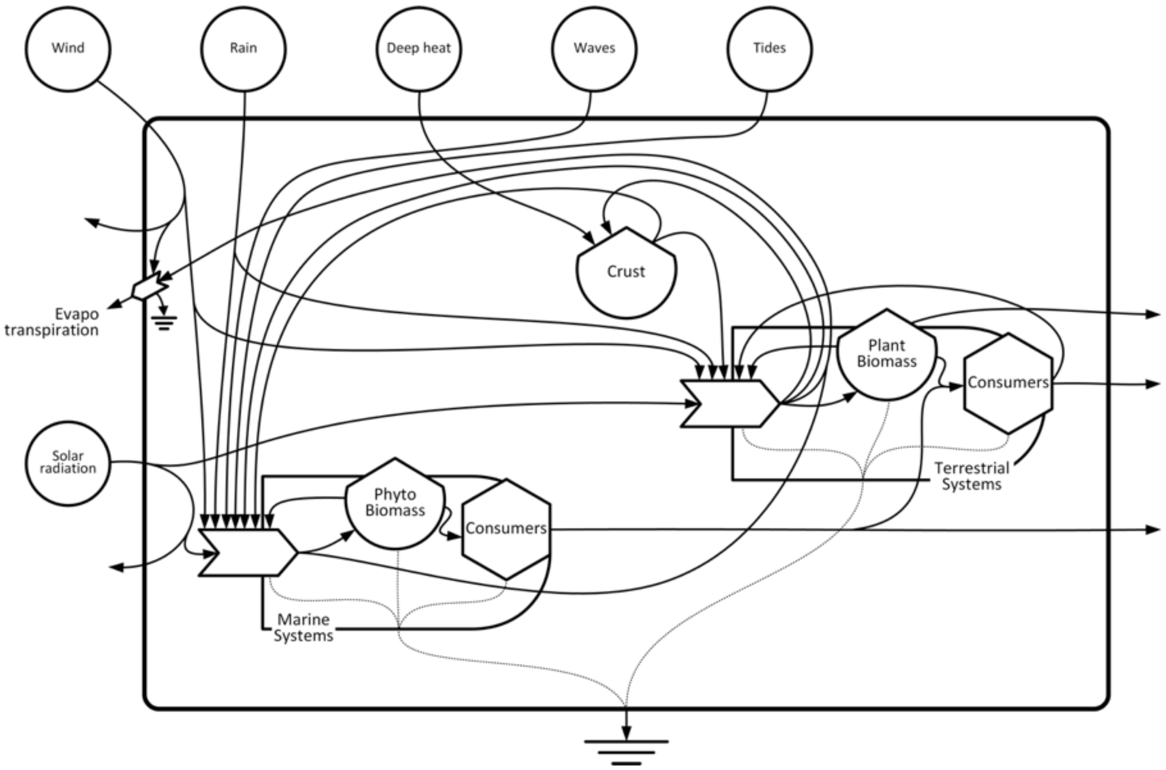

Figure A.3 - System diagram of the driving inputs forces from Renewable category, divided in geo-biosphere tripartite (solar radiation, tides and deep heat (geothermal flows) and secondary and tertiary sources (wind, waves, and rain) (adapted from Brown and Ulgiati, 2016b).

EMA Indicators

EMA indicators are able to evaluate and monitor processes, including circular ones, by following the rules that avoid double counting of feedback flows, keeping track of interactions among system components across scales (Brown, 2015).

According to Zucaro and Santagata (2019), the most used EMA indicators are:

- **EYR** = U/F, shows the system's ability to use local resources by importing outside resources;
- **ELR =** (N+F)/R, measures the stress imposed to an ecosystem by a transformation process;
- **ESI** = EYR/ELR, aims to use more local resources and low environmental pressure;
- %**Ren** = R/U, defines the eMergy fraction from renewable sources;
- **ED** = U/Area, eMergy invested per unit of area;
- **EMERGY** $_{\textbf{Per Capita}}$ = U/person, measures the resources invested to support one average person;
- **EMR** = U/GDP, expresses the eMergy needed to support system economy

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Appendix II Table correlating the output indicators and sustainability dimensions for each method.

