CHAPTER 3

Life cycle assessment as a metric for circular economy

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Abstract

A core component of successful implementation of a circular economy (CE) strategy is the quantification of improvements or changes with respect to environmental impacts, resource usage, waste and/or economic costs. Life cycle assessment (LCA) is a vital tool for the quantification and assessment of effectiveness and impacts associated with CE strategies. Incorporating LCA allows a comprehensive and transparent assessment of products, services or organisations, and can help to identify any potential unintended consequences associated with a change in process or practice. The implementation of LCA can appear complicated for non-practitioners, but there exist clear guidelines on how to conduct life cycle assessments, as described in this chapter. There are several frameworks for the incorporation of LCA into CE strategies, as described here and LCA may play a key role in the development of meaningful indicators for CE with regards to the product level assessment. This chapter includes an assessment of the challenges associated with implementing LCA in CE, which include the difficulty in managing numerous indicators in parallel, and the lack of available data. However, the benefits associated with transparency, consistency, comparability and systems approach highlight its complementarity with a CE strategy.

3.1 Introduction

A core component of successful implementation of a circular economy (CE) strategy is the quantification of improvements or changes to environmental impacts, resource usage, waste and/or economic costs. Life cycle methodologies enable this quantification, to assess and define the environmental performance of circular product designs, as well as large-scale industrial changes such as the implementation of different waste management options[1]. According to, Iacovidou et al.[2] "*LCA is the best known and commonly used tool for assessing the environmental impacts of a product's life from raw material extraction to end of use, disposal and end of life management, making capable and useful comparisons between products, processes and systems*." However, there are several ways to conduct a Life Cycle Assessment (LCA) and incorporate LCA into CE strategies, as well as several challenges relating to data collection, uncertainty and expertise development.

This chapter outlines first where LCA is incorporated into circular economy metrics and frameworks, how LCA can be used to define many of the CE metrics and indicators, followed by the taxonomy of a LCA, how to conduct one and why they are important for CE strategies. The plethora of guidelines associated with different methods or stages of LCA are described and differentiated. Key challenges and barriers associated with incorporating LCA are described before conclusions are given.

3.2 Frameworks implementing circular economy using LCA

Several decision support frameworks for implementing circular economy (CE) strategies, both at the product and organization level, include LCA. For example, LCA plays a key role in the decision support framework developed by Niero et al.[3], in which LCA is combined with the Cradle to Cradle® (C2C) certification program, in the context of packaging. The aim of the 4-step framework is to support the development of continuous loop packaging systems, where LCA is used in the third step to assess the environmental impacts of alternative scenarios of C2C certification. The alternative LCA scenarios encompass different improvement strategies, such as changes in material composition, the use of renewable energy in product manufacturing and supply chains[4], increased recycled content, and recycling rates[5]. The application of the framework combining LCA and C2C certification allows the identification of actions to be prioritized to achieve a continuous material loop for beverage packaging, both from an environmental and an economic point of view, therefore targeting the development of circular product systems.

Another framework, named BECE (Backcasting and Eco-design for the Circular Economy), helps businesses to tackle CE holistically by embedding the concept into corporate decision making and by bringing operational and systems thinking together, thus increasing the likelihood of successful implementation. Key elements are backcasting and eco-design: backcasting is “a strategic business planning tool that aims to achieve a particular desirable future state, by exploring alternative non-predictive pathways toward it by developing different scenarios”[6]; and eco-design is a tool that helps incorporate environmental considerations into product design with the aim of minimizing life cycle environmental impacts[6]. The BECE framework consists of 10 steps, where LCA plays a key role in “product selection and evaluation” (step 5). In this context LCA helps to address potential issues associated with burden shifting, to ensure that circularity is not achieved to the detriment of other impacts, and to identify further opportunities for improvement through eco-design[6].

At the product level, Rönnlund et al.[7] developed an eco-efficiency indicator framework based on LCA, covering ten important issues of product environmental sustainability, including some key aspects for implementing CE, such as material efficiency and reutilization of secondary raw materials. This indicator framework enables an environmental sustainability benchmarking of products and has been conceived within the metallurgical industry.

Niero and Hauschild[8] recommend using the Life Cycle Sustainability Assessment (LCSA) framework intended as a combination of LCA, Environmental Life Cycle Costing (LCC) and Social LCA (S-LCA)[9] to evaluate circular economy strategies, since it is the most comprehensive framework and effective at preventing burden shifting between different life cycle stages and impact categories in the value chain.

As far as the implementation of CE at the organization level is concerned, only a limited number of frameworks are available. The British Standard[10] "*BS 8001:2017 Framework for implementing the principles of the circular economy in organizations*" was developed to provide guidance to organizations in the transition toward more circular and sustainable modes of operation. It is based on an 8-stage flexible framework to assist organizations to develop a road map for continual and transformational improvement. LCA (and S-LCA) are mentioned as quantitative assessment tools as part of the feasibility assessment phase (step 4). Niero and Schmidt Rivera[11] propose to combine the BS 8001:2017 8-step framework with the LCSA framework, thus providing an operative tool to prioritize the selection of the most feasible options to implement the CE vision of an organization.

3.3 Circular economy metrics and indicators using LCA

CE strategies can be applied at the macro (i.e. region, nation, sector), meso (i.e. eco-industrial parks) and micro (i.e. product and organization) levels. Most attempts to define indicators for measuring CE strategy have so far addressed the macro and meso levels, and only a limited number of indicators are available at the product level scale[12, 13]. According to the European Environment Agency[14] these macro and meso level indicators "*give insight into material flows in the economy as a whole, but are unable to capture the mechanisms behind these flows. Life-cycle approaches offer promising possibilities at the product group level* *but remain far from operational*". On the other hand, there are studies showing that LCA play a key role in the development of meaningful indicators for the CE with regard to the product level assessmen[12,15]. A number of reviews on CE metrics have recently been performed and are described below.

According to Bocken et al.[16] CE metrics are categorized in three groups: i) narrowing resource flows (or resource efficiency), aimed at using fewer resources per product; ii) slowing resource loops, i.e. extending and/or intensifying the utilization period of products, thus resulting in a slowdown of the flow of resources; and iii) closing resource loops i.e. aiming at a circular flow of resources, by closing the loop between post-use and production through recycling. LCA has already been used as a metric to assess the environmental sustainability of all three CE categories: e.g. Huysman et al. [17] for narrowing resource flows, Bakker et al. [18] for slowing resource flows and Niero and Olsen[19] for closing resource flows.

