1
Introduction

To date life cycle assessment (LCA) is a method defined by the international standards ISO 14040 and 14044 to analyse environmental aspects and impacts of product systems. Therefore, the introduction of the methodology in Chapters 2–5 relates to these standards. As a prelude, the scope and development of the methodology are introduced here.

1.1
What Is Life Cycle Assessment (LCA)?

1.1.1
Definition and Limitations

In the introductory part of international standard ISO 14040[1] serving as a framework, LCA has been defined as follows:

> *LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.*

A similar definition of LCA was adopted as early as 1993 by the Society of Environmental Toxicology and Chemistry (SETAC)[2] in the 'Code of Practice'.[3]

Similar definitions can also be found in the basic guidelines of[4] DIN-NAGUS as well as in the 'Nordic Guidelines'[5] commissioned by Scandinavian Ministers of the Environment. Those deliberate limitations of LCA to analysis and interpretation of *environmental impacts* have the consequence that the method is restricted to only quantify[6] the *ecological* aspect of sustainability (see Chapter 6). The exclusion

1) ISO (1997).
2) Foundation year 1979.
3) SETAC (1993a).
4) DIN-NAGUS (1994).
5) Lindfors *et al.* (1995).
6) Klöpffer (2003, 2008).

Life Cycle Assessment (LCA): A Guide to Best Practice, First Edition.
Walter Klöpffer and Birgit Grahl.

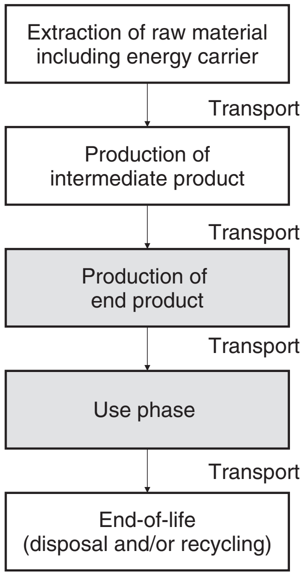

Figure 1.1 Simplified life cycle of a tangible product.

of economical and social factors distinguishes LCA from product line analysis (PLA) (Produktlinienanalyse) and similar methods.[7] This separation was made to avoid a method overload, being well aware that a decision, for example, in the development of sustainable products, cannot and must not neglect these factors.[8]

1.1.2
Life Cycle of a Product

The main idea of a *cradle-to-grave* analysis, that is, the life cycle of a product, is illustrated in a simplified manner in Figure 1.1. Usually, the starting point for building a product tree is the production of the end product and the use phase. Further diversification of the boxes in Figure 1.1 into singular processes, the so-called unit processes, as well as the inclusion of transports, diverse energy supply, co-products, and so on, turn this simplistic scheme, even with simple products, into very complex ‘product trees’ (diverse raw materials and energy supply, intermediate products, co-products, ancillary material, waste management including diverse disposal types and recycling).

Interconnected unit processes (life cycle or product tree) form a *product system*. The centre is a product, a process, a service or, in the widest sense, a human

7) Projektgruppe Ökologische Wirtschaft (1987) and O’Brien, Doig and Clift (1996).
8) Klöpffer (2008).

activity.[9] In an LCA, systems that serve a specific *function* and therefore have a specified performance are analysed.

Therefore, the quantified performance (avail) of a product system is the intrinsic standard of comparison (reference unit). It is the sole correct basis for the definition of a 'functional unit'.[10]

1.1.3
Functional Unit

Besides the *cradle-to-grave* analysis (thinking in terms of systems, life cycles or production trees), the functional unit is the second basic term in an LCA and is therefore to be explained here.

The function of a beverage packaging, for example, is – besides shielding of the liquid – above all, transportability and storability. The functional unit is most frequently defined as the provision of 1000 l liquid in a way to fulfil the technical aspects of the performance. This function can, for instance, be mapped with different packaging specifications (the following examples are arbitrarily chosen):

- 5000 0.2 l[11] pouches
- 2000 0.5 l reusable bottles of glass
- 1000 1 l single-use beverage carton
- 500 2 l PET (polyethylene terephthalate) single-use bottles.

Thus, for a comparison of packaging systems, the life cycle of 5000 pouches, 2000 reusable glass bottles, 1000 cardboards and 500 2 l PET bottles, which are four product systems that roughly fulfil the same function, needs to be analysed and compared.

Slight variations in performance (convenience, e.g. weight, user friendliness, aesthetics, customer behaviour, suitability as advertising medium or other side effects of packaging systems) are not important in this simplistic example. It is, however, important to note that *systems* (not products) with matchable functions are compared.[12] This is the reason why tangible products (goods) can also be compared with *services*, as long as they have the same or a very similar function. Within an LCA, products are defined as goods and services. As with goods, services require energy, transport, and so on. Therefore, it is possible to define services as systems and compare them with tangible products on the basis of equivalent function by means of the functional unit.

