Environmental life cycle assessment: history, method and application to packaging

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Abstract Environmental Life Cycle Assessment (LCA) is one of the assessment methods widely used. LCA has a long history and is first applied to packaging systems. The entire LCA history is peppered with packaging examples. The entire LCA history is peppered with packaging examples. In this study, which is largely based on the author's years research experience in LCA, the key features of LCA are first summarized briefly, next the history of LCA is sketched, and the LCA method is explained. Next, selected applications of LCA are provided with a special focus on packaging including suggestions for future LCA packaging research, and we end with some concluding remarks.

Key words Life cycle assessment(LCA); Packaging; History

环境生命周期评价在包装中的历史、方法和应用

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摘要 环境生命周期评价（LCA）是目前应用最为广泛的评价方法之一。LCA有着悠久的历史，且最早应用于包装系统。整个LCA的历史充满了包装的例子。基于作者在LCA领域多年的研究经历，本研究首先介绍了LCA的主要特点。然后，简述了LCA的发展历史和评价方法。最后，重点介绍了LCA在包装领域的应用，并且对未来包装LCA的研究提出了一些建议。

关键词 生命周期评价；包装；历史

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0 Introduction

Today's society is highly consumption-based. Through advertisements and marketing campaigns we are stimulated on a daily basis to consume products, services and if possible, more and more. Products and services are the key selling items of our economic system. At the same time we are facing huge environmental sustainability challenges with respect to e.g. climate change, land use change, water shortages, toxic pollution and resource scarcity. Products and services are key concepts in addressing these environmental challenges. However, we are not so much looking into products as such but rather at a system of economic or industrial processes needed for the functioning of that product. Thus, the terms ‘product system’ (or even better: ‘function system’) and ‘service system’ enter the area. A product system refers to the entire life cycle of a product, from extraction of natural resources to final waste management of the disposed product, form ‘cradle-to-grave’.

Knowledge of the environmental impacts of such product systems is indispensable if we are aiming for improving the environmental performance of these systems. We preferably need numbers for all relevant environmental impacts of product systems, from the cradle to the grave (whole life cycle), in order to find best solutions for their improvement without shifting impacts to other fields or to other phases of the life cycle (trade-offs). One of the assessment methods widely used for this is environmental Life Cycle Assessment, abbreviated LCA.

LCA has a long history and was, as far as we can trace back, first applied to packaging systems. The entire LCA history is peppered with packaging examples. In this article, which is largely based on (Guinée et al. 2011; Guinée and Heijungs 2017; Heijungs and Guinée 2012)full-fledged life cycle impact assessment and life cycle costing models were introduced in the 1980s and 1990s, and social-LCA and particularly consequential LCA gained ground in the first decade of the 21st century. Many of the more recent developments were initiated to broaden traditional environmental LCA to a more comprehensive Life Cycle Sustainability Analysis (LCSA, the key features of LCA are first summarized briefly, next the history of LCA is sketched, and the LCA method is explained. Next, selected applications of LCA are provided with a special focus on packaging including suggestions for future LCA packaging research, and we end with some concluding remarks.

1 LCA in A Nutshell

LCA offers a method for quantitatively compiling and evaluating the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (International Organization for Standardisation 2006a) and its results may be used to support decision-making in this area. LCA intends to give a complete picture in terms of life cycle phases and environmental impacts. It maps all life cycle activities and related impacts to identify and avoid potential trade-offs through an integral analysis.

LCA has made a long way, and it is still changing. But since a decade or so, there is a broadly accepted set of principles that can claim to be the present-day LCA framework based on a series of standards and technical reports issued by the International Organization for Standardization (ISO)that finally evolved in two Standards: ISO 14040 (International Organization for Standardisation 2006a).The standards are organized into the different phases of an LCA study:Goal and scope definition, Inventory analysis, Life cycle impact assessment, and Life cycle interpretation (Fig.1).

2 Brief History of LCA

This section summarizes the history of LCA. The text is largely based on Guinée et al. (2011).

The first studies that are now recognized as (partial) LCAs date from the late 1960s and early 1970s.One of the first (unfortunately unpublished) studies quantifying the resource requirements, emission loadings and waste flows of different beverage containers was conducted by Midwest Research Institute (MRI) for the Coca Cola Company in 1969. Together with several follow-ups, this marked the beginning of the development of LCA as we know it today. The interest in LCA rapidly