Elia et al.[12] analyzed the current literature on CE assessment and proposed a reference framework comprised of 5 metrics categories for the monitoring phase of a CE strategy: reducing input and use of natural resources; reducing emissions; reducing valuable material losses; increasing share of renewable and recyclable resources; and increasing the value durability of products. Of the five CE requirements identified, LCA allows quantification of all except 'increasing the value durability of products'. Whilst LCA is evidently a useful tool for these CE metrics, barriers to implementation include data availability and uncertainty, time intensiveness, and ease of understanding for non-practitioners. Elia et al.[12] also proposed a taxonomy of index-based methodologies for measuring the adoption of CE based on two factors: i) the index-based method typology (either single synthetic indicator or set of multiple indicators) and ii) the parameter(s) to be measured (i.e. material and energy flow, land use and consumption, and other life cycle based criteria).

Saidani et al.[21] performed a systematic literature review considering both academic and grey literature and identified 55 sets of circularity indicators, developed by scholars, consulting companies and governmental agencies. Furthermore, inspired by existing taxonomies of eco-design tools and sustainability indicators, and in line with the CE characteristics, they developed a taxonomy of circularity indicators including 10 categories. These categories include the levels of CE implementation (e.g. micro, meso, macro), the CE loops (maintain, reuse, remanufacture, recycle), the performance (intrinsic, impacts), the perspective of circularity (actual, potential) they are taking into account, or their degree of transversality (generic, sector-specific). Although most of the identified circularity indicators address material and/or resource circularity, some of the studies combine them with LCA results. The combination of circularity indicators with LCA results has revealed potential trade-offs e.g. between the goals of resources circularity and reducing environmental burden[15, 21, 22].

After a critical appraisal of the BS 8001:2017, Pauliuk[24] proposes a CE indicator dashboard for the quantitative assessment of CE for product systems and organizations. This list is based on different methods, i.e. material flow analysis (MFA), material flow cost accounting (MFCA) and LCA, thus including different categories of indicators, which measure both physical circularity, monetary value, and potential environmental impacts. As far as LCA is concerned, it plays a central role in the category “Climate, energy & other”, which includes the reduction of GHGs, energy demand and water, land, and material use as goals. The Global Warming Potential[25] (GWP), Cumulative Energy Demand[26] (CED) or Cumulative Exergy Demand[27] (CexD) and water, land, material footprints, or a combination thereof are suggested as indicators. Table 3.1 summarizes the categories, indicators and the life cycle thinking tool recommended.

LCA can also be used as an input to conduct cost-environmental impact multi-objective optimization, for example to answer the question “which CE strategies have the highest impact reduction potential in the relevant categories?”. The Eco-cost Value Ratio (EVR) by Scheepens et al.[28] can be used to measure the costs of reducing environmental damage over product price. To address social indicators, social life cycle indicators (i.e. employment, work safety, transparency, supplier relations, etc.) by Benoit et al.[29] are suggested. Furthermore, LCA may be combined with MFA to address the following goals:

- Supply chain footprint of regenerative flows;
- Natural resource conservation, i.e. by answering to the question “What and how much primary resource does the circular economy activity replace?”[30]
- Resource footprint, or mineral depletion indicator

Parchomenko et al.[31] used the method of Multiple Correspondence Analysis (MCA) to assess 63 CE metrics and 24 features relevant to CE, such as recycling efficiency, longevity and stock availability. They identified three main clusters of metrics addressing: i) resource-efficiency; ii) materials stocks and flows; and (iii) product-centric perspective.

Based on a material flow perspective Helander et al.[32] (2019) showed that most available indicators do not capture environmental pressures related to the CE activities they address. They found that many indicators focus on a single CE activity or process, which does not necessarily contribute to increased environmental sustainability overall, and thus they suggested that a material- and resource-based footprint approach, accounting for major environmental inputs and outputs, is necessary—while not sufficient—to assess the environmental sustainability of CE activities. Footprints can indeed be used at different scales, depending on the CE activity they aim to assess, e.g. they can be used by companies, cities, and national and supranational bodies for monitoring and evaluation to support resource governance and waste management.

LCA-based metrics included in the resource-efficiency cluster are frequently combined with other metrics, such as the assessment of Industrial Symbioses (IS-LCA), food waste management systems (FW-LCI), the evaluation of business models (LCA-EVR[28]), or for the identification of more sustainable supply chain partners (SSCN[33]). This reveals the flexibility of the LCA approach to be combined with other metrics, which makes it more challenging to identify clearly opposing CE elements for LCA- based metrics. Some elements like system stability and longevity tend to appear less likely reflected using LCA-based metrics. Moreover, the results showed poor integration of resource-efficiency and product-centric perspectives, while the product-centric and system-dynamic perspectives are least frequently assessed[31].

(Add Table 3.1 around here)

3.4 Life Cycle Assessment Methodology

LCA is a standardised methodology that was first created to study the environmental impacts of systems, products and services[34] with a systems approach i.e. the whole life cycle of the system from the extraction of raw materials, manufacturing and processing, distribution and transport, as well as end-use and waste management. Hence, this tool can be used to identify potential improvements across each life cycle stage and to support decision-makings processes considering environmental aspects affecting ecosystems such as air, soil and water, and resources and human health. Additionally, LCA is used to support marketing strategies in the case of developing product declarations and other environmental certifications[35, 36]. The great value associated with LCA methodology lies within its qualities as a systematic, transparent, comprehensive, and holistic approach.

The LCA methodology is part of the ISO management systems standards, specifically ISO 14040/44[30, 31]. The method consists of four steps: the definition of goal and scope; the life cycle inventory (LCI) analysis; the impact assessment; and the interpretation of the results. Figure 3.1 summarises the 4-step framework, while each step is described below.