Method	Dimension	Indicator	Description
EMergy Accounting (EMA)	**Circularity**	Landfill to Recycle Ratio (LRR)	Ratio of the eMergy required to disposal (landfill) a material over the eMergy required to recycle the material
		Recycle Benefit Ratio (RBR)	EMergy required in providing a material from a raw resource over the eMergy required to recycle
		Recycle Yield Ratio (RYR)	Ratio of the eMergy in a recycled material (EMR) over the eMergy linked to the recycling of the mater
	Economic	EMergy Money Ratio (EMR)	EMergy needed to support system economy
	Environmental	EMergy Sustainability Index (ESI)	Compares the outside/local information to the non-renewable/renewable information
		EMergy Yield Ratio (EYR)	Local-vs-imported resources use
		Empower Density (ED)	Land development and human activities
		Environmental Load Ratio (ELR)	Matches non-renewable and imported eMergy to renewable eMergy. It measures the stress imposed to an ecosystem by a transformation process
		Exergy	Potential energy used to produce a resource
		Renewability (%Ren)	Fraction from renewable sources
		Total EMergy (U)	Environmental production cost
		Unit EMergy Value (UEV)	EMergy intensity
	Social	Population eMergy intensity (EMergy *per capta*)	Resources invested for the support of one average person
Environmental Life Cycle Costing (LCC)	**Economic**	Benefit Cost Ratio	Shows the relationship between the relative costs and benefits of an offering (e.g. Products, projects) expressed either in monetary or qualitative terms.
		Breakeven point	The point at which total cost and total revenue are equal, there is no net loss or gain.
		Internal Return Rate	It is a discount rate that makes the net present value of all cash flows from a particular offering equal to zero. This metric is used to estimate the profitability of potential investments.
		Life cycle costing (or total life cycle costing)	Sum of all costs from different life cycle phases considered in the study
		Net Present Value	Difference between the present value of cash inflows and the present value of cash outflows over a period of time, normally used to assess the profitability of an offering (e.g. Service, project).
		Payback Period	The amount of time it takes to recover the cost of an investment (i.e. Length of time an investment reaches breakeven point)
Life Cycle Assessment (LCA)	**Environmental**	Acidification	Deposition of sulphur dioxides, nitrogen oxides, NH3 ions per unit area/hectare/pH levels
		Climate change (GWP)	Emitted total of carbon dioxides, methane, nitrogen oxide and Chlorofluorocarbons
		Eco-toxicity for aquatic freshwater	Sum of quantities of ions weighted according to their toxicity and their residence time in the environment
		Freshwater eutrophication	Total concentration of pollutants released into surface and ground water sources
		Land transformation	Area of land owned and its characteristics/Habitat changes, impact on protected areas
		Ozone depletion	Total concentration of ozone depleting substances in CFC-11 equivalent emissions
		Photochemical ozone formation	Sum of quantities of ions weighted according to their toxicity and their residence time in the environment
		Resource depletion - mineral, fossil	Total amount of materials (virgin/recycled), non/renewable, non/hazourdous, fuels, water, electricity etc
		Resource depletion - water	
		Terrestrial eutrophication	Total concentration of pollutants released in the ground surface and soil
	Social	Human toxicity, cancer effects	Rates of occupational illness, accident/non-routine discharges, particulate matter, electromagnetic waves