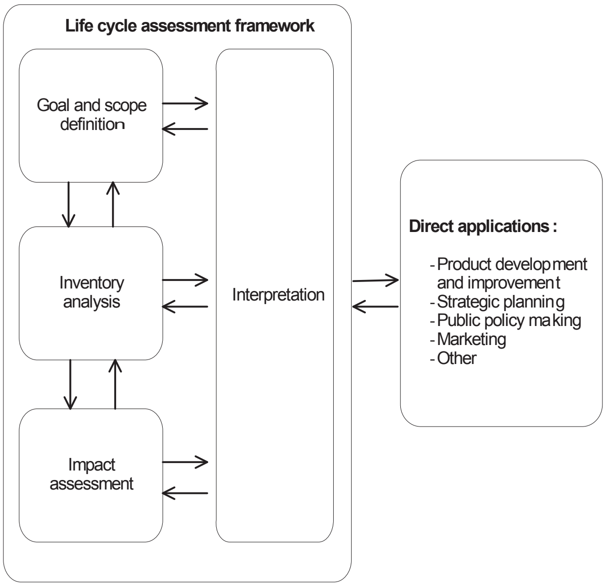

Fig.1 The general methodological framework for LCA (International Organization for Standardisation 2006a)
图1 LCA方法框架（国际标准化组织2006a）

increased from the early 1980s onwards. In 1984 the Swiss published a report (Bundesamt für Umweltschutz 1984) that presented a comprehensive list of the data needed for LCA studies, thus catalyzing a broader application of LCA.

The period 1970～1990 comprised the decades of conception of LCA with widely diverging approaches, terminologies and results. There was a clear lack of international scientific discussion and exchange platforms for LCA. During the 1970s and the 1980s LCAs were performed using different methods and without a common theoretical framework. LCA was repeatedly applied by firms to substantiate market claims. The obtained results differed greatly, even when the objects of the study were the same, which prevented LCA from becoming a more generally accepted and applied analytical tool(Guinée et al. 1993). The 1990s saw a remarkable growth of scientific and coordination activities world-wide. Also the first scientific journal papers started to appear in the Journal of Cleaner Production, in Resources, Conservation and Recycling, in the International Journal of LCA, in Environmental Science & Technology, in the Journal of Industrial Ecology and in other journals.

The Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role in bringing LCA practitioners, users and scientists together to collaborate on the continuous improvement and harmonization of LCA framework, terminology and methodology. Next to SETAC, ISO has been involved in LCA since 1994. Whereas SETAC working groups focused at development and harmonization of methods, ISO adopted the formal task of standardization of methods and procedures. The 1990s thus marked a decade of harmonization and standardization. During this period, LCA also became part of policy documents and legislation. The main focus was on packaging legislation(EC 1994).

The first decade of the 21st century has shown an ever increasing attention to LCA. In 2002, the United Nations Environment Programme (UNEP) and the SETAC launched an International Life Cycle Partnership, known as the Life Cycle Initiative. In 2005 the European Platform on Life Cycle Assessment was established to promote the availability, exchange, and use of quality-assured life cycle data, methods and studies for reliable decision support in (EU) public policy and in business. In the USA, the U.S. Environmental Protection Agency started promoting the use of LCA and also US environmental policy got increasingly life-cycle based all over the world (Unites States Congress 2007). In this same period, several life cycle-based carbon footprint standards have been, or are being, established. The period 2000-present can be marked as the decade of elaboration. From 2000 onwards, increasing attention was to life cycle costing (LCC) (Hunkeler et al. 2008) and social life cycle assessment (SLCA) (Benoît and Mazijn

2009) approaches, which have merged with LCA in what is today called life cycle sustainability assessment (Guinée 2015).

3 LCA: the Method

Below, we will discuss the main idea and content of the four phases distinguished in Fig.1 in separate subsections. The text is largely based on Guinée and Heijungs (2017).

3.1 Goal and Scope Definition

There is no explicit ISO definition of the first phase of LCA. However, it obviously centres on formulating the question and stating the context of answering this question. In the goal and scope definition, the basic idea of the LCA study is defined as clearly and unambiguously as possible.

The goal of the LCA deals with defining the intended application, the reasons for carrying out the study, the intended audience, and whether the results are to be used in comparative assertions disclosed to the public. The choices made here have an influence on the rest of the LCA procedure, for example, depending on the intended audience a critical review may be needed.

In the scope definition, the product system or systems to be studied, and the function the system delivers are defined. For instance, one might be interested in the product systems incandescent light bulb versus the LED bulb, with the function of lighting a room.

An important aspect of the scope definition is the functional unit. It is obviously pointless to compare an incandescent bulb with a LED bulb: the life spans and performances differ considerably, and the function is not having a light bulb, but having light of a certain quality. A functional unit for analysing lighting systems could thus better be phrased as, for example, “lighting a standard room of 15 square meter with 1000 lumen for 1 hour”. As LCA employs mathematically a linear calculation rule, the results will scale by choosing a numerically different functional unit (say, “lighting a standard room of 20 square meter with 800 lumen for 3 hours”), but the alternatives considered will scale up or down consistently, so this will not affect the conclusions. A consequence is, however, that LCA cannot tell if a product is “environmentally friendly”; LCA can only indicate if product X is “more environmentally friendly” than product Y, or that the use phase is the “least environmentally friendly” part of the life cycle for product Z.

The scope definition furthermore sets the main outline on a number of subjects that are discussed and further refined in more detail in the later phases.

3.2 Inventory Analysis

ISO defines inventory analysis (LCI) as the “phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (International Organization for Standardisation 2006a). It will be clear that quantification is an important aspect here, and numbers, in terms of data and calculations, are of central concern in the inventory analysis.