[Figure 3.1 near here]

Step 1: Definition of Goal and Scope

Given the value of LCA as a comprehensive and transparent tool for environmental performance assessment, the clear definition of the goal and scope of the study is vital. Defining the goal must illustrate the purpose of the study, who will receive the benefit of it and the decision-context of the study (i.e. support decision of government policy). The scope relates to the goal of the study, study boundary, functional unit, data requirements and assumptions, impact assessment method, allocation methods, limitations of the study and critical review[35, 36]. Critical review provides general quality assurance, support transparency, and depending of the intention of the study it could be a compulsory step for certification[37]. The goal and scope of the study may change during the development of the study, due to data limitations or in light of preliminary findings or systematic iterations, which is one of the key characteristics of LCA.

The functional unit (FU) defines the unit of analysis and must be quantifiable (measured) and clear: it is the reference flow that the LCA will be performed on. This also helps with comparisons with other studies as well as validation. The FU usually refers to units of mass, volume, area, energy but could relate to a specific condition and purpose.

Once the purpose and audience of the study is defined, and particularly the decision-context is clarified, the LCI method or modelling framework must be identified. There are two LCI methods, namely attributional (A-LCI) and consequential (C-LCI). Attributional is the traditional style of assessment and as defined by Curran et al.[17], “A-LCA considers the flows in the environment within a chosen temporal window”, i.e. it considers the potential environmental impact associated with the specific inputs and output flows used in the systems and its life cycle in a specific time frame. Curran et al.[38] state that the C-LCI “considers how the flows may change in response to decisions”, hence how the potential environmental impacts directly and indirectly associated to the inputs and outputs flows of a system and its life cycle would be affected by changes or stimulus in the system or its life cycle. A-LCI is typically used for understanding the impacts associated with a product and its life cycle while C-LCI is usually use to assess the implications of broader changes in system pathways such as with changes in policy. Hence, C-LCI is usually used for decision- and policy-making purposes[39].

The system boundary also depends on the goal and scope of the study and must be clearly defined. The inclusion and exclusion of stages and systems should be clarified, and inputs/outputs included for each process involved. Additionally, cut-off criteria e.g. mass, energy and environmental significance, must be defined, as well as data quality and allocation issues (see step 2 for details). As defined by ILCD[37]: "In principle all quantitatively relevant activities that can be attributed to a system (or a result of the consequences, in the case of consequential modelling) should be included in the system boundaries unless they are quantitatively irrelevant, applying the cut-off criteria. The need for inclusion and the possibility of exclusion of activities can only be decided for the given case in view of the required completeness and precision of the results".
Assumptions relating to data manipulation and aggregation must be described and documented in a consistent manner across the study, to ensure transparency, accuracy, completeness and precision as well as to allow study repetition by other practitioners[35, 36, 37].

Finally, the selection of the impact assessment method and indicators should be selected accordingly with the goal of the study. The most popular impact assessment methods are ReCiPe[40], CML 2002[41], ILCD[42], Eco-indicator 99[43], IMPACT 2002+[44]. Some impact assessment methodologies are developed for specific categories of indicators, such as USEtox[45, 46] that focuses on toxicity related aspects. A comprehensive analysis and comparison of most of the current impact assessment methods is given by EC-JRC[47] for information, and further assessment of the effects of using different assessment methods is given in Renou et al.[48].

Step 2: Life Cycle Inventory Analysis

The definition of the goal and scope provides a structure to develop the Life Cycle Inventory (LCI). LCI first involves the collection, calculation and validation of the data; at this point, the redefinition of the system boundary could be assessed if difficulties are encountered while building the LCI. Decisions should be made after performing sensitivity analysis and considering issues such as the cut-off criteria defined in the scope.

The quality of data input governs the representativeness of the LCA results and may involve an array of different sources. Up-to-date primary data sources (e.g. from recent industrial or governmental sources) should be prioritised particularly for direct emissions sources or those that are expected to dominate results. However this data may not be available, in which case historical or secondary source data is used instead. Secondary data includes well-known databases (i.e. Ecoinvent[49], GaBi Database[50]; Open LCA Database[51]; Life Cycle Data Network[52]), government reports, sector or industry best available technology (BAT) reports, peer reviewed academic, government and industry publications. The data collection process may be iterative: the potential importance of certain data sources may not be known until output results are analysed; at this point an assessment of data quality and importance on the result will drive the collection of more up-to-date/ better quality information.

In terms of representativeness and quality of data, the geographical and time context are key aspects and must be considered when comparing and validating results. In the case of primary data, confidentiality may restrict use and publication. If so, both confidentiality and transparency must be addressed when building the inventory and reporting, which may be via:

a. the inclusion of a separate complementary report, not publicly available, containing the confidential information for reviewers (who sign confidentiality agreements) to assess the analysis and ensure quality, robustness and reproducibility of the study; or

   b. the aggregation and synthesis of confidential data to reduce confidential characteristics whilst enabling reproducibility.

The final step of the LCI is the incorporation of the LCI modelling framework and allocation or system expansion /substitution approaches, previously defined in step 1. Allocation refers to[35, 36] "partitioning the input or output flows of a process or a product system, between the product system under study and one or more other product systems". Allocation is a vital consideration for multi-output processes, where the embodied emissions must be fairly accounted for. A clear differentiation between products and waste is also an important consideration. The ISO 14044[36] standard describes three steps to deal with allocation:

1. If possible, allocation should be avoided; some suggestions to achieve this are:
   a. Divide the unit process and allocate it in sub-processes;
   b. Expand the product system to include the functions related to the co-product.

2. If allocation cannot be avoided, the inputs and outputs of the system should be distributed within its products or functions considering a faithful representation of the physical relationships between them.

3. If physical relationships cannot be defined or do not fully represent the system, the inputs and outputs of it should be assigned within its products or functions considering an accurate representation of other relationships. For instance, a well-considered characteristic is the economic values of co-products [31, 48]; recently new considerations combining such as biophysical characteristics have been considered[53].

Step 3: Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) starts with the definition of the impact assessment methods and indicators categories from the goal and scope. LCIA is formed by mandatory and optional elements. The mandatory elements comprise the selection of the indicators, impact assessment method and the characterisation models. The selection criteria of these elements should be justified and documented, aligning with the goal and scope of the study. The optional elements include normalization, grouping, weighting and data quality analysis[36], where the assumptions and information required to perform these steps must be documented and clearly explained.