9) SETAC (1993a).
10) Fleischer and Schmidt (1996); see ISO 14040 (2006a).
11) $1\,l = 1\,dm^3$.
12) Boustead (1996).

1.1.4
LCA as System Analysis

LCA is based on a simplified system analysis. The simplification consists of an extensive linearisation (see system boundaries and cut-off criteria in Section 2.2). Interconnections of parts of the life cycle of a product that always exist in reality lead to extremely complex relationships in the modelling, which are most difficult to handle. There are, nevertheless, possibilities to handle the formation of loops and other deviations from the linear structure, for example, by an iterative approach or matrix calculus.[13)]

Example

LCA deals with the comparison of product systems, and not of products. This means the following:

Within the product segment 'towel dispenser', for example, paper towels and cotton rolls are two possible variations. The cotton roll needs to be cleaned to fulfil its function. This means, the cleansing process (detergent, water and energy consumption) is part of the product system and must surely be considered. In addition, washing machines must be applied for cleaning.

Has the production of washing machines to be considered as well?

Their production requires, for example, steel. Steel is made from iron ore that needs to be transported, and so on. It is obvious that limitations need to be set, because every small product is linked to the entire industrial system. On the other hand, nothing essential shall be omitted.

System analysis and the meaningful selection and definition of system boundaries are therefore important and labour-intensive tasks within every LCA.

The main advantage of the life-cycle approach 'from cradle to grave' lies in its ability to easily detect the shifting of environmental burdens, the so-called *trade-offs*, which may, for example, occur owing to material substitutions. Therefore, it is of no use to seemingly solve an environmental problem if, later, in different life cycle stages or environmental media, the same or additional problems occur. The same applies when an unreasonable energy or resource consumption may be connected with the substitution. These kind of activities do not solve the problem at its base.

It is not arguable that in rare cases, especially those of health hazards (e.g. substitution of hazardous substances), such suboptimal decisions may be applicable.

13) Heijungs (1997) and Heijungs and Suh (2002).

Example

As fossil resources diminish, substitution of the raw material base with renewable resources is an objective of science and development. For example, variants of loose-fill packaging chips made of polystyrene and potato starch[14)] have been investigated through LCA. As the resources used and the production processes of both materials fundamentally differ, a thorough analysis of the product systems is necessary. For instance, on the one hand, the overall agricultural system including growth, maintenance and harvest needs to be considered during the production of renewable base products; on the other hand is the crude oil drilling or mining. Other life cycle stages of the loose-fill packaging systems differ fundamentally as well, depending on the raw material base. It cannot be decided at first sight whether substitution of the raw material base may have an ecological advantage for a product system.

1.1.5 LCA and Operational Input–Output Analysis (Gate-to-Gate)

There is always a risk of problem shift when system boundaries that are too restrictive have been chosen. This is often the case when only operational input–output analyses have been conducted (frequently misused terms are *ecobalance of the enterprise, corporate-LCA* or *ecobalance* without additional explanation).

If, for instance, the system boundary is set equal to the fence around a factory (gate-to-gate), the fundamental concept of LCA is not satisfied: Neither the production of pre-products nor the disposal of end products is considered; the same is applicable with transports (e.g. *just in time*), outsourcing and parts of waste management activities (e.g. municipal waste water sewage plants).

Example

Pseudo improvement by outsourcing

A manufacturer of fine foods intended to not only advertise his products for taste and salubriousness but also for environmental aspects. For this purpose, data concerning energy and water consumption were gathered in an operational input–output analysis (gate-to-gate), which allowed the allocation of on-site environmental burdens to the production of different salads. It was striking that potato salad had an immense water supply. The reason was that potatoes, usually covered by earth, had to be washed. This waste water was then assigned to the potato salad. Some weeks later, the water supply per kilogramme salad had drastically diminished. This was not due to a technical innovation at the cleaning

14) BIfA/IFEU/Flo-Pak (2002).

plant but due to outsourcing of the washing to another enterprise. For this reason, washing water was not a factor anymore in the operational input–output analysis within the system boundary of the investigated site.

Nevertheless, operational input–output analyses are useful for many applications, for example, as data bases in environmental management systems.[15)]

A simple consideration shows that operational input–output analyses also provide data bases for the LCA of products: Every production process, for example, the production of 500 g of potato salad in a screw cap glass jar, takes place at a specific company, at a specific site. If data, for example, for energy and water consumption of the system '1000 screw cap glasses, each containing 500 g potato salad supplemented by cucumber, egg and yoghurt dressing' have to be procured, every company that is part of the production and transportation of the packed product as well as businesses involved in the waste management of the used packaging must have analysed their processes in such a way that the data can be allocated to the product under investigation. This is not simple: an agricultural corporation generally does not only produce milk and a dairy not only yoghurt; the manufacturer of glass jars provides glasses for diverse customers, and so on. If, however, all companies involved in manufacture, distribution and end-of-life management of the product (supply chain) had data from their specific operational input–output analysis in a product-related format, these results could be merged. Nevertheless, product-related data acquisition is not common practice in operational input–output analyses.

