LCA Compendium – The Complete World of Life Cycle Assessment
Series Editors: Walter Klöpffer · Mary Ann Curran

Walter Klöpffer *Editor*

Background and Future Prospects in Life Cycle Assessment

Springer

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LCA Compendium - The Complete World of Life Cycle Assessment

Series Editors
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Aims and Scope
Life Cycle Assessment (LCA) has become the recognized instrument to assess the ecological burdens and human health impacts connected with the complete life cycle (creation, use, end-of-life) of products, processes and activities, enabling the assessor to model the entire system from which products are derived or in which processes and activities operate. Due to the steady, world-wide growth of the field of LCA, the wealth of information produced in journals, reports, books and electronic media has made it difficult for readers to stay abreast of activity and recent developments in the field. This led to the realization of the need for a comprehensive and authoritative publication.

The *LCA Compendium* Book Series will discuss the main drivers in LCA (SETAC, UNEP/SETAC Life Cycle Initiative, etc.), the strengths and limitations of LCA, the LCA phases as defined by ISO standards, specific applications of LCA, Life Cycle Management (LCM) and Life Cycle Sustainability Assessment (LCSA). Further volumes, which are closely related to these themes will cover examples of exemplary LCA studies ordered according to the importance of the fields of application. They will also present new insights and new developments and will keep the whole work current. The aim of the series is to provide a well-structured treatise of the field of LCA to give orientation and guidance through detailed descriptions on all steps necessary to conduct an LCA study according to the state of the art and in full agreement with the standards.

The *LCA Compendium* Book Series anticipates publishing volumes on the following themes:

- Background and Future Prospects in Life Cycle Assessment
- Goal and Scope Definition in Life Cycle Assessment
- Life Cycle Inventory Analysis (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation, Critical Review and Reporting in Life Cycle Assessment
- Applications of Life Cycle Assessment
- Special Types of Life Cycle Assessment
- Life Cycle Management (LCM)
- Life Cycle Sustainability Assessment (LCSA)
- Life Cycle Assessment Worldwide

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Background and Future Prospects in Life Cycle Assessment

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Foreword

The regulatory approaches to control point-source releases of waste that were used in the 1970s and 1980s were instrumental in creating a change for improved environmental management. However, because these were based on a single stage in the product's life cycle (e.g., production, use, or disposal), or a single issue (e.g., individual chemical limits), they did not always lead to a net environmental benefit.

With the improvement in the treatment of air and water emissions and waste from manufacturing operations, there was recognition that end-of-pipe treatment can only go so far. Additional examination of what enters the end-of-pipe treatment led to the development of pollution prevention and pre-treatment programs. These programs were influenced by a combination of government regulations and organizations who realized that they could save money by preventing pollution. 3M's Pollution Prevention Program (3Ps), for example, was a landmark program initiated in the 1980s which has saved 3M nearly one billion USD since the 1980s. As well, it has prevented emissions and waste from entering the environment.

At the same time, society realized that attempting to solve our environmental problems went beyond the manufacturing facilities. We realized that products (and packaging) were creating an enormous amount of solid waste after their useful life was over. We also learned that how much electricity used in the use stage of a product influenced the amount of mercury being released into the environment by coal power plants, to provide another example. Many other observations were occurring by organizations and leaders who were asking whether there were other ways to more completely understand that full impact of society on the planet. Life cycle assessment (LCA) surfaced as one of those emerging tools that was advanced enough to fill the gap to allow us to more fully understand the risks, opportunities, and trade-offs among the many stages of product system life cycle and the multiple impacts that could occur at each stage.

In 1990, the Society of Environmental Toxicology and Chemistry (SETAC) sponsored an international workshop (in Smugglers Notch, Vermont, USA) where the term 'life cycle assessment' was coined. SETAC, the International Organization for Standardization (ISO), and the United Nations Environment Programme (UNEP) have since established and advanced the understanding and use of the LCA framework, methodology, and data.

LCA, as governed by the ISO standards 14040 and 14044, has become a recognized instrument to assess the ecological burdens and human health impacts connected with the complete life cycle (creation, use, end-of-life) of products, processes and activities, enabling the practitioner to model the entire system from which products are derived or in which processes and activities operate.

We have seen a dramatic shift in the development and application of LCA over that last 20 years, as part of the modern era of LCA. Our initial efforts were to develop and enhance basic methodological elements, e.g., goal and scope definition, inventory analysis, impact assessment, and data quality and availability. These efforts are continuing. However, over the last 5–8 years, we have seen an increase in the demand for life cycle information as shown by green building, retail, electronic, and purchasing expectations. With this demand there is the need to make the life cycle information available to non-LCA specialists in professional functions, like procurement, innovation, marketing, etc. While LCA will continue to be a tool for specialists, life cycle information will be embedded in existing decision support tools (e.g., CAD systems) and business practices (e.g., the stage gate process). Mainstreaming of life cycle information is upon us and its use will grow steadily to allow us to speed and scale up the transition to more sustainable product systems.

This book series on LCA is the first work of its kind—a major undertaking to create a comprehensive collection of writing aimed at illuminating all aspects of LCA. Volumes in the series will discuss such topics as the main drivers in LCA (SETAC, UNEP/SETAC Life Cycle Initiative, etc.), the strengths and limitations of LCA, the gaps and research needs in LCA, LCA phases as defined by ISO standards, specific applications of LCA, Life Cycle Management (LCM) and Life Cycle Sustainability Assessment (LCSA). Written by international LCA experts, this book series will be an invaluable resource for those involved in assessing environmental performance through all stages of goods and services.