There are two impact assessment-modelling approaches – midpoints and endpoints. The midpoint approach refers to[54] "a point in the cause-effect chain (environmental mechanism) of a particular impact category, prior to the endpoint, at which characterization factors can be calculated to reflect the relative importance of an emission or extraction in a Life Cycle Inventory (LCI)". For example, a mid-point climate impact is the global warming potential, defined in terms of radioactive forcing and atmospheric half-lives of emissions, rather than an eventual damage caused by the emission. The endpoint approach considers the potential damage to ecosystems, human health and resources that an emission would have, hence, the endpoint converts (and aggregates) midpoint categories into damage related impact categories[55].

The endpoint approach results in higher uncertainties due to the broader damage assessment and additional required assumptions and data[56], but offers a potentially more tangible and policy-focused metric. The endpoint approach requires the aggregation of impacts into single units corresponding to ecosystems, human health and resources, making it much simpler to understand the trade-off between impacts, compared to midpoints. The midpoint approach has lower uncertainty but is not always easy to understand for non-practitioners and is difficult to communicate effectively.

Step 4: Life Cycle Interpretation

The interpretation of results should stem from the goal and scope of the study. The interpretation first recognises and discusses the relevant issues found in the results. Key aspects to include in the interpretation of results involve an assessment of the key contributing life cycle stages, and of the consistency and comprehensiveness of the study. Sensitivities relating to underlying assumptions, methodological aspects relating to assessment methods and indicators, as well as system boundaries are typically considered in parallel to the results. The development of conclusions and recommendation, and the discussion of the limitations of the study is the final aspect of interpretation[35, 36].

3.5 Life Cycle Assessment Standards and Guidelines

The ISO Standard 14040/44 framework has served as a base for the development of environmental assessment guidelines, focussing on the analysis of products and organisations, countries and sector specific. Due to the worldwide concerns about climate change, most of the guidelines focus on the assessment of greenhouse gas emissions (GHG), also known as carbon footprinting. However, growing interest in resource management due to increased pressures e.g. on water use, has also led to the development of guidelines for water footprinting. Figure 3.2 summarises some of the most common and recent guidelines that show their connection with the LCA framework. The following section briefly describes them.

[Figure 3.2 near here]

Carbon footprint refers to the assessment of the GHG emissions associated to a product, system or organization, accounting for its whole life cycle. Most guidelines focus on products, but frameworks at organization levels have been also developed[57]. Although the ISO 14040/44 is the main basis for almost all the carbon footprint guidelines, the ISO 14060 series[58] are the main international standard series that provide a common, comprehensive, transparent and consistent framework to help quantify, monitor, report and verify GHG accounting. Additionally, they aim to help develop GHG management strategies, plans, and mitigation actions. These guidelines also enable performance and progress assessments related to GHG mitigation actions. Depending on the scope, the guidelines are divided on product level (ISO 14067) and organizational level (ISO 14069). Furthermore, country-specific and sector-specific guidelines have been also developed. The following section describes some of the most widely used guidelines.

3.5.1 Carbon Footprint of Products

In the last decade, several guidelines, frameworks and standards have been developed to help accounting and reporting GHG emissions, particularly at the product level. Numerous studies have assessed the commonalities and differences across these plethora of guidelines[59-61]. At product level, the ISO 14067 2013/2018 is the main current guideline that defines the requirements, principles and framework to carry out and communicate the carbon footprint of a product (CFP). This guideline follows the ISO 14040/44 and also complies with the 14020 series related to environmental product declaration (e.g. ISO 14020, ISO 14024 and ISO 14025).

Prior to the release of the ISO 14067, other guidelines were developed by organizations such as World Resources Institute (WRI) and the World Business Council on Sustainable Development (WBCSD), who produced the GHG Protocol Product Standard: Product Life Cycle Accounting and Reporting Standard[62] in 2011. This protocol complements two other previously published guidelines produced by WRI/WBCSD, namely the GHG Protocol Scope 3 and the GHG Protocol Corporate Standard, which together deliver a comprehensive and systematic framework to assess and manage value chain GHG for businesses and organisations from all economic sectors. These guidelines not only provide a carbon footprint framework but also examples and case studies, guidance for developing the GHG inventories and also recommendations to set emission targets.

The European Union also released guidelines to contribute to the environmental assessment of products through the *Product Environmental Footprint (PEF), which "is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle*"[63]. The Product Environmental Footprint Category Rules (PEFCR) in the context of the PEF pilot initiative aims to ensure that LCA is carried out focusing on significant contributors (foreground and background processes) in life cycle stages, and relevant impact categories. This set of guidelines provides a detailed framework that helps to harmonise the process of developing a product carbon footprint, with the further aim of developing a product declaration.

3.5.2 Environmental Labelling

The ISO 14020 series provide guidelines for environmental labelling and communication. Each of these guidelines provides specific frameworks to help businesses and organisations to communicate the environmental characteristics of their products and services. For instance, ISO 14024 (Type I label) provides guidelines for developing the voluntary declaration of environmental labelling, guiding the selection of product category, functions and environmental criteria to demonstrate the compliance and get certification. The ISO 14021 (Type II label) specifies how to communicate, written or spoken, the environmental characteristics of products; the guidelines are not restricted to any specific environmental characteristics. Finally, the ISO 14025 (Type III label), which follows the LCA framework (ISO 14040/44), delivers a detailed methodology to assess and report the environmental impacts of products from similar groups of characteristics. This standard introduces the concepts of Product Category Rules (PCR) and Environmental Product Declaration (EPD). PCR is a set of guidelines and requirements for each specific product group that aid the development of EPD in a transparent manner and enable future comparison within products[64].

EPD is a voluntary environmental impact declaration that allows the documentation of the environmental impacts of a product. These declarations are independently assessed and they aim to aid the transparent and comparable communication of the life cycle environmental impacts of products[65].