Coupling of such operational input–output analyses along the life cycle of products would provide the possibility of LCA chain management.[16)] Companies that are part of a product system could explore and realise potentials for the optimisation in co-operation. There is the hope that, in this way, life cycle thinking and, in the end, also life cycle acting, may emerge (*Life Cycle Thinking* and *Life Cycle Management* – LCM).

1.2 History

1.2.1 Early LCAs

LCA is a relatively recent methodology, but not as recent as many believe. Approaches to life cycle thinking have already been reported in early literature. The Scottish economist and biologist Patrick Geddes has developed as early as in

15) Braunschweig and Müller-Wenk (1993), Beck (1993) and Schaltegger (1996).
16) Udo de Haes and De Snoo (1996, 1997).

the 1880s a procedure that can be considered as precursor for Life Cycle Inventory (LCI).[17] His interest focused on energy supply, especially on coal.

The first LCAs in the modern sense were conducted around 1970, termed *Resource and Environmental Profile Analysis* (*REPA*) at Midwest Research Institute in the United States.[18] As with nearly all early LCAs or 'proto-LCAs',[19] these were an analysis of resource consumption and emissions caused by product systems, the so-called inventories without impact assessment. To date, such studies are called *Life Cycle Inventory studies*.[20] The new methodology was first applied to compare beverage packaging. The same applies for the first LCA conducted in Germany[21] in 1972 under the leadership of B. Oberbacher at Battelle-Institute in Frankfurt, Main. The new method – originally proposed by Franklin and Hunt, USA – additionally captured costs (among others, those of disposal procedures). Interestingly, light polyethylene pouches, already in use at that time, obtained best results, similar to the results in more recent studies.[22]

Further, early LCAs were conducted by Ian Boustead in the United Kingdom[23] and Gustav Sundström in Sweden.[24] In addition, Swiss studies,[25] which can be considered as proto-LCAs, date back to the 1970s. They were conducted at the EMPA in St. Gallen; see memories of Paul Fink, former director of the EMPA.[26]

1.2.2
Environmental Policy Background

Why did the development of LCA start in the early 1970s? At least two reasons can be determined:

1. Rising waste problems (therefore, studies on packaging)
2. Bottlenecks in energy supply and acknowledgement of limited resources.

While the former issue (i) was implemented into a just-emerging environmental policy by the authorities in most developed countries, public awareness of the latter (ii) was raised by the bestseller *The Limits to Growth* (the report to the Club of Rome).[27] Something must have been in the air because the book caused a sensation in 1972, the year of its publication. Did a change of paradigm occur? Was the throw-away mentality of post-war generation suddenly under scrutiny?

The theory in the 'Club of Rome' study was confirmed by reality through the first oil crisis in 1973/1974. Although the study was over-pessimistic with regard to the exhaustion of oil resources, it demonstrated the vulnerability of an industrial

17) Quoted by Suter and Walder (1995).
18) Hunt and Franklin (1996).
19) Klöpffer (1994, 1997, 2006).
20) ISO (1997).
21) Oberbacher, Nikodem and Klöpffer (1996).
22) Schmitz, Oels and Tiedemann (1995).
23) Boustead (1996) and Boustead and Hancock (1979).
24) Lundholm and Sundström (1985, 1986).
25) BUS (1984).
26) Fink (1997).
27) Meadows *et al.* (1972, 1973).

society which, to a great extent, relies on crude oil. To date, nothing has changed concerning this aspect, on the contrary.

System analysis, well known only to specialists, had its breakthrough as a commonly accepted method. The International Institute for Applied Systems Analysis (IIASA) at Laxenburg, Vienna, was founded. In Germany, car-free Sundays happened; an atmosphere of departure emerged, to date unimaginable, with a plethora of ideas on how to develop alternative energy sources as well as on how to use conventional forms of energy more efficiently. Some of them were realised, but most of them were not (yet).

1.2.3
Energy Analysis

With this mainly energy-political background, it is not surprising that, from the theoretical side, *energy analysis or process chain analysis* was developed first, which today is an important integral part of the LCI[28] (see Chapter 3). In Germany, this development was mainly promoted by Professor Schäfer at the Technical University Munich[29] and in industry before.[30] The (primary) energy demand summarised through all stages of the life cycle is called *cumulative energy demand* (*CED*).[31] It used to be an important part of the LCI in the time of the proto-LCAs and is still used in LCAs.

By way of political solutions to the oil crisis in the 1980s, interest in LCA with respect to its precursors declined but experienced an unexpected upswing at the end of the decade.

1.2.4
The 1980s

Studies on LCA were sparse in the first half of the 1980s in the German language area. Exceptions are the study of BUS, later Federal Agency for Environment, Forestry and Agriculture, Bern,[32] which has already been named, a thesis by Marina Franke at TU Berlin[33] and the development of PLA by the Ökoinstitut.[34] PLA surpasses LCA as it is based on a needs assessment (NA) analysing the usefulness of a product and consumer behaviour. Here, the product-related environmental analysis is complemented by the investigation of social aspect (SA) and economical aspect (EA) of the product system:

$$PLA = NA + LCA + SA + EA$$

with LCA = inventory + environmental impact assessment.

