Life Cycle Assessment

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Chapter Title: Life Cycle Assessment

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Description

Life cycle assessment (LCA) methodology is a standardized method for assessing the potential environmental impact of a product or service throughout its lifetime (ISO 14040). As such, it represents a valuable tool by which researchers and organizations can identify, and avoid, unnecessary environmental burdens that have a negative impact on the ecological health of the globe. Environmental sustainability challenges mainly stem from humanity's current production and consumption habits. In this regard, there is a need to develop production practices and consumption behaviors that support sustainable development. It is imperative that we find solutions by which we can reduce environmental impacts and resource use within production chains. The first ISO standard for LCAs was published in 1996, and updated versions 14040 and 14044 were published in 2006. These LCA standards act as valuable guidelines and standards by which practitioners can reduce their (Klöpffer & Grahl 2014) carbon footprint and product environmental footprint. It also acts as a tool that can support decision making pertaining to various questions related to the environmental impacts of products and systems.

Introduction

The LCA methodology was developed as a means of evaluating the impact that a product has on the environment throughout its life cycle. The method aims to define the environmental effects of the whole production and distribution system, the most significant environmental impacts, and the most significant life cycle phases related to the most significant environmental impacts.

The contemporary economies of the majority of industrial countries are predominantly based on a take-make-and-dispose system, even though recycling practices have recently been developed in many countries. This take-make-and-dispose system relies on humanity having access to ready forms of resources and energy, a sufficient number of sinks for waste, and enough money to cure the adverse environmental impacts (Webster 2016, 332). However, although our current way of living is established on these grounds, we cannot continue along this route.

Climate change, the diminishing quality of air in cities, and lack of arable land are examples of the sustainability challenges that humankind is facing. The magnitude of these sustainability challenges is continuing to expand due to the growing number of people in the world, the increasing number of middle-class people, and rising consumption.

The challenges mainly stem from the current production and consumption habits. Market liberalization has shifted production to regions in the world in which the cost of labor and commodities is significantly lower than that on offer in developed countries. In many cases, this mainly results from a lack of legislation that protects the environment, workers, and stakeholders in low-cost manufacturing economies. However, the sustainability challenges are not limited to less-developed nations. Global environmental challenges, like climate warming, are not dependent on where the impact is produced. Besides existing consumption habits, trends like urbanization and increasing standard of living have incurred unexpected environmental implications in developed countries.

Due to the length and scale of production chains and the ever-more complicated production processes involved, it is imperative that any evaluation of environmental impacts spans the end-to-end life of a product, from raw material through to disposal. The LCA was developed to utilize database information pertaining to the existing processes in the event measurement data is not available or is considered too expensive to compile. LCAs also allow the use of calculated or estimated data if such information is determined to be in line with the use purposes of the results. Therefore, LCAs are recognized as one of the best methodologies for the evaluation of the environmental impacts of products (Cherubini et al. 2009).

A Brief History of the LCA

In the 1960s, people were mostly unconcerned about the sustainability of economic growth. However, gradually, as energy consumption rapidly increased, waste disposal issues became more common, and evidence started to emerge that industrial manufacturing was causing air and water pollution, questions concerning resource use and energy consumption emerged throughout the product chain.

As a result, in co-operation with the scientific community and industry representatives, developed a methodology that could be employed to the assess resource and energy use, solid waste disposal, and pollutants associated with a manufactured product during the course of its life cycle. This methodology was referred to as Resource and Environmental Profile Analysis (REPA), and it was inspired by material flow accounting (Klöpffer & Grahl 2014, 7.) The first applications of the methodology were focused on chemical intermediates and beverage packages at the 1960s (Bjørn et al. 2018.) The sufficiency of resources came under further public scrutiny following the Club of Rome’s report titled Limits of Growth in 1972 (Klöpffer & Grahl 2014, 7). This report assessed the connection between economic growth and sufficiency of material and energy resources. At the same time, the oil crisis also turned the discussion towards the efficient use of resources.

Public and academic awareness of the environmental impacts of production increased as evidence about the depletion of the ozone layer, climate change, acidification, and eutrophication emerged. Consequently, it was necessary to develop the REPA methodology so that it could quantify resource use and emissions while also assessing the environmental impacts and ecological consequences associated with a product throughout its life cycle. This was somewhat challenging as, in most cases, the uncertainties related to environmental sustainability increase exponentially the further the point of evaluation is from the actual source of emission. Therefore, as a starting point to assist studies that incorporated environmental impact assessments, the so-called midpoint approach was developed. This approach was justified by the fact that, in many cases, it is more important to assess the potential for environmental impacts without increasing the uncertainty that is inherent in the results.