		Human toxicity, non-cancer effects	
		Ionizing radiation	
		Particulate matter / respiratory inorganics	
Sustainable Value Stream Mapping (Sus-VSM)	**Economic**	Cycle Over time (C/O)	Set-up time (per process step)
		Cycle Time (C/T)	Time spend on each process step
		Inventory #	Average number of products per inventory step
		Inventory time	Time product spends in inventory
		Process Cycle Efficiency (PCE) percentage	VA/T divided by the PLT
		Production Lead Time (PLT)	Time a product spends in the entire process, including both process and inventory steps
		TAKT	The maximum time available between production runs of a unit to meet customer demand
		Uptime percentage	Up-time of process steps
		Value Added Time (VA/T)	Production Lead Time minus the time products spend in inventory
		Workers #	Number of workers (per process step), can also be done using Full Time Equivalent (FTE) measures
	Social	Decibel Average (D or Dba)	Noise levels per process step
		Electric systems risk (E)	Electrical systems hazard risk level per process step
		High-Speed Components risk (S)	High-speed components hazard risk level per process step
		Physical Load Index (PLI)	Physical Load Index is indicator measuring how much strain is put on workers per process step & in-between steps
	Environmental & Social	Pressurised systems risk (P)	Pressurised systems hazard risk level per process step
	Economic & Environmental	Hazardous chemicals / materials risk (H)	Chemicals/substances hazard risk level per process step
		Energy consumption per step	Energy use (per process step, inventory and in transport)
		Energy Consumption Process total	Energy use in entire process (excluding transport)
		Energy Consumption Transport total	Energy use in transport and inventory (e.g. Cooling)
		Raw Material Final	Raw material weight of the final product, after the process
		Raw Material Original	Raw material weight of the original product entering the process
		Raw Material Usage - (removed)	Material removals (per process step) in weight (e.g. KG)
Social Life Cycle Assessment (SLCA)	**Social**	Access to Immaterial Resources	Respect, work to protect, provide or improve community services, intellectual property rights, freedom of expression and access to information
		Access to Material Resources	Respect, work to protect, provide or improve materials (water, land, biological resources) and infrastructure (roads, facilities, schools)
		Child Labour	Identify the nature of any child labour under and its existence
		Community Engagement	Community stakeholder inclusion in relevant decision-making processes.
		Cultural Heritage	Local cultural heritage respect and the right to pursue their cultural development acknowledgment
		Delocalization and Migration	Organizations contribution to delocalization, migration or “involuntary resettlement” within communities and the appropriated treatment of populations
		End-of-Life Responsibility	Address the social impacts of product or service end-of-life
		Equal Opportunities/Discrimination	Assess equal opportunity management practices and the presence of discrimination in the opportunities offer to the workers by the organizations and in the working conditions
		Fair Competition	Fair way and in compliance with legislations competitive activities

		Fair Salary	Wages are in compliance with established standards and if the wage provided is meeting legal requirements
		Feedback Mechanism	Effectiveness of management measures to support consumer feedback
		Forced Labour	No use of forced or compulsory labour in the organization
		Freedom of Association and Collective Bargaining	Compliance of the organization with freedom of association and collective bargaining standards
		Health and Safety	Identify the existence and scope of systematic efforts to address consumer health and safety across the organizations involved in the life cycle of a product and/or service
			Rate of incidents and the status of prevention measure and management practices

Social Life Cycle Assessment (SLCA)	**Social**	Hours of Work	Verify if the number of hours really worked is in accordance with the ILO standards and when overtime occurs, compensation in terms of money or free time is planned and provided to workers
		Local Employment	Local employment impact, directly or indirectly
		Privacy	Respect and protect consumer privacy management systems
		Promoting Social Responsibility	Promotion of social responsibility among its suppliers and through its own actions
		Respect of Indigenous Rights	Respect for rights of indigenous peoples, as a group or as individuals
		Respect of Intellectual Property Rights	Safeguard and value the creators and other producers of intellectual goods and services
		Safe and Healthy Living Conditions	General safety conditions of operations and public health impacts
		Secure Living Conditions	Security of local communities' impact
		Social Benefit/ Social Security	Social benefits and social security of workers
		Supplier Relationships	Potential impacts or unintended consequences of its procurement and purchasing decisions on other organizations, and take due care to avoid or minimize any negative impact
		Transparency	Communication on all issues regarding its product and social responsibility in a transparent way