3.5.3 Country Specific Guidance

Most of the country specific carbon footprinting guidelines were either developed before the ISO 14060 series development, or they have adapted the ISO standard to national requirements. Most of the guidelines also comply with the labelling standard 14020 series. For instance, in the UK[66] the "PAS 2050: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services" was first created in 2008 to help industries and other organisations to assess the GHG emissions of their products and services, offering a systematic, operational and comprehensive framework to implement the IPCC 2007 guidance. Although PAS 2050 was created in the UK, it has been recognised and used worldwide[66, 67]. In 2012, Japan also released its own carbon footprint guidelines called JEMAI CFP Program[68], which is also based on ISO 14040/44. This initiative which started in 2008, led by Japanese Ministry of Economy, Trade and Industry, aims to help applying the LCA standard focussing on communication and labelling aspects. The JEMAI CFP Program has a complete Japanese database to assess the Carbon footprint of products, which complement their own product certification framework, called Ecoleaf[69], which also complies with the ISO 14025. Similar efforts were seen in South Korea, where the Korean Environmental Industry and Technology Institute (KEITI) presented their own carbon-labeling scheme in 2009. The interest in carbon footprinting and labeling led to the creation of the Asia Carbon Footprint Network (ACFN), which aims to develop a common framework for carbon footprinting and labelling across Asia. Furthermore, in 2015, The Chinese Manufacturers' Association of

Hong Kong (CMA) developed a carbon footprint and labeling scheme aiming at businesses in Hong Kong[67]. In Europe, France has also developed its own carbon footprint and labeling guidelines, having product-specific communication guidelines as an extra feature[70].

3.5.4 Sector Specific Guidance

As with country specific guidelines, sector- or subject-specific frameworks were born from the current ISO 14040/44 standard and product carbon footprint frameworks. For instance, with help from Carbon Trust, the UK Dairy Industry developed in 2010[71], its own "Guidelines for the Carbon Footprinting of Dairy Products in the UK". The dairy sector has adapted the PAS2050 framework to the unique issues associated with the dairy industry. For the construction sector, the European Commission Intelligent Energy for Europe Programme and nine European organisations developed the framework - ENSLIC Building Project[72] – to promote the "use of LCA in the European building and property industry". Although a specific framework has not been agreed, the energy sector is one the most widely studied, with several guidelines and policy mechanisms develop, overviews of the research carried out in the field[73, 74], and methodologies applied to specific energy generation such as photovoltaic[75]. The EU Renewable Energy Directive (RED 2008/28/EC, and now RED II 2018/2001/EU)[76] stipulates national renewable energy targets for each member state combined to reach 20% by 2020 and 32% by 2030. Each member state estimates their contribution to renewable energy and to GHG emissions reduction as per the directive via emission factors. The use of liquid biofuels accounts for estimates of the impact of indirect land use change (ILUC) to encourage the use of more benign biofuel production.

The UK Renewables Obligation[77] is a mechanism to increase large-scale renewable electricity producers in the UK. An obligation is placed on electricity producers to obtain a specified quantity of Renewables Obligation Certificates (ROCs)[77], which are given to renewable electricity produces per unit of electricity produced. Each type of renewable electricity is given a certain quantity of certificates per MWh of electricity produced based on their life cycle emissions and broader sustainability characteristics.

For transport, the UK's renewable fuel transport obligation (RFTO)[78] mandates a proportion of transport fuel must be derived from renewable sources and stipulates a methodology for the reporting of each fuel's 'renewability' factor. These factors are derived within the guidance for different biogenic and non-bio renewable fuels to account for differences in their life cycle GHG impact.

The application of the LCA standards in the field of waste management has been also widely studied[79], although there lack of consensus is still present with several guidelines and methodologies[80-83].

3.5.5 Organisation Level

Similar to product carbon footprint guidelines, the assessment of GHG emissions at an organizational level has also seen the development of several guidelines and protocol[61]. For instance, the Organizational Environmental Footprint (OEF), developed by the European Commission, is defined as[84] "a multi-criteria measure of the environmental performance of a product-providing organization from a life cycle perspective."

The ISO/TS 14072, published in 2014 by the International Organization for Standardization, ISO/TS 14072 "Environmental management — Life cycle assessment – Requirements and guidelines for organizational life cycle assessment" is defined as a "compilation and evaluation of the inputs, outputs, and potential environmental impacts of the activities associated with the organization as a whole or portion thereof adopting a life cycle perspective". It is a global initiative, which can be utilized by any organization with interest in applying LCA, and extends the application of ISO 14040-44 to all the activities of an organization.

In 2015, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) partnership Life Cycle Initiative (UNEP/SETAC Life Cycle Initiative) published a "Guidance on Organizational Life Cycle Assessment (O-LCA)", hereafter UNEP Guidance[85]. This Guidance attempts to align with ISO/TS 14072, and therefore adopts the same definition of O-LCA as ISO/TS 14072, but utilizes the term O-LCA. It is also a global initiative, and is intended to be used by organizations of all sizes. It complements the ISO/TS 14072 standard, but aims to be a more detailed accompanying document and thus includes different case studies that involve the use of environmental multi-impact assessments with life cycle approaches.

The ISO 14064 standard also provides guidelines to help assess GHG emissions, providing a tool to help quantify, monitor, report and validate emissions for businesses, governments, regions and other organizations. This framework guides issues related to the quantification of GHG emission and mitigation opportunities, to help with the development, implementation and monitoring of action and activities related to GHG management. Hence, this standard also provides guidelines related to inventory development and quality management, auditing and verification.

3.5.6 Water Footprint

Water footprint refers to the total water use and changes of its quality across the life cycle of a system, as well as the potential impacts associated with this resource. Water footprinting follows the LCA standard (ISO 14044) and regulated by the ISO Standard 14046[86] "Environmental management - Water footprint - Principles, requirements and guidelines (ISO 14046:2014)". Although water footprinting can be developed as a stand-alone assessment (related to water only), it is a complement to an LCA study as it assesses in detail, the impacts associated with water use. Additionally, water footprint incorporates important aspects that LCAs often lack i.e. regional or local characteristic and temporal dimensions.

3.5.7 Environmental Life Cycle Costing

Thus far, there is no official standard guideline for the economic LCA of products. However, the environmental life cycle costing (LCC) methodology, developed by SETAC[87] has been commonly used. To align with the LCA methodology, a code of practice has been developed that builds on the ISO 14040/44. Hence, LCC requires the development of the four-step framework and uses a life cycle thinking approach, considering all the stages of system (e.g. production of raw materials, manufacturing, etc.)