28) Mauch and Schäfer (1996).
29) Mauch and Schäfer (1996) and Eyrer (1996).
30) Kindler and Nikles (1979, 1980).
31) VDI (1997).
32) BUS (1984).
33) Franke (1984).
34) Projektgruppe Ökologische Wirtschaft (1987).

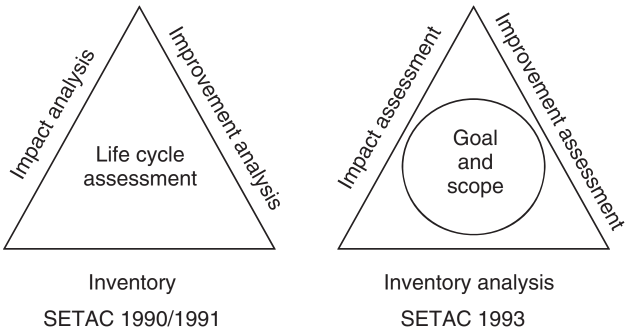

Figure 1.2 The SETAC-triangle in LCA guidelines ('code of practice').[35]

PLA therefore comprises all three aspects of sustainability according to the Brundtland Commission[36] (see Chapter 6) and Agenda 21,[37] which was adopted at the UNO World Conference in Rio de Janeiro, 1992.

1.2.5 The Role of SETAC

A strong upswing in the interest in LCA in Europe and North America – where the terms 'life cycle analysis' and 'life cycle assessment', originated – led to two international conferences that can be considered as the starting point for the newer development[38]:

In 1990, a workshop was organised by SETAC in Smugglers Notch, Vermont, on *A Technical Framework for Life Cycle Assessment*. One month later, a European workshop took place on the same topic in Leuven.[39]

In Smugglers Notch, the famous LCA triangle was conceptualised, and later persiflaged as 'holy triangle' (Figure 1.2). From 1990 to 1993 SETAC and SETAC Europe were leading agents in the development, harmonisation and early standardisation of LCA. Their reports[40] are part of the most important information sources concerning the development of the methodology. In the German-speaking part they were only equalled by the Swiss *Ecobalance of Packaging Materials 1990*,[41] updated in 1996 and 1998.[42] The UBA (Umweltbundesamt) (Berlin) study in 1992 also had a great influence.[43] A French adoption of history and methodology, *L'Ecobilan*, was published at about the same time.[44] The development of LCA in the United

35) SETAC (1993a).
36) World Commission on Environment and Development (1987).
37) UNO (1992).
38) Klöpffer (2006).
39) Leuven (1990).
40) SETAC (1991, 1993a,b, 1994), and SETAC Europe (1992).
41) BUWAL (1991).
42) BUWAL (1996, 1998).
43) UBA (1992).
44) Blouet and Rivoire (1995).

States[45] and in Japan[46] was presented in special issues of the *International Journal of Life Cycle Assessment*.

The special contributions from the Centre of Environment of University Leiden (Centrum voor Milieukunde Leiden, CML) under the leadership of Professor Helias Udo de Haes were appreciated in a study on sociology of scientific knowledge by Gabathuler[47] and in a supplementary issue of the *International Journal of Life Cycle Assessment*.[48] The greatest achievement of CML was, without any doubt, a stronger focus on the ecological aspects of LCA, compared to the earlier more technical ones. Nevertheless, a prior Swiss LCA had already featured a simple method of impact assessment.[49] In practice, the CML method tended to overemphasise chemical releases in the impact assessment. At the same time – due to the absence of generally adhered indicators – it underestimated the impacts of the overuse of natural resources such as minerals, fossils, biota and land[50] (see Chapter 4).

1.3 The Structure of LCA

1.3.1 Structure According to SETAC

A first attempt to structure LCA was by the SETAC triangle of 1990/1991 already quoted (Figure 1.2)

Inventory in the context of LCA (LCI) means material and energy analysis of the examined system from cradle to grave. The resulting inventory table contains a list of all material and energy inputs and outputs (see Figure 1.3 and Chapter 3).

These numbers of LCI need an ecological analysis or weighting. Inputs and outputs are sorted according to their impact on the environment. Thus, for instance, all releases into the air causing acid rain are aggregated (see Chapter 4). This procedure was formerly called *Impact Analysis* by SETAC, and later *Impact Assessment*.

The interpretation of the data procured in LCA has already been postulated in Smugglers Notch. It was called *Improvement Analysis*, later renamed *Improvement Assessment*. The introduction of this component was regarded as great progress because the interpretation of the data was conducted according to specific rules. The Environmental Agency Berlin (UBA)[51] has included this task in 1992 in its recommendation to the conduct of LCAs as an option. The rules for interpretation were later modified during the standardisation process of ISO (see Section 1.3.2). To date this phase is named *interpretation*[52] (see Figure 1.4).