The LCI is built up on the basis of the unit process. A unit process is the “smallest element considered in the life cycle inventory analysis for which input and output data are quantified” (International Organization for Standardisation 2006a). Examples of unit process are coal mining, steel production, refining of oil, production of furniture, use of a TV, recycling of waste paper, and transport by lorry. Each of these processes is described in quantitative terms as having inputs and outputs. As a matter of fact, a unit process is in LCA considered as a black box that converts a bundle of inputs into a bundle of outputs. Inputs come in several types: products (including components, materials, and services), waste for treatment, and natural resources (including fossils, ores, biotic resources, and land). Outputs come in several types as well: again products (including components, materials, and services), waste for treatment, and residuals to the environment (including pollutants to air, water, and soil, waste heat, and noise); see Fig.2.

Unit processes form the building blocks of an LCA. The essential feature of LCA in which it distinguishes itself from the analysis of just a process is that it connects different unit process into a system. A flow diagram is a graphical representation of the system of connected unit processes, see Fig.3.

As we can see Fig.4(Because the purpose is to show how unit process are connected, only the flows from and to other unit processes are displayed, and flows from and to the environment are hidden. All transport, machinery, etc. has been left out as well.), some unit processes are connected with one another in simple upstream-downstream connections, e.g., packaging production is upstream connected to plastic production. But there are also more complicated connections, e.g., electricity linking to different parts of the system, and recycling feeding back to production. Flow diagrams are in fact huge webs of interconnected unit processes. In the present era of digital databases, LCA studies can easily comprise several thousands of unit processes.

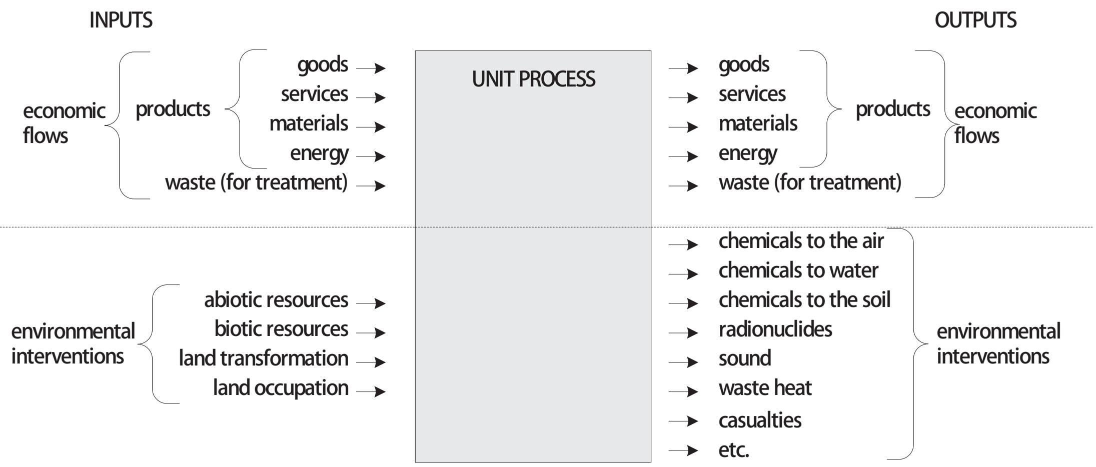

Fig.2 Basic structure of a unit process (or product system) in terms of its inputs and outputs
图2 单元过程（产品系统）输入和输出基本框架图