The first international ISO standards pertaining to LCA were published in 1996, and they also included the impact assessment phase. The assessment of environmental impacts continued to evolve alongside the emergence of new findings in the scientific context. For example, the environmental assessment of chemicals benefitted ecotoxicology (a science developed for assessing the effects of toxic chemicals derived from natural or synthetic sources on biological organisms). Even after the publication of the international LCA standards, the methodology was scarcely utilized among industry representatives primarily because the formative applications were still considered to be too resource intensive and, as such, the costs outweighed the benefits of any LCA assessments. The approach involved typically consisted of a bottom-up method that aimed to collect nearly all the input and output data from the production chain before identifying the main environmental impacts and the life cycle stages at which those impacts could be observed. However, the uncertainty regarding some impact category data and the inconsistency in data quality related to alternative product chains frequently led to the conclusion that the methodology was still in its infancy. After ten years, the updated versions were released, and a top-down approach was recommended by which the focus of the study was firmly placed on reducing resources.

Throughout these developments, awareness of the sustainability challenges continued to grow, and the need to help customers to choose more sustainable products and services was increasingly recognized. As a result, the first instructions to calculate carbon footprint for products and services, called PAS 2008, was published in the United Kingdom in 2008. The guidelines were developed based on LCA standards, but as they were purely focused on climate change, they were precise.

The introduction of carbon footprint calculation standards clearly increased the demand for LCA-qualified professionals. It also encouraged the development of the widely accepted international standards and, in 2012, the first international standard "Product Life Cycle Accounting and Reporting Standard" was published by the GHG Protocol after businesses, governments, and other bodies convened at the World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD). Two years later, the first carbon footprint ISO standard was published (ISO 14067:2013).

The popularity of the carbon footprint standards also instigated the development of other footprint methodologies by which the issues threatening sustainability could be addressed. The Water Footprint Standard ISO 14046 was released in 2014. It was based on the LCA ISO standards and the carbon footprint ISO standards. A nutrient footprint methodology has also since been developed, and some publications are already available in scientific forums (e.g., Grönman et al. 2016; Leach et al. 2012; Metson et al. 2012). Land footprint suggestions have also been presented, but scholars have yet to agree on a universal definition of land footprints. Generally speaking, during the last decade, land use-related impacts have been acknowledged as representing one of the main challenges in LCAs, as the methodology was initially developed to assess industrially manufactured products and services. In more recent times, researchers have turned their attention to developing LCA-based handprint indicators.

LCA Methodology

The LCA is a tool that can be used to assess the environmental impacts a product incurs during its life cycle (ISO 14040). The method is structured, comprehensive, and internationally standardized (Väisänen 2014). There is broad agreement in the scientific community that LCAs represent one of the best methodologies for the evaluation of environmental loading associated with product and services (Cherubini et al. 2009). An LCA is used as a basis for many other applications, like the carbon and water footprint and the product environmental footprint (PEF) guidelines, which provide more detailed information about the calculation principles associated with these specialized applications than the original LCA standards.

Both environmental aspects and potential environmental impacts across the full lifecycle of the product are studied in the LCA. One of the main objectives of the LCA method is to employ a systematic overview and perspective to avoid shifting the environmental burdens from one life cycle stage to another or from one process to another. Typically, the LCA does not address economic or social aspects, although the life cycle approach and methodologies may also be applied to them (EN ISO 14044:2006). The LCA method is defined by the international standards ISO 14040 and 14044, and these standards focus on environmental impacts. Therefore, the overview of the methodology provided in this chapter relates to these standards.

In an LCA, the life cycle of a product is modeled as a product system that performs at least one defined function. The essential feature of a product system is demarcated by its function, and it contains the processes that are required during different life cycle phases. These processes are linked to each other by flows (intermediate products, waste, products or elementary flows).

An example of a product system is presented in Figure 1 (Väisänen 2014).