LCC accounts for all costs associated with the life cycle of a product[87], considering all life cycle stages[88] from the production of materials or components, processing or manufacturing, the use and maintenance, and end-of-life management. Additionally, research and development can be also considered[87].

Hence, LCC accounts for all costs, which relates all the mass and energy flow from LCA with their respective monetary flows, associated to the whole the life cycle of a product[89, 90]; for example, LCC of a ready-made meal[91] is described as:

$$LCC = C_{RM} + C_M + C_D + C_T + C_U + C_{E\text{-}o\text{-}L}$$

where:

LCC	Total life cycle cost of the ready-made food product
C_{RM}	Cost of raw materials (cultivation and processing of ingredients)
C_M	Cost of manufacturing (ready-made food product)
C_D	Cost of distribution (retailer and wholesalers)
C_T	Cost of transport
C_U	Cost of use phase

$C_{E\text{-}o\text{-}L}$ Cost of disposal (unless recycling when the cost is subtracted)

Other economic indicators have been also used, depending on the system under study. For instance, value added, which represents the profit margin (sales minus the costs of raw materials and services, has been commonly use in the assessment of food goods[91, 92], housing and construction[93].

LCA and LCC can be used in combination to identify the contribution from the main actors of the value chain, i.e. consumers, producers and waste management operators in the case of a comparative analysis of aluminium cans[8]. When the economic aspect was considered in the comparative LCA-LCC analysis of aluminum cans production, use, collection and recycling in two different cities (Bologna and Copenhagen), a trade-off emerged since the best option from an environmental point of view (closed loop recycling) is also leading to higher costs. Another example of combined application of LCA and LCC is in the case of aluminum cans [94].

3.5.8 Social Life Cycle Assessment

The incorporation of the social aspects of sustainability under a life cycle perspective has been a long-term challenge. Some early efforts to develop social LCA (S-LCA) started with the development of social indicators. Some examples are the ones developed by Azapagic and Perda[95] and the IChemE Sustainability Metrics focusing on industries. For example, social aspects include those related to workplace (e.g. Promotion rate, Lost time accident frequency), society (e.g. Indirect community benefit per unit value added) and others (e.g. Discrimination). Metrics were also developed by the AIChE via the Sustainability Index[96], although not under a life cycle perspective.

Currently, the methodology most widely used is the latest guideline released by UNEP/SETAC[97, 98], which develops a S-LCA that follows the LCA methodology approach. This methodology divides the stakeholders in five groups, namely workers, consumers, local community, society and value chain actors. Each group or subsector has a set of aspects that are critical to consider, which are accounted for by quantitative, semi quantitative or qualitative indicators. For instance, for the subcategory workers, one of the aspects is “hours of work” and one of the indicators is “Number of hours effectively worked by employees (at each level of employment)”.

3.5.9 Integration of Environmental, Economic and Social: Sustainability Assessments

Holistic Life Cycle Sustainability Assessments (LCSA) integrate the environmental, economic and social dimensions of sustainability. The framework developed by UNEP/SETAC[98] combines the life cycle assessment (LCA) methodology for the environmental assessment, the economic assessment through the life cycle costing (LCC) assessment methodology and the social life cycle assessment (S-LCA) for the respective social considerations. Within the guidelines, UNEP/SETAC[99] stated that “although normalization, aggregation and weighting are optional steps according to ISO 14040, any aggregation and weighting of results of the three techniques used are not recommended because of the early stage of LCSA research and implementation and because the individual aims of each of the techniques applied are not directly comparable to the other”.

However, the integration of multiple metrics and perspectives presents an important challenge – how to consider the trade-offs across different impacts or indicators and the three dimensions of sustainability. This is exacerbated by the difficulties in integrating a large number of indicators for supporting decision-making processes. In the case of LCA, the framework does consider weighting and normalisation as a mechanism to integrate environmental indicators, however this necessitates a highly subjective decision to quantify the relative importance of the different impacts (e.g. weighing global warming potential against depletion of resources)[100].

Although there are several methodologies and approaches to integrate indicators and sustainability dimensions, there is no consensus. For instance, to address the weighting issue in the three dimensions of sustainability, Hofstetter et al.[101] developed the “Life Cycle Sustainability Triangle”, which is based on the graphic representation of chemical mixtures that allow weighting three parameters. There is also the “Life Cycle Sustainability Dashboard” (LCSD) developed by Traverso et al. [102] and adapted from the “Dashboard of Sustainability” methodology[103, 104]. This methodology and its correspondent software allow the integration of indicators and groups them into categories defined by the user. The indicators are then ranked and the performance is evaluated. LCSD has been used by UNEP/SETAC, owing to its transparency and reader-friendly characteristics[105], but this “does not mean that other emerging methods are neither appropriate nor transparent nor user-friendly”.

From an engineering perspective, multi objective optimisation (MO) has been mentioned as a tool that has been mainly used to integrate environmental and economic indicators[106]. However, multi-criteria decision analysis (MCDA) is the method most broadly used, as it allows the integration of indicators and sustainability dimensions including stakeholders’ perspectives, by providing a single score index[106, 107].

3.6 Benefits and Challenges of Using LCA in CE

Inevitably, there are various challenges and barriers to incorporating LCA into CE strategies. Indeed, in their analysis of corporate sustainability reports in the Fast Moving Consumer Goods (FMCG), Stewart and Niero[108] outlined a lack of references to sustainability performance indicators or assessment methodologies with regard to CE activities. Regarding packaging, food and beverage, household goods & textiles and personal care & household products, only a limited number of companies present a dedicated set of key performance indicators for their CE approach. Such indicators are based on metrics addressing either material efficiency, LCA results or use of the C2C certification program[108]. One of the outcomes of the 63rd discussion forum on life cycle assessment "How can LCA support the circular economy?", held in Zurich in 2016[1], was that "*LCA and other assessment tools should be used to evaluate options for CE solutions to ensure a positive balance of efforts and benefits in both new product designs and increased recycling."*

But there are several drawbacks and challenges associated with the implementation of LCA. Some such drawbacks are listed in Table 3.2 alongside benefits[109-111]. Particular challenges include the representativeness of the study, given the difficulty in obtaining relevant data of sufficient resolution and scope. Thus, many simplifications may be required to complete the study, including 'steady-state' assumptions (e.g. for attributional LCA) and the application of linear relationships for indicators.