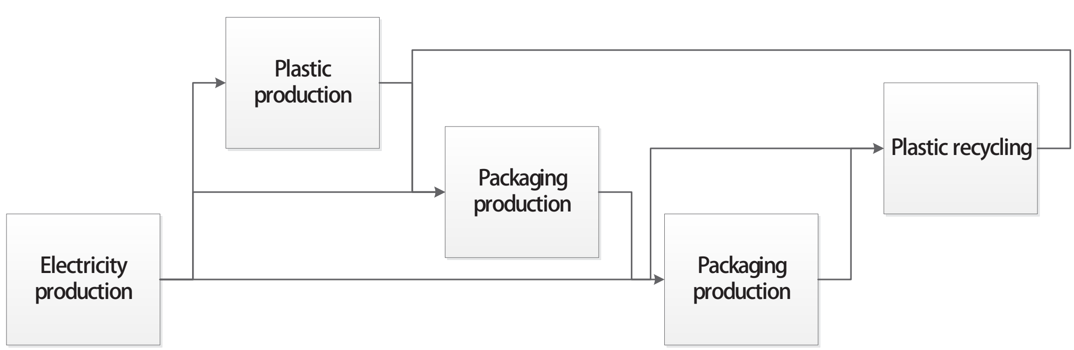

Fig.3 Show a fragment of such a flow diagram
图3 流程图

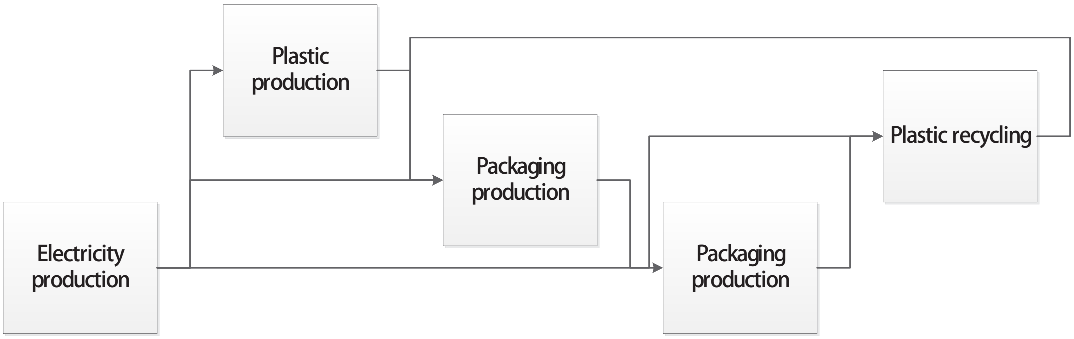

Fig.4 Simplified flow diagram for an LCA on a hypothetical plastic packaging
图4 塑料包装LCA简图

LCA is primarily a quantitative model. For each of the unit processes included, quantitative data should be collected. Moreover, in order to be able to process the data and perform the calculations automatically, a clear and unambiguous representation is needed. This implies, amongst others, harmonization of nomenclature (e.g., not using "carbon dioxide" for one unit process and "CO_2" for another one), and harmonization of units (e.g., not mixing up kg and lbs).

In an LCA, we must next find out how much we need. For instance, a product may need 3 kg of aluminium, while we have collected data for 1 kg (needing for example 2 kg of aluminium oxide and 20 kWh of electricity per kg aluminium, and releasing 200 g of CO_2 per kg aluminium). The basic assumption of the LCA model is that technologies are linear. This means that we can scale the data of a unit process by a simple multiplication. In the example, 3 kg of aluminium would require 6 kg of aluminium oxide and 60 kWh of electricity, while it would release 600 g of CO_2. The assumption of linear technology is an important restriction of LCA; yet it is an important step in making the calculation and data collection feasible.

In scaling the unit processes, the web-like nature of the system quickly creates complications, as everything depends upon everything. The calculation of the scaling factors, and with that of the emissions to and extraction from the environment, is greatly simplified by considering the problem as a system of linear equations: one unknown (the scaling factor) for every unit process, and one equation (a balance) for every flow. Thus, solutions may be obtained by matrix algebra. The details of this are not discussed here; see (Heijungs and Suh 2002) for a detailed exposition.

The approach mentioned above may fail in a number of cases. We mention two complications:

· for some products, upstream production processes or downstream disposal process may be difficult to quantify;

· for some unit processes, the balance equations become impossible due the fact these processes produce not just one product but several products.

The first issue can be solved by a procedure known as cut-off, the second one by allocation.

Cut-off is a solution to the problem that the system is theoretically infinitely large. To produce a TV, we need machines, and these machines are produced by machines, and these machines in turn need machines, etc. But of course we have an intuitive idea that some very distant upstream processes will be quite unimportant. This means that we will cut-off certain inputs, or alternatively, estimate missing parts by means of similar processes (e.g., estimating production of a freezer by production of a fridge), or by economic input-output tables(Guinée et al. 2002).

The second problem has given rise to one of the biggest controversies in LCA theory. The problem can be stated simply: if a transportation process needs gasoline, the upstream unit process is a refinery that produced not only gasoline, but also diesel, kerosene, heavy oils, and some more. The direct impacts (from pollutants like CO_2), but also the flows to and from other processes that may lead to impacts (e.g., from oil drilling) may be argued not be attributable to gasoline only, but in need to be distributed over gasoline, diesel, and all other co-products. This is hardly contested, but the debate focuses on how to do this(Wardenaar et al. 2012; Guinée and Heijungs 2007).

After appropriate cut-off and allocation steps, the final inventory results can be calculated. Typically, this is a table with the quantified inputs from and outputs to the environment, for each of the alternative systems considered, expressed in relation to the functional unit (Tab.1). With the present-day software and databases, this inventory table may be 1000 lines long, or more. It contains not only the familiar pollutants and resources, such as CO_2, NO_x, and crude oil, but also more exotic items, such as 1-pentanol, cyprodinil, and dolomite. Typically, these so-called elementary flows are aggregated over the entire system, so that the CO_2 number is the life cycle emission of CO_2.

3.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (International Organization for Standardisation 2006a). Its motivation comes from two observations:

· the final result of the inventory analysis, the inventory table, is too long (e.g., 1000 different items) to handle;

· the inventory table contains many items that are require expert knowledge (such as 2-methyl-2-butene) to understand in terms of importance.

Impact assessment, and in particular the characterization step, solves both issues: it "involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category" (International Organization for Standardisation 2006b).

While the unit process is the central element of the inventory analysis, the central element in impact assessment is the impact category. ISO (2006b).defines it as "class representing environmental issues of concern to which life cycle inventory analysis results may be assigned". Perhaps more helpful are some examples: climate change, toxicity, and depletion of fossil energy carriers.