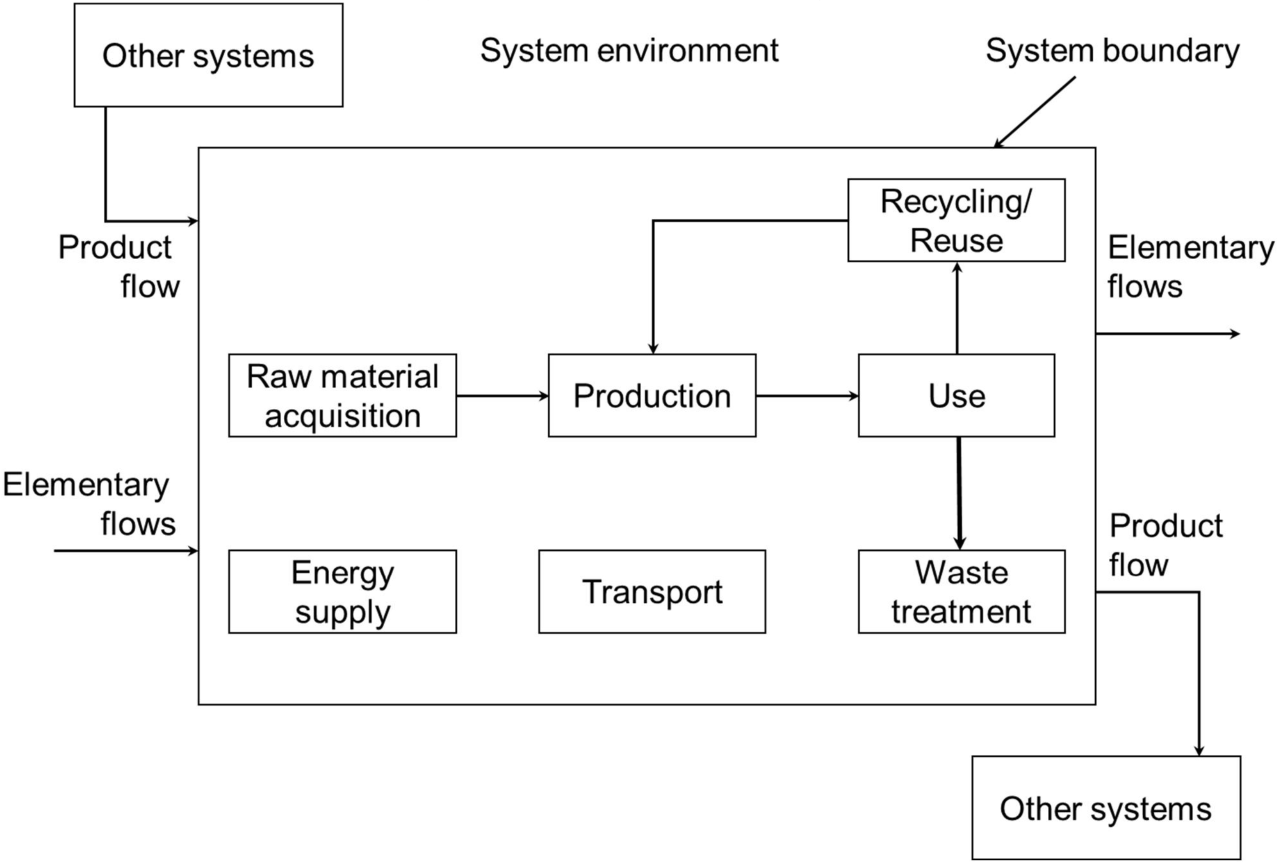

Figure 1. Product system (ISO 14040:2006).

Following the guidelines given in the ISO standards 14040 and 14044, an LCA involves four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment

(LCIA), and life cycle interpretation (ISO 14040). These four steps are presented in Figure 2.