45) Curran (1999).
46) Special issue Japan: Finkbeiner and Matsuno (2000).
47) Gabathuler (1998).
48) Huijbregts *et al.* (2006).
49) BUS (1984).
50) Klöpffer and Renner (2003).
51) German: Umwelbundesamt (UBA).
52) ISO (1997).

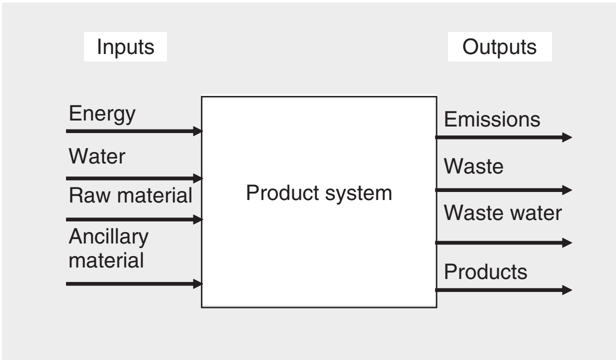

Figure 1.3 Analysis of matter and energy of a product system.

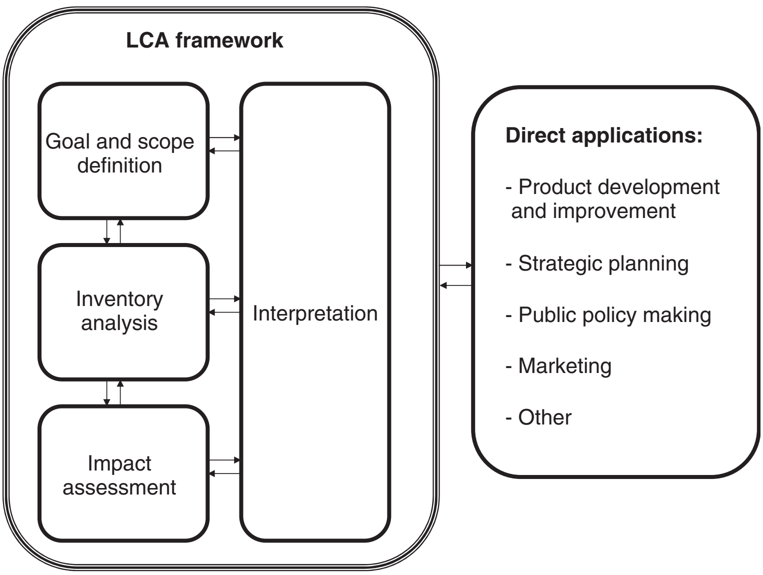

Figure 1.4 LCA phases according to ISO 14040:1997/2006.

1.3.2 Structure of LCA According to ISO

To date, the structure developed by SETAC has essentially been maintained by ISO[53] with the exception of *Improvement Assessment*, which was replaced by *Interpretation*. The optimisation of product systems was not adapted as standard content by ISO, but was listed besides other applications of the standard. The structure of the international standard is depicted in Figure 1.4.

53) ISO (1997, 2006a).

The phases of LCA have been renamed, compared to earlier structures, and the following terms are now internationally mandatory:

- Goal and Scope Definition
- Life Cycle Inventory Analysis
- Life Cycle Impact Assessment
- Interpretation.

The arrows in Figure 1.4 allow an iterative approach that is often necessary (see Chapter 2). Direct *applications of an LCA* lie out of scope of the standardised components of an LCA. This makes sense because, besides foreseeable applications during the standardisation process, others were developed in practice and have been summarised as 'other applications'. Examples can be found in Table 1.1.

1.3.3 Valuation – a Separate Phase?

A special status is attached to the former component *valuation*,[54] which has not been assigned in the standardised structure. A valuation is always necessary when the results of a comparative LCA are not straightforward. A trade-off of system A against system B needs to be made when, for example, the former has lower energy consumption, but on the other hand has releases of substances leading to water eutrophication and to the formation of near-ground ozone: What is of greater importance? For these decisions, subjective and/or normative notions of value are necessary, common in daily life, for example, during purchase decisions.[55] For this reason, a valuation based on exact scientific methods cannot be made. Therefore, it was proposed by SETAC Europe at Leiden 1991[56] to introduce *valuation* as a component of its own. This proposition was seized by UBA Berlin[57] and by DIN-NAGUS[58] later on. However, because subjective notions of value cannot be standardised, a methodology was developed to support the process of conclusion. In the SETAC 'Code of Practice'[59] these methodological rules were subordinated to the phase 'Impact Assessment'. No changes were made by the standardisation process of ISO: Methodological rules are integrated into the phase 'Impact Assessment'[60] (see Section 4.3). The final survey of results that leads to a conclusion[61] is supposed to take place in the final phase of an LCA, 'Interpretation'[62] (see Chapter 5).