As climate change (often used interchangeable with global warming) is a well-known issue, we will illustrate the main ideas of impact assessment with this case. The inventory table contains a number of greenhouse gases: CO_2, CH_4, N_2O, etc. These are known to contribute all to the phenomenon of climate change. We should now find a way to convert the emission data into the chosen impact indicator. For this we can use the workon quantitative models of the impacts of greenhouse gas emissions by the UN-based International Panel on Climate Change (IPCC). One result of this work are the so-called global warming potentials (GWPs), which are quantitative measures of the relative strength of different greenhouse gases. Many LCIA methods apply GWPs for climate change. We will illustrate their usage below.

As a concrete example of how characterization works, let us study a fragment of a hypothetical inventory table, containing the following information: emission of CO_2 100 kg, emission of CH_4 1 kg, emission of SO_2 1 kg. Characterizing

Tab.1 Example of a hypothetical inventory table
表1 清单表

Elementary flows	Packaging 1	Packaging 2	Unit
NMVOC, non-methane volatile organic compounds, unspecified origin[air_high population density]	1.40E-06	4.57E-07	kg
Carbon dioxide, fossil[air_low population density]	2.83E-01	4.96E-02	kg
Ammonia[air_high population density]	7.82E-07	2.68E-07	kg
Nitrogen oxides[air_high population density]	3.76E-04	6.24E-05	kg
Particulates, < 2.5 um[air_high population density]	3.87E-05	6.88E-06	kg
Particulates, > 10 um[air_high population density]	5.52E-07	1.04E-06	kg
Particulates, > 2.5 um, and < 10um[air_high population density]	6.87E-07	1.02E-06	kg
Zinc, ion[water_river]	4.69E-08	4.57E-08	kg
Lead[water_river]	3.59E-08	2.98E-07	kg
Nickel, ion[water_river]	9.84E-09	5.19E-09	kg
Mercury[water_river]	4.20E-10	4.22E-11	kg
Copper, ion[water_river]	5.97E-09	4.79E-09	kg
Chromium, ion[water_river]	7.10E-09	1.77E-08	kg
Cadmium, ion[water_river]	7.68E-10	1.56E-09	kg
Arsenic, ion[water_river]	3.15E-08	1.47E-08	kg
Phosphate[water_river]	1.83E-08	1.48E-08	kg
Ammonium, ion[water_river]	3.86E-07	2.18E-06	kg
Nitrate[water_river]	6.82E-06	1.02E-06	kg
Nitrate[air_high population density]	1.24E-09	3.42E-10	kg
Calcite, in ground[resource_in ground]	-4.23E-03	-1.34E-03	kg
Sylvite, 25 % in sylvinite, in ground[resource_in ground]	-9.76E-08	-2.53E-08	kg
Water, cooling, unspecified natural origin[resource_in water]	-1.22E-02	-2.65E-03	m3
Water, river[resource_in water]	-2.38E-03	-5.56E-03	m3
Sodium, ion[water_river]	1.48E-04	1.06E-04	kg
Potassium, ion[water_river]	5.21E-06	1.58E-06	kg
Chloride[water_river]	5.45E-04	1.37E-04	kg
Calcium, ion[water_river]	7.74E-05	1.97E-05	kg
Magnesium[water_river]	1.49E-05	3.25E-06	kg
Sulfur[water_river]	1.30E-07	4.61E-08	kg
Hydrogen chloride[air_high population density]	3.85E-07	1.68E-07	kg
Hydrogen fluoride[air_high population density]	2.03E-08	9.09E-09	kg

greenhouse gases with GWPs requires a table with GWPs. In such a table, one can find that the GWP of CO_2 is 1 (by definition) and that the GWP of CH_4 is 25 (kg CO_2-equivalent/kg CH4). SO_2 has no GWP; it is assumed not to contribute to climate change. Characterization now proceeds in the case of climate change by calculating

$$1\times100+25\times10=350\text{kg}CO_2-\text{equivalent} \quad (1)$$

For the more general case, this can be written as

$$GW=\sum_s GWP_s\times m_s \quad (2)$$

where GW is the global warming score, s the substance (the different greenhouse gases), GWP_s the GWP of substance s, and m_s the emitted amount of substance s in kg. This may be further generalized as

$$I_c=\sum_s CF_{c,s}\times m_s \quad (3)$$

where c codes for the impact category, I represents the indicator result for category c, and $CF_{c,s}$ the characterization that links substance s to impact category c. This formula is the operational formula for characterization. With a table of characterization factors specified, it makes clear

· that LCIA builds on the results of LCI (as is clear from the term m_s);

· that characterization converts the results of LCI into a common metric (as is clear from the multiplication by CF);

· that characterization aggregates the converted LCI results (as is clear from the summation symbol).

The results from characterization is a list of numbers, for instance a score for climate change, a score for toxicity, etc. ISO refers to such numbers as “category indicator results”, but most LCA practitioners prefer names like “score”, sometimes expanded with the name of the impact (like in “toxicity score”). The complete list is known by names like “LCIA profile”, “characterization table”, etc.