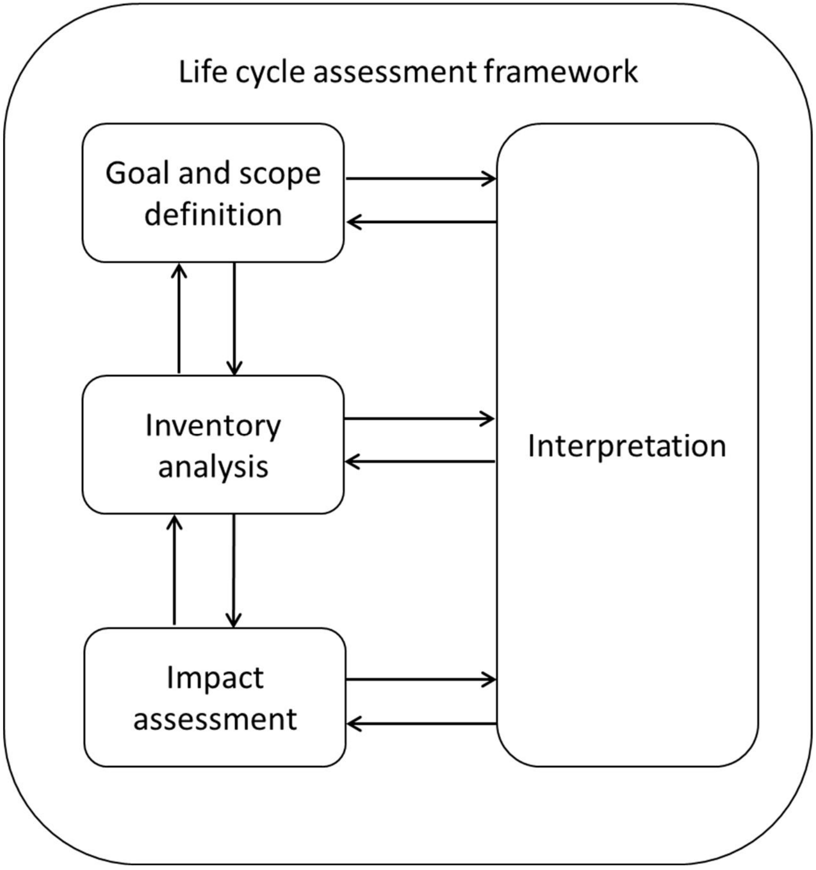

Figure 2. LCA framework (ISO 14040:2006).

The first step in the LCA is goal and scope definition (ISO 14040). During this phase, the purpose and nature of the study are defined together with the target group of the outputs. The goal definition outlines the basis for the research and the framework under which it is performed. It is also essential to describe how the results will be employed in comparative assertions that are intended to be disclosed to the public because this has implications in terms of the study requirements and how the findings will be critically reviewed during the results interpretation phase. Since LCA studies form a part of a more extensive decision-making process, it is crucial to clearly define what role the results are anticipated to play or how these results should be viewed. The LCA is a scientific method by which potential environmental impacts can be assessed; however, it does have some inherent limitations that entail that the outputs can be considered to be representative of the whole situation. Therefore, it is vital to define the extent of the usability of the results. If the report is intended to inform a new policy or regulation, it will be underpinned by very different requirements to those that are designed to help a company decide the environmental implications of one of its processes. The data requirements and sensitivity will also vary across these two instances and, as such, the resources required to complete the LCA will also vary.

Determining the scope of the study involves setting the system boundaries in the form of a flow diagram. Dividing a product system into its components in the form of processes and flows facilitates the identification of the inputs and outputs of the product system (Väisänen 2014). The boundaries and the level of modeling are designed to ensure that the goal is achieved (ISO 14040:2006). LCA, as the name suggests, is the study of the entire life cycle of a product. When an LCA is carried out, usually all phases of the life cycle are considered, including material acquisition from environment, material processing and transportation, production of the product, distributor to users, use, re-use, maintenance, and disposal, at which the point the materials have no use value (see Fig. 1). When the entire life cycle is considered, the approach can be referred to as a cradle-to-grave assessment. Sometimes the questions that an LCA aims to answer do not require modeling the entire life cycle; in such, cases a partial LCA can be performed. In a partial LCA, the system under study is limited from the beginning or the end: cradle-to-gate, where the assessment ends after the production phase, or gate-to-grave, where only use phase and recycling or disposal are considered. In fuel studies, well-to-wheels, well-to-tank, or tank-to-wheels are used to describe the system boundary settings.

LCA is a relative approach (ISO 14040:2006) that can be used to compare one system to another (Fava 2005). It is designed around the functional unit of a product or service, which originates from the function of the studied service or product. The functional unit describes the object of the study and the second step in the LCA, inventory analysis, is carried out based on the functional unit and the corresponding reference flow, which indicates the amount of product required to fulfill the defined functional unit (ISO 14040; Fava 2005).