54) In German: Bewertung.
55) DIN-NAGUS (1994), Giegrich *et al.* (1995), Klöpffer and Volkwein (1995) and Neitzel (1996).
56) SETAC Europe (1992).
57) Schmitz, Oels and Tiedemann (1995).
58) (DIN NAGUS (1994) and Neitzel (1996).
59) SETAC (1993a).
60) ISO (2000a).
61) Grahl and Schmincke (1996).
62) ISO (2000b).

Table 1.1 Examples of early LCA applications according to ISO 14040.

Application	Query	Project
Environmental law and – policy	Packaging regulation	Beverage packaging[a]
	Waste oil regulation	Waste oil recovery[b]
	Genetically modified organisms (GMO)	GMO in agricultural LCA[c]
	Agriculture	Weed control in viticulture[d]
	PVC	PVC in Sweden[e]
	Public procurement	Cost-benefit analysis of environmental procurement[f]
	Integrated product policy	EuP directive[g]
Comparison of products	Surfactants	ECOSOL LCAs[h]
	Beverage packaging	Comparison of packagings[i]
	Food packaging	Comparison of packagings[j]
	Floor coverings	ERFMI survey[k]
	Insulating materials	Insulation of buildings[l]
Communication	Consumer consultation	ISO type III declaration[m]
	Chain management	PCR[n]: electricity, steam, water[o]
	Ecological building	EPD[p]: building products[q]
	Carbon footprint	PCR: product declaration[r]
		Carbon-neutral enterprise[s]
Waste management	Concepts of disposal	Graphic papers[t]
	Recycling	Plastics[u]
Enterprise	Ecological valuation of business lines	Environmental achievement of an enterprise[v]

[a] Schmitz *et al.* (1995) and UBA (2000b, 2002).
[b] UBA (2000a)
[c] Klöpffer *et al.* (1999).
[d] IFEU/SLFA (1998).
[e] Tukker Kleijn and van Oers (1996).
[f] Rüdenauer *et al.* (2007).
[g] Kemna *et al.* (2005).
[h] Stalmans *et al.* (1995) and Janzen (1995).
[i] IFEU (2002, 2004, 2007) and Detzel and Böß (2006).
[j] IFEU (2006) and Humbert *et al.* (2008).
[k] Günther and Langowski (1997, 1998).
[l] Schmidt *et al.* (2004).
[m] Schmincke and Grahl (2006).
[n] Product category rules.
[o] Vattenfall (2007).
[p] Environmental product declaration.
[q] Deutsches Institut für Bauen und Umwelt (2007).
[r] Svenska Miljöstyrningsrådet (2006) and BSI (2008).
[s] Gensch (2008).
[t] Tiedemann (2000).
[u] Heyde and Kremer (1999).
[v] Wright *et al.* (1997).
GMO, genetically modified organisms.

In Germany, the discussion on valuation has, during the final years of the 1990s, increased to such an extent that

- the former Minister of the Environment, Angela Merkel,[63] joined the discussion;
- the association of the German Industry (BDI) published a widely noticed policy brief[64] and
- UBA Berlin elaborated an ISO-conformal valuation methodology.[65]

1.4 Standardisation of LCA

1.4.1 Process of Formation

LCA standards ISO 14040 and 14044 belong to the ISO 14000 family concerning various aspects of environmental management (Figure 1.5).

The committee responsible for DIN in Germany is the NAGUS.[66] Similar committees existed in other countries. National propositions are brought together in the Technical Committee 207 (TC 207) of the ISO at international level. All nations that are members of TC 207 by their standardisation organisations participate and international standards are developed. Generally, this process takes several years.

LCA standardisation by national standardisation organisations[67] and, above all, by ISO has been conducted since the beginning of the 1990s with great effort.[68] This was difficult to achieve because individual phases of LCA – in particular, Impact Assessment and Interpretation – were still under technical/scientific development. On a national level, only two standardisation organisations have developed their own LCA standards before ISO 14040 was enacted: AFNOR (Association Française de Normalisation, France) and CSA (Canadian Standards Association, Canada). To date, a singular internationally accepted standardisation is aimed at promoting international communication, and this is why France and Canada have stepped into the ISO process.

The most important standardisation activity for LCA is therefore conducted by ISO. European Standardisations (Comité Européen de Normalisation, CEN) and their subsequent national organisations adapt ISO regulations and translate them into their individual languages (CEN 14040 standards are available in three

63) Merkel (1997).
64) BDI (1999).
65) Schmitz and Paulini (1999).
66) Normenausschuss Grundlagen des Umweltschutzes (Environmental Protection Standards Committee).
67) e.g. CSA (1992), DIN-NAGUS (1994) and AFNOR (1994).
68) ISO (1997, 1998, 2000a,b), Marsmann (1997), Saur (1997) and Klüppel (1997, 2002).
69) Normenausschuss Grundlagen des Umweltschutzes (NAGUS) in DIN Deutsches Institut für Normung e. V. (2013).