Some LCA studies concentrate on just one impact category. For instance, the carbon footprint (of a product, not of a company or country) is a form of LCA that addresses just climate change through GWPs. At the other extreme, some LCA studies incorporate 15 or more impact categories. For consistency reasons, the choice of impact categories is often made on the basis of a recommended impact assessment guidebook or its implementation in software. Thus, in practice one often sees LCA-studies reporting the use of “IMPACT2002+”, “TRACI”, “CML-IA”, “ReCiPe”, “PEF” or “ILCD”, etc. All these methods comprise a recommended set (“family”) of impact categories with a category indicator and set of characterization factors. ISO does not specify any choice in these matters. Tab.2 gives an example of characterization results for two hypothetical packagings adopting the Product Environmental Footprint (PEF)-family (European Commisison 2017) of impact categories and characterization factors.

An optional next step is normalization referring to calculating “the magnitude of the category indicator results relative to some reference information” (International Organization for Standardisation 2006b). It is an optional step for ISO, and indeed, many LCIA studies stop at the characterization. The reference information is in most cases that total impact in a certain region in a certain time period, e.g., in the country of decision in one year. Normalization is done “to understand better the relative magnitude for each indicator result” (International Organization for Standardisation 2006b). Without normalization, the indicator results are in quite different units, e.g., kg CO_2-equivalent for climate change and MJ primary energy for fossil energy depletion. To put these results in perspective, the normalization expresses them as a share of the total impact size in the region. Arbitrary differences due to a choice of units disappear, and it becomes clear to which impact category a product contributes relatively

Tab.2 Example of characterization results for two hypothetical packagings
表2两个包装产品的特征化结果示例

Impact category	Packaging 1	Packaging 2	Unit
climate change//GWP 100a	6.77E-01	9.22E-02	kg CO2-Eq
ecosystem quality//freshwater and terrestrial acidification	1.22E-03	6.20E-04	mol H+-Eq
ecosystem quality//freshwater ecotoxicity	1.94E+00	6.52E-01	CTUh.m3.yr
ecosystem quality//freshwater eutrophication	2.66E-04	4.20E-05	kg P-Eq
ecosystem quality//ionising radiation	2.74E-07	3.85E-06	mol N-Eq
ecosystem quality//marine eutrophication	3.95E-04	1.06E-04	kg N-Eq
ecosystem quality//terrestrial eutrophication	3.88E-03	1.06E-03	mol N-Eq
human health//carcinogenic effects	2.26E-08	6.52E-09	CTUh
human health//ionising radiation	1.06E-01	1.11E+00	mol N-Eq
human health//non-carcinogenic effects	7.68E-08	4.54E-08	CTUh
human health//ozone layer depletion	2.62E-08	4.72E-09	kg CFC-11-Eq
human health//photochemical ozone creation	9.69E-04	2.87E-04	kg ethylene-Eq
human health//respiratory effects, inorganics	1.72E-04	6.50E-05	kg PM2.5-Eq
resources//land use	3.18E-01	8.19E-02	kg Soil Organic Carbon
resources//mineral, fossils and renewables	8.16E-07	4.26E-06	kg Sb-Eq

much. The units of the normalize indicator results are equal; nevertheless such numbers cannot meaningfully be added because the severity of the different impact categories has not yet been accounted for. This can be done in the weighting step; see below. Normalization fulfils several functions: it provides insight into the meaning of the impact indicator results, it helps to check for errors, and it prepares for a possible weighting step.

Weighting is a final step of the impact assessment phase. Weighting, like characterization, converts and aggregates, but while characterization does so for the LCI results, weighting starts with the characterization (or normalization) results. Typically, weighting factors are applied, either to the characterization indicator results, or to their normalized version. The weighting factors themselves are supposed to reflect value judgements, such as social and political priorities. Weighting typically produces one final number, by means of

$$W = \sum_{c} WF_c \times I_c$$

where I_c again symbolizes the impact score (or normalized impact score) for impact category c, WF_c the weighting factor for this impact category, and W the weighted result.

3.4 Interpretation

ISO (2006a)defines the interpretation as the "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations". Several elements are mentioned by ISO:

· identification of significant issues;

· an evaluation that considers completeness, sensitivity and consistency checks;

· conclusions, limitations, and recommendations.

· appropriateness of the definitions of the system functions, the functional unit and system boundary;

· limitations identified by the data quality assessment and the sensitivity analysis.

The text of ISO on interpretation is very concise, and no details are given on procedures and techniques to be employed. The same applies to most guidebooks on LCA. They mention carrying out an uncertainty analysis, but give no clear guidance on how this should be done.

In another context, we have introduced the distinction between procedural and numerical approaches (Guinée et al. 2006; Heijungs and Kleijn 2001):

· procedural approaches include all types of analyses that deal with the data and results in relation to other sources of information, like expert judgements, reports on similar products, intuition, reputation of data suppliers, and so on.