The goal and scope of an LCA should be consistent and defined based on the intended application of the study. The LCA has an iterative nature and, thus, the scope may need to be refined during the study (ISO 14040, ISO 14044). Two different approaches to an LCA are presented in the ISO 14040 standard. The first assigns flows and potential environmental impacts to a specific product system, while the second studies the environmental consequences of possible (future) changes between alternative product systems (Väisänen 2014). The intended use of the first approach could be, for example, environmental footprints and the second approach can be used, for example, when the interest is to examine the potential environmental impacts of decisions concerning large systems; such as switching from partly fossil-fueled electricity production forms to renewables on a system scale.

The goal and scope definition of an LCA forms a foundation for inventory analysis (LCI). In the LCI analysis, data for input and output flows from the processes that form the studied product system are collected (Figure 3). LCI analysis gives the inventory of the input and output flows of the studied system, which transition across the system boundary. These results are described in the form of numerical values and cover the entire life cycle. In other words, the inventory flows that cross the system boundary line can be used as a basis for the impact assessment phase (LCIA). The results are presented, for example, in the form of kg/functional unit or MJ/functional unit depending on the type of flow. During the data collection process, it is crucial to collect the data to such an extent that the study requirements defined in the goal and scope definition phase are met (Köppler & Grahl 2016). For example, if the study aims to assess global warming impact, it is important to collect all the flows that have an influence on this impact category. In this way, the goal and scope definition helps to ensure that the study remains focused on the relevant information and there is no unnecessary data collection.

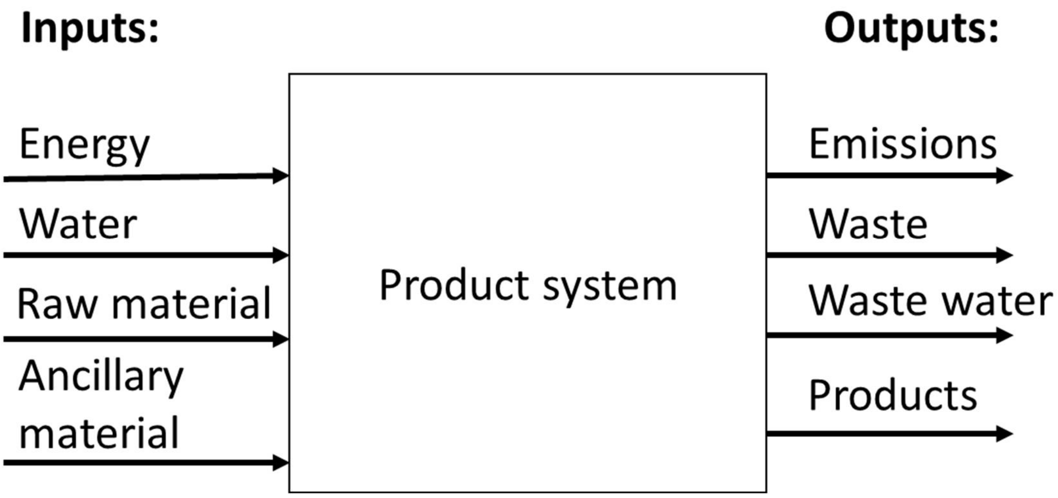

Figure 3. For LCA input and output flows of the system under study need to be defined (Klöpffer & Grahl 2014).

The third step in the LCA is impact assessment, during which the data produced during the LCI are assigned to impact categories (e.g., climate change, eutrophication) (Klöpffer & Grahl 2014). The impact categories and characterization models will have been specified earlier within the scope definition. This process, during which the input and output flows are connected to relevant impact categories is called classification (ISO 14044). The impact assessment phase includes three mandatory elements: 1) Selection of impact categories, category indicators, and characterization models; 2) classification; and 3) calculation of category indicator result (characterization) (Figure 4.) (Klöpffer & Grahl 2014). After the characterization, the results are presented in the unit of characterization model category indicator; for example, with the values of kgCO_2-eq./functional unit when the IPCC model for the global warming is selected as a characterization model. The selections need to be justified and consistent with the goal and scope of the LCA.