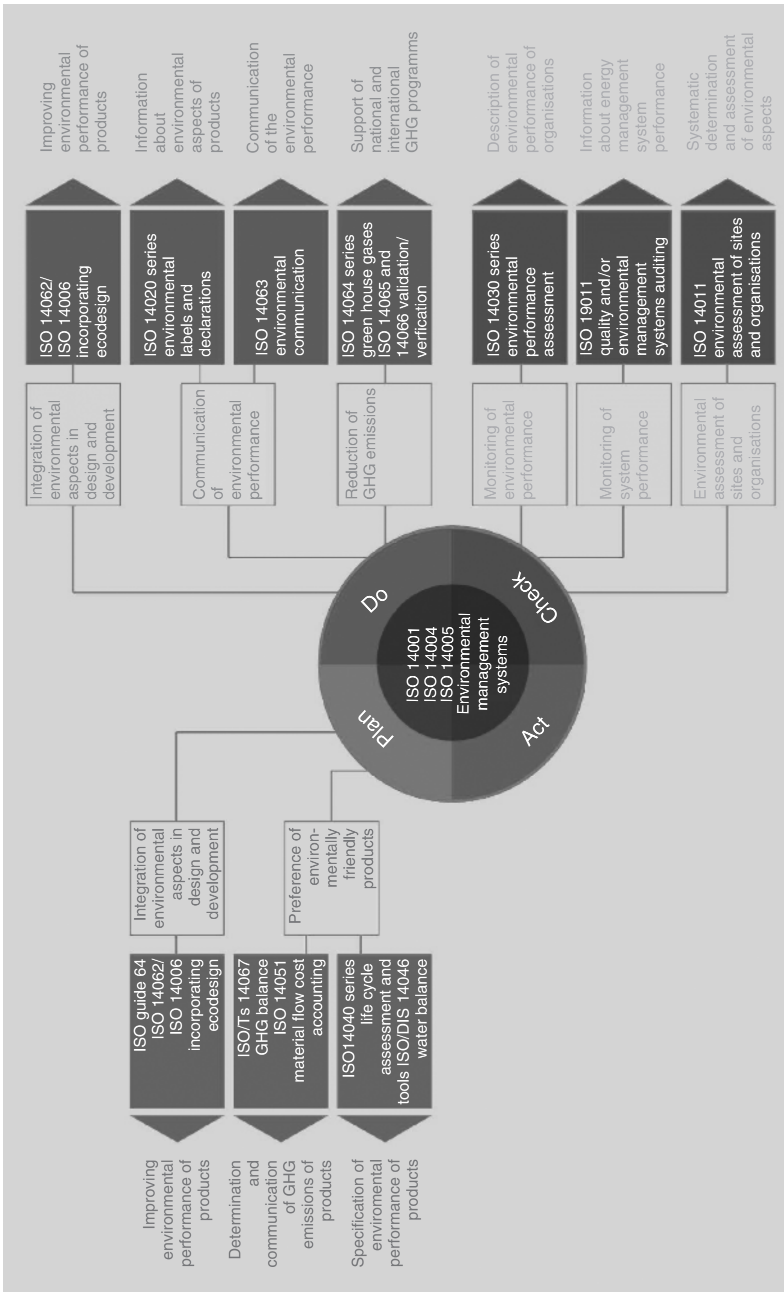

Figure 1.5 ISO 14000 Model.[69]

official languages, English, French and German). DIN-NAGUS and similar national committees' activity is focused on preliminary work for the ISO work groups, the work-out and harmonisation of supplementary comments, the translation of ISO texts and supplementary standardisation for specifically national issues.

The first series of the international LCA standards closely followed the structure of Figure 1.4:

- ISO 14040 LCA – principles and framework; international standard 1997
- ISO 14041: LCA – goal and scope definition and inventory analysis; international standard 1998
- ISO 14042: LCA – life cycle impact assessment; international standard 2000;
- ISO 14043: LCA – interpretation; international standard 2000.

1.4.2
Status Quo

A revision of the international standards in 2001–2006 led to restructuring without any essential technical changes.[70] The basic standard continues to be called ISO 14040[71] with no mandatory directives. Directives have been summarised in a new standard ISO 14044[72] comprising all four LCA phases in Figure 1.4.

Two technical reports (TRs) and two technical specifications (TSs) have been added:

- ISO/TR 14047:2012 Illustrative example on how to apply ISO 14044 to impact assessment situations
- ISO/TS 14048:2002 Data documentation format
- ISO/TR 14049:2012 Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
- ISO/TS 14067:2013 Carbon footprint of products – Requirements and guidelines for quantification and communication.

Two new TS and one TR are under preparation:

- ISO TS 14071 Critical review processes and reviewer competencies – Additional requirements and guidelines to ISO 14044 (see Section 5.5)
- ISO TS 14072 Additional requirements and guidelines for organisations
- ISO/AWI TR 14073 Water footprint – Illustrative examples on how to apply ISO 14046.

TRs and TSs are non-mandatory documents but meant for help and support.