· numerical approaches include those approaches that somehow deal with the data that is used during the calculations, without reference to those other sources of information, but as algorithms that use and process the data in different ways, so as to produce different types of "smart" data reduction that provide an indication of reliability, key issues, discernibility, robustness, and so on.

This distinction helps to understand some important roles of interpretation. On the one hand, it is about comparing the data and results with previous findings, and to put the results in the context of decision-making and limitations. On the other hand, it is devoted to a systematic analysis with the help of statistical and other decision-analytic techniques. The latter type may be incorporated in software, and indeed, an increasing number of software packages contain options for running Monte Carlo analysis, doing sensitivity analysis, carrying out statistical significance tests, etc.

The development of methods in this area is booming, see (Henriksson et al. 2015a, 2014). but current practice is quite meagre, unfortunately. We still see many LCA studies without uncertainty or sensitivity analysis, even though methods and software increasingly facilitates this. There is of course a psychological argument that a contractor pays for finding out something, not for increasing the doubt. And as many LCA practitioners spend several months on collecting data, it is never a nice thing to waste this effort in a last-minute uncertainty analysis. But decision-making obviously means also taking into account the limits of knowledge. Moreover, as discussed before, a proper analysis of uncertainties and sensitivities helps to prioritize the steps earlier on in the framework: collecting data, setting boundaries, making choices.

4 Applications

LCA has been applied to a wide range of products and services. Until the late 1990s bibliographies of LCA case studies performed were kept up to date (Grotz and Rubik 1997) on a continuous basis. Using internet search machines results in a list of hundreds of LCA case studies documented in scientific papers or reports. Even more studies have been made for company-internal purposes, without publication in the scientific literature or on the web. LCA has been applied to simple products as shopping bags and packaging to more complex products such as mobile phones, PCs, cars and buildings. Studies may involve both an environmental comparison between existing products but also the development of new products (eco-design). LCA has also been applied to services such as LCAs on hazardous waste site clean-up options, on waste management strategies and on different modes of freight transport (road, rail, water). As in the case of product-LCAs, it is the function provided which is the core object of these service-LCAs, but in this case the function is cleaning up a hazardous waste site, waste management or freight transport.

The results of these case studies were often in line with general expectations, but there were also numerous counter-intuitive results. We randomly provide 2 examples of the latter below. Next we briefly discuss packaging examples.

4.1Biofuels

Fargione et al. (2008) stirred the biofuel debate by introducing the concept of “biofuel carbon debt”. The increasing demand for biofuels was initially increasing the production of biofuels from food crops such as corn, sugarcane, soybeans, and palms. As a result, land in undisturbed ecosystems, especially in the Americas and Southeast Asia, was being converted to biofuel production as well as to crop production (indirect land use change) when existing agricultural land was diverted to biofuel production (direct land use change). This land clearing releases huge amounts of CO_2 as a result of burning or microbial decomposition of organic carbon stored in plant biomass and soils over a long time. Fargione et al. (2008) called the amount of CO_2 released during the first 50 years of this process the “carbon debt” of land conversion. Over time, biofuels can afterwards repay this carbon debt if their production and combustion have less net GHG emissions compared to the life-cycle emissions of the fossil fuels they displace. Their conclusion was that “converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels in Brazil, Southeast Asia, and the United States creates a “biofuel carbon debt” by releasing 17 to 420 times more CO_2 than the annual greenhouse gas (GHG) reductions that these biofuels would provide by displacing fossil fuels. In contrast, biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials incur little or no carbon debt and can offer immediate and sustained GHG advantages.” As policies throughout the world were increasingly promoting biofuels, this publication significantly influenced reconsidering these policies.

4.2 Vehicles

Hawkins et al. (2013)it is important to address concerns of problem-shifting. In addition, while many studies have focused on the use phase in comparing transportation options, vehicle production is also significant when comparing conventional and EVs. We develop and provide a transparent life cycle inventory of conventional and electric vehicles and apply our inventory to assess conventional and EVs over a range of impact categories. We find that EVs powered by the present European electricity mix offer a 10% to 24% decrease in global warming potential (GWP developed a very comprehensive and transparent LCA study comparing the life cycle environmental performance of conventional and electric vehicles. They found that “EVs powered by the present European electricity mix offer a 10% to 24% decrease in global warming results relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km. However, EVs exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts, largely emanating from the vehicle supply chain. Results are sensitive to assumptions regarding electricity source, use phase energy consumption, vehicle lifetime, and battery replacement schedules”. For EVs production impacts thus become more important while for conventional cars the use phase is by far the most important phase. The environmental performance of the

EV can be improved by extending the lifetime of the EV, reducing the impacts of the EV production supply chain and by wider adoption of cleaner electricity sources.

4.3 Packaging

Packaging has been the starting topic of LCA in the late sixties and early seventies (Hunt and Franklin 1990), and continued to be a popular topic throughout the history of LCA. Within packaging, beverage packaging studies have been the most popular topic(Bundesamt für Umweltschutz 1984; Hocking 1991; Basler & Hofman Ingenieure und Planer 1974; Bernstad Saraiva et al. 2016; Keoleian et al. 2004).