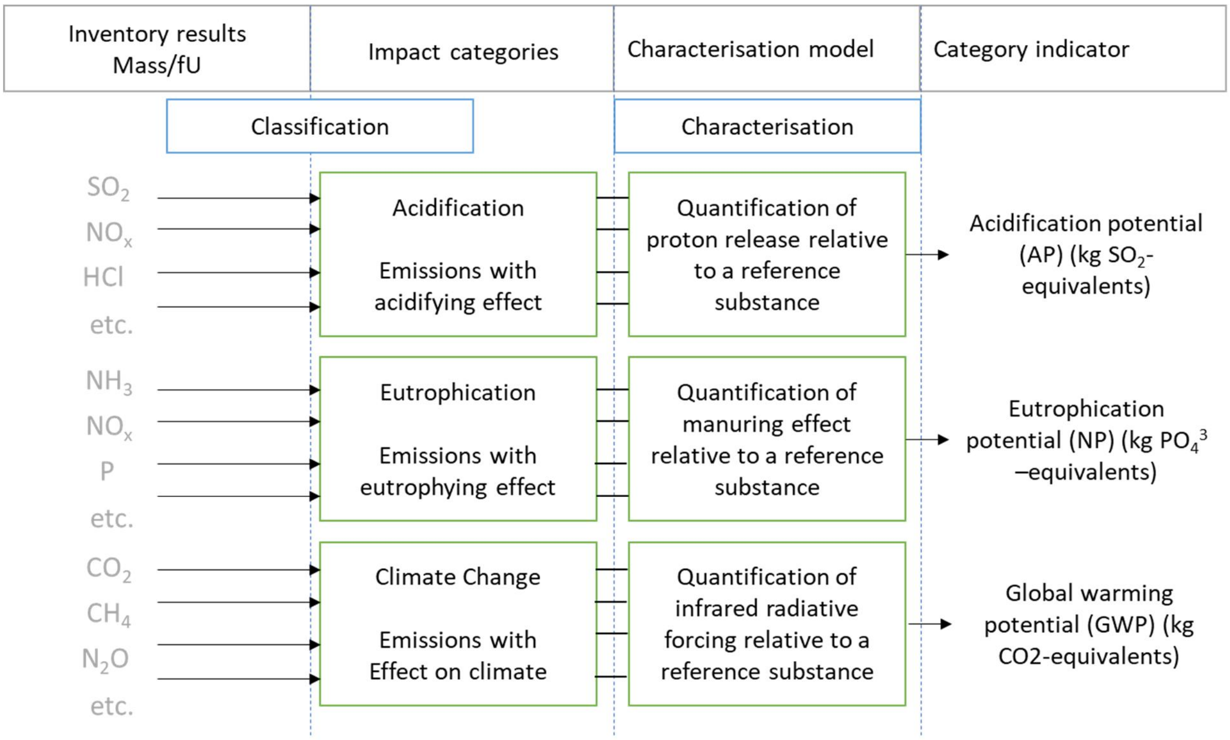

Figure 4. Phases of the Life Cycle Impact Assessment (Klöpffer & Grahl 2014).

In addition to these mandatory elements, the ISO 14044 standard presents four optional features: normalization, grouping, weighting, and data quality analysis. During these phases, the results after the mandatory phases are further processed to facilitate the interpretation of the findings. During the normalization, the characterization results are compared to some reference information, and this phase can provide information about the relative importance of the LCIA result. For example, the reference information can be the emissions produced in a particular area. In this case, the results will be normalized in the form of % of emission of one area. In the grouping impact, categories are assigned either by sorting them on a nominal basis or ranking them according to a given hierarchy (e.g., high, medium, and low priority). In the weighting, numerical factors based on value choices are used to change the order of the impact assessment results in a way that some impact categories are weighted higher than others. During the weighting exercise, the results can be aggregated to one single value, such as in the guidelines of product environmental footprint guides (Figure 5.). Identifying a single value that will be used to measure all environmental impacts within a system makes it more straightforward to compare the systems because the weighting steps are based on value choices; the result is not scientifically based. The last optional element, data quality analysis, studies the significance, uncertainty, and sensitivity of the LCIA results and can include Pareto analysis, uncertainty analysis, and sensitivity analysis (ISO 14044). When these methods are employed, the data that makes the most significant contribution to the indicator results, reliability of the results and, impact of selection of data or assumptions to the LCIA results will be understood better.