How to handle the trade-off issue is key for the success of CE. Trade-offs exist first in terms of material circularity and environmental impact, as highlighted by Geissdoerfer et al.[112] in their analysis of the linkage between sustainability and the CE concept. Furthermore trade-offs exist with regard to different sustainability aspects (environmental, economic and social), as highlighted by Figge et al. [113] and Niero and Kalbar[15], who encourage further research on the combination between circularity measures and life cycle sustainability.

In order to advance the assessment of CE strategies at the product level, Niero and Kalbar[15] propose to couple material circularity and LCA indicators by means of the Multi Criteria Decision Analysis (MCDA) and recommend the use of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (or similar methods) to make sense of the complementary CE indicators, namely material circularity and LCA indicators.

3.7 Summary

In summary, LCA is a vital tool for the quantification and assessment of effectiveness and impacts associated with CE strategies. Incorporating LCA allows a comprehensive and transparent assessment of the product, service or organisation, and can help to identify any potential unintended consequences associated with a change in process. The implementation of LCA can appear complicated for non-practitioners, but there exist clear guidelines on how to conduct LCAs, as described in this chapter. There are several frameworks for the incorporation of LCA into CE strategies, as described here and LCA may play a key role in the development of meaningful indicators for CE with regard to the product level assessment. Furthermore, LCA allows the environmental assessment of CE strategies in relation to design and product life cycle, which provide clear and quantifiable evidence to support decision-making. The environmental indicators can be also complemented with social and economic ones, as the LCA framework also allows the development of economic and social assessment under a life cycle perspective, which complement the development of indicators associated to these aspects.

Finally, the holistic and system approach characteristics embedded in the LCA, LCC and S-LCA framework enable understanding of the impacts and effects of each CE strategy across the whole life cycle, which help avoiding shifting impacts across stages and impacts categories. This chapter includes an assessment of the challenges associated with implementing LCA in CE, which include the difficulty in managing numerous indicators in parallel, and the lack of available data. However, the benefits associated with transparency, consistency, comparability and systems approach highlight its complementarity with a CE strategy.

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Table Captions

Table 3.1 CE Indicators aided by life cycle thinking methodologies – Life cycle assessment (LCA), Life cycle costing (LCC) and Social life cycle assessment (S-LCA) (Adapted from Pauliuk[24])

Table 3.2 The benefits and challenges associated with implementing LCA in CE. Source[109-111]

Figure Captions

Figure 3.1 Life Cycle Assessment Framework[35,36]

Figure 3.2 Environmental assessment guidelines based on LCA ISO Standard

Table 3.1 CE Indicators aided by life cycle thinking methodologies – Life cycle assessment (LCA), Life cycle costing (LCC) and Social life cycle assessment (S-LCA) (Adapted from Pauliuk[24])

Group	Category	CE Indicator	Life cycle thinking methodologies [a]
Circular Economy (BS 8001:2017)	*Regenerate*	Footprint of regenerative flows	LCA
Life cycle	*Maintain financial value*	Ratio between recirculated and total economic product value	LCC
Resource Efficiency	*Natural resource conservation*	Amount and type of primary resource that is replaced by the CE activity/strategy	LCA
		Resource footprint or mineral depletion indicator	LCA
Climate, Energy	*Reduce greenhouse gases*	Quantification of greenhouse gas emissions and improvement opportunities offered by CE activity/strategy	LCA

Group	Category	CE Indicator	Life cycle thinking methodologies [a]
and others	*Reduce energy demand*	Cumulative energy demand (CED), cumulative exergy demand	LCA
	Reduce water, land, and material use	Water, land, material footprints	LCA
	Reduce exposure to critical materials	Quantification of vulnerability to supply restriction and supply risk and the environmental impacts associated to it.	LCA
	Address social indicators	Social life cycle indicators	S-LCA
	Reduce cross-impacts	Assessment of CE strategies that provide the highest environmental impact improvement in the relevant categories	LCA
		Ratio of economic costs of reducing environmental damage over product price	LCA, LCC

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[a] Other tools such as material flow analysis (MFA) and material flow cost accounting (MFCA) might be used encompass the life cycle thinking tools.

Table 3.2 The benefits and challenges associated with implementing LCA in CE. Source [109-111]

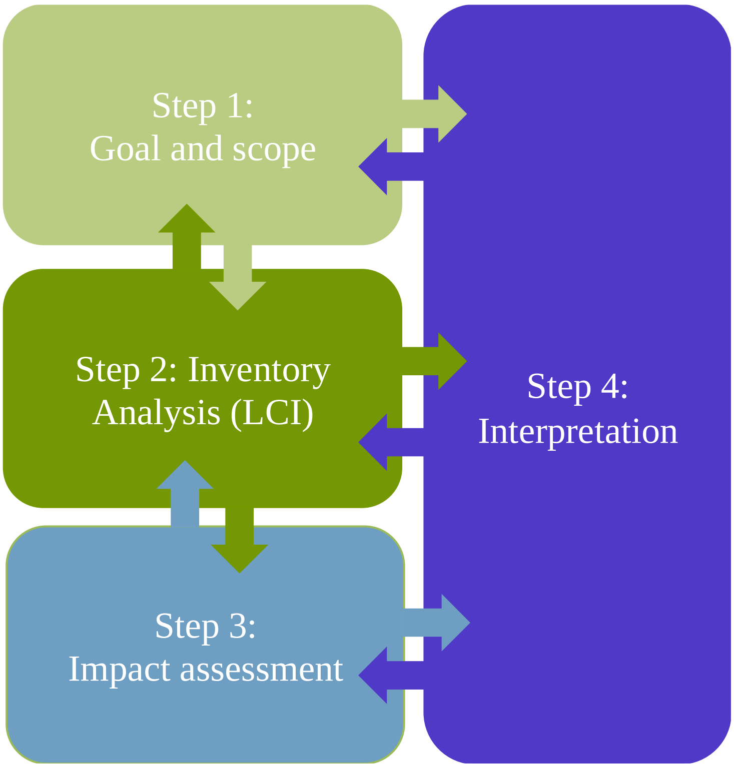
Benefits	Challenges
- Allows the understanding of the environmental impacts of a product or service including it whole life cycle.	- Usually performed in a steady-state basis, so difficult to understand the impacts of changes in the future (e.g. new technologies, etc.).
- Provides a quantitative assessment that supports decision-making processes.	- Does not provide the understanding of local impacts.
- A scientific-based method that uses a holistic approach (life cycle)	- Due to the complexity of representing the whole life cycle of the system, several simplifications and assumptions are made,