The methodology of LCA according to ISO 14040/44 is also the basis for a new standard under preparation aiming at the calculation of one specific impact (called *footprint* analogue to 'Carbon Footprint' in ISO/TS 14067 (see above)):

70) Finkbeiner *et al.* (2006).
71) ISO (2006a).
72) ISO (2006b).

- ISO 14046 Water footprint – Requirements and guidelines.

A detailed review of ISO standards in the context of ISO 14040 has been recently published by Finkbeiner (Finkbeiner, 2013).

As many as 24 national standardisation organisations participated in the first round of ISO standardisation talks and another 16 had the observer status. The final vote led to an overall acceptance of 95%. *LCA is therefore the only internationally accepted standardised method for analysing environmental aspects and potential impacts of product systems*.

Chapters 2–5 focus on the objective content of individual phases of LCA, their advantages and shortcomings.

1.5
Literature and Information on LCA

Until the mid-1990s, almost only 'grey' LCA literature was available. Meanwhile, a series of books have been published.[73] Papers from national and international organisations provide essential information to LCA, mostly SETAC and SETAC Europe,[74] The Nordic Council,[75] US EPA (United States Environmental Protection Agency),[76] UBA Berlin[77] BUS/BUWAL Bern,[78] the European Environment Agency Copenhagen (EEA)[79] and the European Commission (EC).[80]

Recently, the Joint Research Centre 'Institute for Environment and Sustainability' of the EC (Ispra, Italy) published the ILCD Handbooks (*International Reference Life Cycle Data System*), which can be downloaded for free (*http://lct.jrc.ec.europa.eu/pdf-directory/ILCDHandbook.pdf*).

Since 1996, *The International Journal of Life Cycle Assessment* has been published by ecomed publishers Landsberg/Lech and Heidelberg and, since the beginning of 2008, by Springer, Heidelberg. Current information can be found at *http://www.springer.com/environment/journal/11367*.

The journal has rapidly developed into a leading publication organ of the promotion of LCA methodology.[81] *International Journal of Life Cycle Assessment* is also available electronically, and quite a number of articles as well as open access papers can be downloaded free of charge.

Further journals with regular contributions to LCA are the *Journal of Industrial Ecology* (MIT Press, part of Wiley-Blackwell since 2008), *Cleaner Production* (Elsevier)

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73) Schmidt and Schorb (1995), Curran (1996), Eyrer (1996), Fullana and Puig (1997), Wenzel, Hauschild and Alting (1997), Hauschild and Wenzel (1998), Badino and Baldo (1998), Guinée *et al.* (2002), Baumann and Tillman (2004), Klöpffer and Grahl (2009) and Curran (2012).
74) Fava *et al.* (1991, 1993, 1994), SETAC (1993a), SETAC Europe (1992), Huppes and Schneider (1994), Udo de Haes (1996) and Udo de Haes *et al.* (2002).
75) Lindfors *et al.* (1994a,b, 1995).
76) EPA (1993) and SAIC (2006).
77) (UBA (1992, 1997), Klöpffer and Renner (1995) and Schmitz and Paulini (1999).
78) BUS (1984), BUWAL (1990, 1991, 1996, 1998).
79) Jensen *et al.* (1997).
80) EC (2010).
81) Heinrich (2013).

and *Integrated Environmental Assessment and Management*, IEAM (SETAC Press). Increasingly, *Environmental Science and Technology* (ACS) also publishes LCA-related papers. However, *International Journal of Life Cycle Assessment* is the only journal entirely devoted to LCA.

Other specialised journals also publish LCA literature. In 1995, for instance, the comprehensive ECOSOL – Surfactants-LCI of the European surfactants producers, conducted by Franklin Associates, published two issues of the journal *Tenside, Surfactants and Detergents*.[82]

A detailed treatment of all aspects of LCA and related methods such as Social Life Cycle Assessment (SLCA), Life Cycle Sustainability Assessment (LCSA) and LCM is being published in the LCA compendium (Springer 2014ff).[83] This work is conceived for 10 base volumes, and subvolumes as needed.

The significance of publication for propagation and discussion of methods, theories and results of research cannot be overestimated. Especially within new branches of science, peer reviews judge scientific validity on a day-to-day basis.[84] They serve as fine adjustments for the great principles of epistemology with special focus, according to Popper, on falsifiability,[85] which cannot be examined unambiguously for LCA. The scientific character of LCA is discussed critically in the following chapters dealing with the phases of LCA.

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82) Janzen (1995), Klöpffer, Grießhammer and Sundström (1995), Berna, Cavalli and Renta (1995), Stalmans *et al.* (1995), Hirsinger and Schick (1995a,b,c,d), Thomas (1995), Berenbold and Kosswig (1995), Postlethwaite (1995a,b), Schul, Hirsinger and Schick (1995) and Franke *et al.* (1995).
83) Klöpffer and Curran (2014) and Klöpffer (2014).
84) Klöpffer (2007).
85) Popper (1934).

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