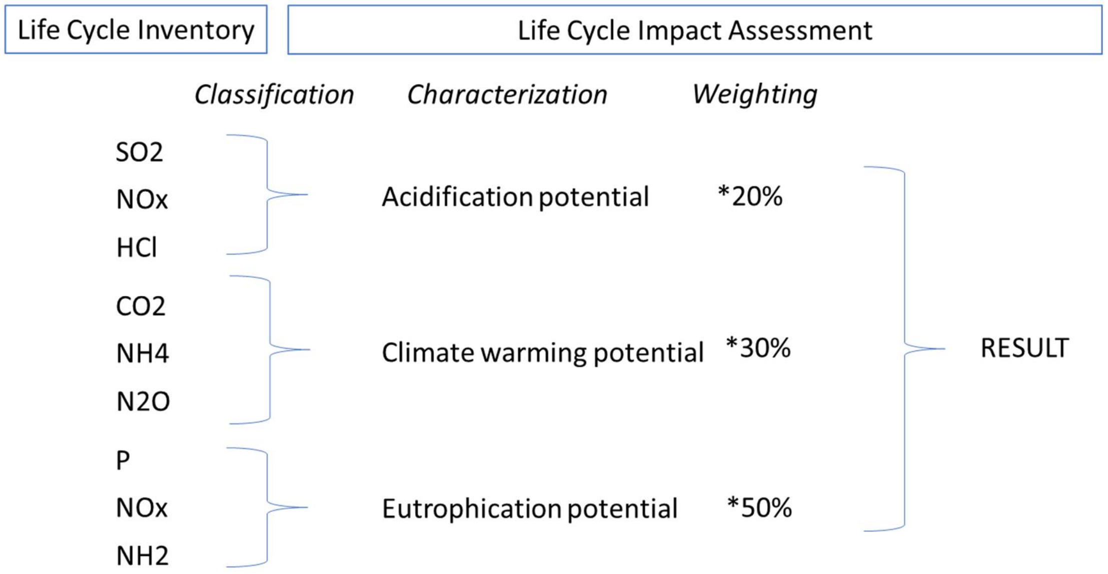

Figure 5. Results can be aggregated to a single aggregated value by using weighting factors for environmental impact category indicator results.

The fourth and the last step in LCA is interpretation. During this phase, conclusions are drawn from the previous LCI and LCIA results, and recommendations are developed in line with the study objective. During the interpretation phase, all assumptions, including the boundary conditions, should be once again critically assessed (Köppler & Grahl 2016). In the interpretation phase, the quality of data and applied method sufficiency to support the results need to be examined and documented. The regulations are stronger if the LCA is to be used for comparative assertions that will be made publicly available. In such a case, there is a requirement for the outputs to undergo a critical review by internal or external experts or a panel of interested parties, as stated in ISO 14044. Additional requirements and guidance for third-party reports are provided in the ISO 14044 standard.

Different Applications: Footprints, Ecodesinging, and Ecolabelling

From the environmental sustainability point of view, it is necessary to identify the most reasonable solutions not only in terms of product development options, but also when comparing alternative system solutions to cover energy needs, water supply needs, or waste treatment needs, among others. In applications of this nature, the LCA supports decision making and aims to find answers to questions such as the following:

- Is the proposed system more environmentally sustainable than the original one?
- Is the proposed system more environmentally sustainable than its competitors?
- Could the environmental impact of the product chain be reduced if alternative raw materials are used?
- Could the environmental impact of the product chain be reduced if alternative manufacturing methods are used?
- Could the environmental impact of the product chain be reduced if a life cycle stage is located in a country that has abundant water resources?

- Could the environmental impact of the product chain be decreased if the processing phase delivers a more effective way of utilizing secondary flow?

In recent times, product packaging increasingly incorporates footprint labels that help consumers choose the most sustainable product. Footprint calculations consider the whole life cycle and the calculation ISO standards (ISO 14067:2018 carbon footprint, ISO 14046:2014 water footprint) are based on the LCA ISO standards of LCA (ISO 14040:2006 and ISO 14044:2006). The carbon footprint standards provide more detailed instructions on how to calculate the greenhouse gas emissions of a product chain for communication purposes.

To support environmentally conscious decision making at a consumer level in the European Union (EU), the EU has introduced new directives (Ecodesign Directive 2009/125/EC, Energy Labelling Directive 2010/30/EU). The aim of these directives has been to encourage manufacturers to direct their attention to the product design phase, which is estimated to determine more than 80% of the environmental impacts of a product (Wenzel et al. 1997). The Ecodesign Directive aims to improve the environmental performance of energy-related products throughout their life cycle. At present, the main focus is on energy efficiency during the use phase; however, based on estimations, in the future more and more demands have to be set to other environmental aspects as energy consumption decreases and life span of electronics gets shorter. (Dalhammar, 2013.)