Although we know that LCA is and has been applied to packaging systems a lot, we don’t find LCAs so much published in scientific journals. We analyzed the overall use of LCA measured by counting English scientific articles in Elsevier’s Scopus using the keywords “life cycle assessment” or “life cycle analysis” excluding “life cycle cost analysis”, and compared that to an analysis of the scientific literature using the keywords “life cycle assessment AND packaging” or “life cycle analysis AND packaging” excluding “life cycle cost analysis”. The results are shown in Fig.5.

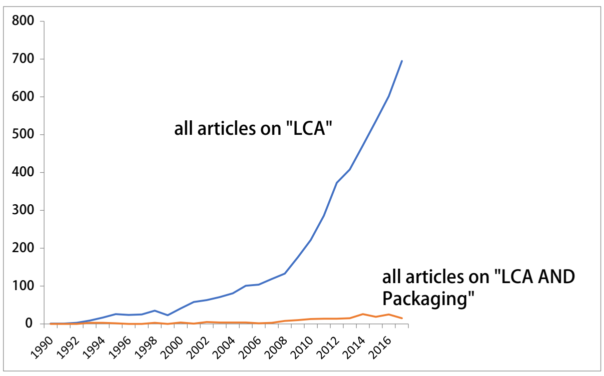

Fig.5 Number of English scientific articles identified in Elsevier’s Scopus (November 2018) on “LCA” and “LCA and Packaging”
图5 截止2018年11月Elsevier的 Scopus数据库中发表的关于LCA和包装LCA的相关文献数量对比

On the one hand it is quite surprising to find that there are so few LCAs on packaging published in the scientific literature. On the other hand, Rubik and Frankl (2000) showed that about 20% of LCA studies performed by business is related to packaging but as businesses are often not too keen on publishing their results, let alone in scientific journals, it might explain why we see so little packaging examples in scientific literature.

LCAs have often been criticized and raised fierce debates. This is not difficult to understand since products are the basis of our economy and no business likes negative environmental marketing for his product. Moreover, products constitute also complex systems as shown above, and the results of LCA studies can unfortunately not be validated by easy, independent measurements. Recently, Schweitzer et al.(2018) reported on misuse of LCAs in food packaging policy. A key point raised by these authors is increasingly getting attention right now: LCAs don’t yet address littering and related marine plastic soup problems. Marine littering is one of the biggest challenges of these times, and it is for a large part related disposed packaging.Recently, representatives of the LCA community published the so-called Declaration on Marine Litter in LCA(Sonnemann and Valdivia 2017) calling for methods to address the problem of marine litter in LCA. There is no solution yet, but projects aiming for new methods are ongoing (for example, https://fslci.org/medellindeclaration/ andhttps://quantis-intl.com/wp-content/uploads/2018/03/ocean_plastics_pollution_quantis_ea_2018.pdf). It is important to realize that LCA is not a ‘supertool’ and that we should communicate impacts (including contributions to the plastic soup) separately in addition to LCA results in the meantime.

The great pacific garbage patch is one of today’s biggest challenges. All societal stakeholders need to do their share in solving this problem. Governments can, for example, implement full deposit systems on all beverage containers, and ban all avoidable single-use plastic applications. But science and industry can also make a difference here by working with the highest priority on fully biodegradable alternatives for single-use plastic applications that cannot be avoided.

5 Conclusions

LCA has a history that dates back to the late sixties and early seventies. Packaging has always been a popular topic of LCA studies throughout its history. Since that time, LCA has developed into a mature method that is currently widely applied by consultants, industry and governments as part of environmental policies (Sonnemann et al. 2018; EC 1994).

LCA is quite resource intensive and needs a lot of data and work. Nevertheless, an increasing number of databases is becoming available (see for example: https://nexus.openlca.org/ and https://www.lifecycleinitiative.org/applying-lca/lca-databases-map/) and also China is working on its national database (http://www.ike-global.com/products-2/lca-software-ebalance). Data are crucial and data quality and uncertainty highly determines the quality and uncertainty of LCA results together with allocation choices(Henriksson et al. 2015c; Mendoza Beltran et al. 2018; Henriksson et al. 2015b).

LCA is an assessment method and drives on assumptions and choices, and it may thus be tempting in some cases to tweak assumptions and choices to suit particular interest. This is also called the "hired gun" effect. To avoid this, assumptions and choices need to be made explicitly, where possible and relevant in consultation with stakeholders, and transparently reported. Conclusions also need to account for key assumptions and choices made, together with a proper reflection on data availability and quality.

Finally, an increasing number of LCA studies is dealing with scenarios exploring possible configurations of new technology systems, comparing their potential impacts to existing technologies. Such studies are very relevant, particularly if performed ex-ante, parallel to the technology development trajectory, and supporting the technology developer to assess whether developments are on the 'right' track. This is a promising future direction of LCA and can underpin claims of environmental sustainability with proof … or not.

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