- Allows a consistent assessment of the environmental impacts generated in each stage, process and activity included in the life cycle of the system studied	which will affect the results of the assessment. However, the ISO standard provides a framework to help with the transparency of these assumptions and to avoid arbitrary decisions.
- Provides opportunities for indirect supply chain management	- LCA is mainly based on physical characteristic and less so in economic ones, hence it is not easy to include effects such as market changes, new technology development, among others.
- Avoids ‘problem shifting’, which means that the possible solutions include the understanding of the effects across the supply chain; hence it will help to avoid improving impacts in one stage by causing unexpected problems in other stage.	- LCA assesses the potential impacts of a system based on a specific functional unit,

- Allows the comparison among products, processes and designs. - Supports decision-making for businesses (e.g. environmental performance of products/services) and governments (e.g. waste management facilities, regulations and policies).	which could be defined arbitrary, and with lack of time and space definition. - LCA predominantly uses a linear approach. - Data availability is a critical issue, in terms of quality and representativeness.

THE FOLLOWING IMAGES SHOULD BE SUPPLIED AS SEPARATE FILES in one of the following formats: TIFF/PDF/EPS/DOC/XLS/PPT/JPEG/CDX

Figure 3.1 Life Cycle Assessment Framework



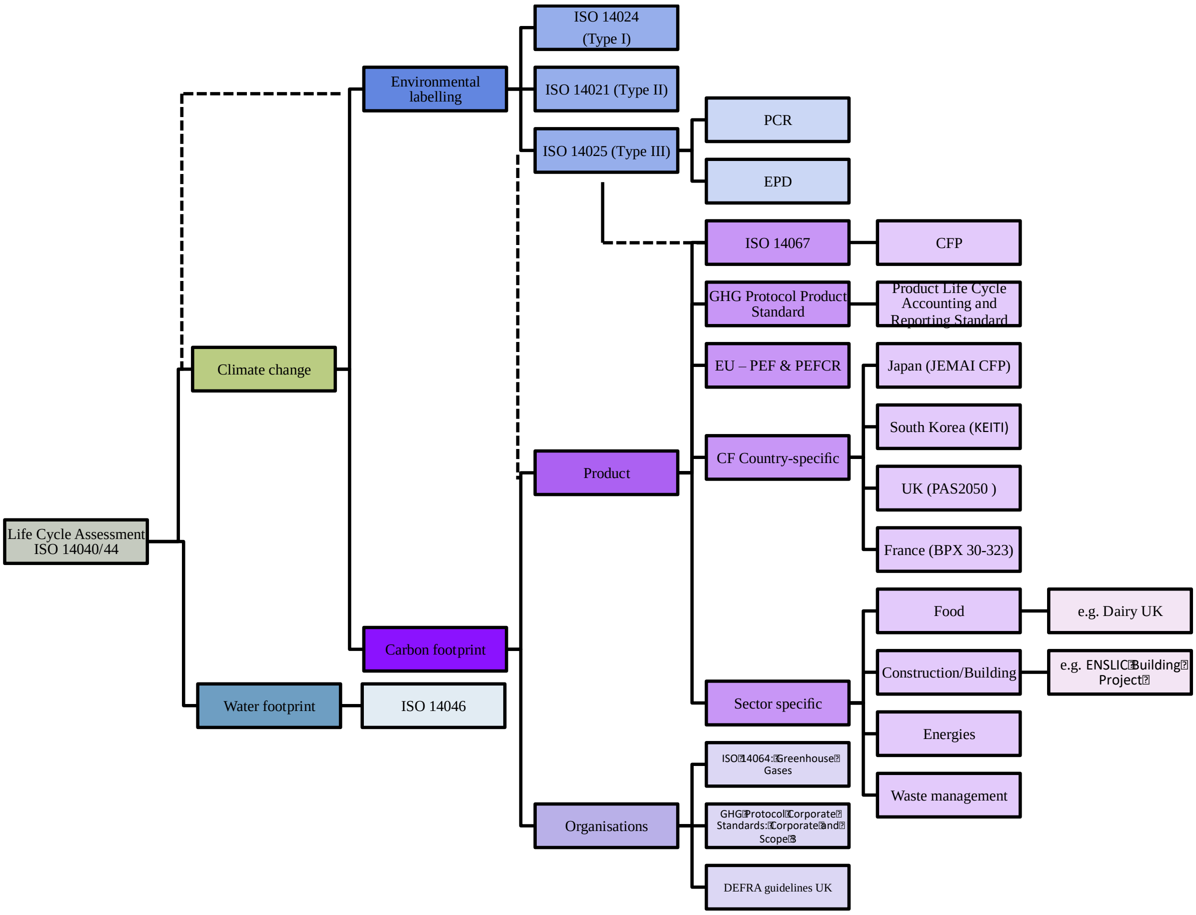

ISO 14024 (Type I)
Environmental labelling
ISO 14021 (Type II)
PCR
ISO 14025 (Type III)
EPD
ISO 14067
CFP
GHG Protocol Product Standard
Product Life Cycle Accounting and Reporting Standard
EU – PEF & PEFCR
Japan (JEMAI CFP)
Climate change
South Korea (KEITI)
CF Country-specific
Product
UK (PAS2050)
Life Cycle Assessment ISO 14040/44
France (BPX 30-323)
Food
e.g. Dairy UK
Carbon footprint
Construction/Building
e.g. ENSLIC Building Project
Water footprint
ISO 14046
Sector specific
Energies
ISO 14064: Greenhouse Gases
Waste management
Organisations
GHG Protocol Corporate Standards: Corporate and Scope 3
DEFRA guidelines UK

Figure 3.1