Significant effort has been invested in the development of LCAs that cover additional sustainability concerns, including social and economic dimensions. This would be especially important in cases that involve developing existing product chains to enable them to fulfill the sustainability expectations of a company's stakeholders.

Discussion

Business motivation to conduct a life cycle analysis

The primary motivating factors that encourage companies to carry out LCA studies are cost savings and profitability. Besides considering environmental aspects, economic aspects are of significance because they influence the extent to which an investment is sustainable over a longer-term period (Ristimäki et al. 2013). In parallel to an LCA, life cycle costing (LCCA), environmental life cycle costing, or social life cycle costing (SLCC) can be carried out to provide more information about the risks that may arise in the near future or within a non-limited time frame (Hunkeler et al. 2008). Together, the methodologies support decision making on a long-term basis and ensure the sustainability of investments from multiple perspectives.

Risk management is the third leading reason why companies should utilize LCA studies. For example, legislation can change due to increasing awareness about the issues that threaten sustainability. Also, competitors may adopt aggressive sustainability strategies to utilize the growing interest from customers to support sustainable development. To prepare oneself for environmental risks, the LCA results need to be examined in combination with the LCCA information.

The role of life cycle assessment in fulfilling a company's sustainability strategy

Nearly all companies are required to comply with some form of legal requirements related to sustainability. However, not all companies occupy a position within the product chain from which they have an opportunity to impact the decisions of other actors. In such a case, it may be sufficient to follow changes in legislation and emerging drivers.

Some companies need to meet stakeholders' expectations regarding environmental or sustainable responsibility. However, others are not under such pressure, even from their B2B customers. This could be because they have a relatively small footprint at that stage of the life cycle or because they operate in markets that have yet to emphasize these aspects. It is essential to bear in mind that the situation may change in the future when raising awareness and/or improvements achieved in other parts of the production chain may put smaller actors under the spotlight.

In the opposite case, in which a company is approached with inquiries about their responsibility, it should be in a position to provide data pertaining to activities; for example, its carbon or water footprint. Also, companies that are positioned closer to the final user within the life cycle may need data for environmental product declarations as part of certification processes.

A sustainability risk is an uncertain social or environmental event or condition that can cause a significant negative impact on the company (WBCSD 2017). By being prepared to provide responses and data in response to stakeholder inquiries, companies are protected against any risks that are derived from sustainability issues. However, companies may also pursue further advantages by assisting their suppliers and customers to meet their respective sustainability goals. Sometimes, this may entail entering into strategic partnerships with other companies to discover an ultimate solution. LCAs and LCCAs may be needed to identify the costs and benefits of such undertakings from the perspectives of all parties.

However, in most cases, small steps towards sustainability are not enough; instead, radical changes to current practices are needed. Therefore, the real forerunners from the sustainability point of view are companies that have engaged in the development of products and services that can meet the sustainability demands of the future. LCAs and LCCAs represent useful tools in this process.

Summary

The LCA is a standardized method for assessing the potential environmental impacts of products, product systems, and services. As such, it can be used to facilitate various decision-making situations. Today, the LCA plays a significant role in helping organizations and researchers to recognize and implement methods of tackling sustainability challenges and ensure that any sustainability changes that are suggested make sense from the resource use point of view. The LCA methodology also forms the basis for the two internationally standardized LCA-based footprints (carbon footprint and water footprint). In addition, current on-going product environmental footprint guidelines for development follow the principles of LCA. The purpose of the LCA is to search for the most beneficial environmental impact reduction points within the production chain, while the use of footprint measurements enables different production systems to be compared.

The approach aims to prevent environmental problems shifting from one life cycle stage to others. The methodology consists of four main steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. By following these phases, practitioners can ensure that the study is outlined, conducted, and verified in a way that produces reliable and valid scientific results. The guidelines for completing the different LCA phases are described in the ISO 14040 and 14044 standards. If the LCA is used for comparative assertions and to be made publicly available, the study will need to be performed according to stronger regulations and the results verified by a critical review before publication.

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