I encourage you to read, learn and apply the information and knowledge in the chapters and volumes as they are released. Use them as a reference to apply life cycle assessment frameworks, methodologies, information, data and insights. Let's work together to mainstream the use of life cycle information to improve the sustainability of product systems.

James A. Fava

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Acknowledgments

The *LCA Compendium* Book Series complements *The International Journal of Life Cycle Assessment*, which has been published by Springer since 2008. Since this is the first volume of the *LCA Compendium*, we first acknowledge and appreciate that Springer accepted to publish this complementary work, the first of its kind in the field of Life Cycle Assessment. In particular we thank Paul Roos (Environmental Sciences) for recognizing the possibility of such an extensive publication and for his guidance in bringing it to life. We also thank Betty van Herk for organizing the preparation of the manuscripts.

Next, we would like to thank all the volume editors who have committed to editing further volumes and the many authors who agreed to write specifically defined chapters on all important issues related to LCA.

Our next thank you is to Almut B. Heinrich, former managing editor of *The International Journal of Life Cycle Assessment*, who is acting as the managing editor for this book series.

Turning to this volume, we thank our fellow contributors: James Fava, Matthias Finkbeiner, Guido Sonnemann, Sonia Valdivia, Almut B. Heinrich, and the many co-authors, first for their clear-sighted willingness to cooperate on this new book series and second, for devoting their time in sharing their expertise and experience in the individual chapters.

Walter Klöpffer and Mary Ann Curran
Series Editors—*LCA Compendium*

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Chapter 1
Introducing Life Cycle Assessment and its Presentation in 'LCA Compendium'

Walter Klöpffer

Abstract This chapter spans the time from the early days of Life Cycle Assessment—LCA (the time of the so-called 'proto-LCAs' between about 1970 and 1990), until recent trends of simplified/streamlined LCAs, the footprint specifications (carbon footprint, water footprint) and Life Cycle Sustainability Assessment—LCSA.

Important benchmarks along this span are the harmonisation of LCA by SETAC (Society of Environmental Toxicology and Chemistry) and the standardisation of LCA by ISO (International Standardisation Organisation).

The basic discussions within SETAC occurred between 1990 and 1993.

The first attempt to develop a suitable LCA-structure was achieved during the SETAC workshop 'A Technical Framework for Life Cycle Assessments' in August 1990, held in Smugglers Notch, Vermont, USA. The LCA-structure, the famous 'SETAC triangle', consisted of three components: Inventory—Impact Analysis—Improvement Analysis.

SETAC revised the framework during the Sesimbra workshop in 1993. It was the merit of SETAC to initiate a standardisation process which culminated in the 'Guidelines for Life-Cycle Assessment: A Code of Practice'. The LCA-structure, again a triangle, now included four components: Goal Definition and Scoping—Inventory Analysis—Impact Assessment—Improvement Assessment.

This structure was only slightly modified by the ISO standardisation process: The fourth phase 'Improvement Assessment' (formerly 'Improvement Analysis') was replaced by 'Interpretation'.

After the harmonisation of LCA by SETAC, the International Standardisation Process was soon initiated (Autumn 1993 in Paris), but it took seven years for the first series of LCA standards to be published (ISO 14040, ISO 14041, ISO 14042, ISO 14043).

The successful first series of ISO LCA standards superseded the SETAC 'Code of Practice', the Nordic guidelines and several national standards and became the uncontested model of an environmental life cycle standard. The series 14040 ff was revised once and condensed into two standards 14040 and 14044 (2006).

The four-phase structure was not altered

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This chapter discusses the four phases of the LCA-structure by SETAC and ISO which are the subject of four volumes—Goal and Scope Definition in LCA; Life Cycle Inventory Analysis; Life Cycle Impact Assessment; Interpretation, Critical Review and Reporting. The remaining volumes follow a structure outside the ISO-framework: Applications of LCA, Special Types of LCA, Life Cycle Management, and Life Cycle Sustainability Assessment.

Keywords Carbon footprint · Goal and scope definition in LCA · Harmonisation of LCA by SETAC · Improvement analysis · Interpretation · ISO (International Standardisation Organisation) · Life cycle assessment—LCA · Life cycle impact assessment—LCIA · Life cycle inventory analysis—LCI · Life cycle sustainability assessment—LCSA · Proto-LCAs · SETAC (Society of Environmental Toxicology and Chemistry) · SETAC triangle · Simplified LCA · Standardisation of LCA by ISO · Streamlined LCA · Water footprint

1 What is Life Cycle Assessment?

Life Cycle Assessment (LCA) is a science-based, comparative analysis and assessment of the environmental impacts of product systems. It is distinguished from other environmental assessment methods by two constitutive and unique features: the analysis from 'cradle-to-grave' and the 'functional unit'. Together, the application of these features allows the comparison of product systems fulfilling the same, or very similar, purpose. In order to explain the basic principles of LCA and the most important terms, we paraphrase the relevant international guidelines and standards (SETAC 1993; ISO 1997, 2006a). 'Cradle-to-grave' means that all the important steps in the life cycle of a product are included in the analysis, namely the extraction of raw materials from the environment (soil, water, air), the production of materials and the final products, their use and waste removal or recycling. Any transportation that occurs across these steps is also accounted for. The 'products' are defined as 'goods and services' in all relevant standards. The final products in services are intangible but need the same processes, energy sources, etc. as tangible products or goods; the definition of the life cycle has to be modified accordingly case-by-case.

The concept of 'life cycle' used in LCA is always the physical life cycle, rather than the 'marketing life cycle' which starts with planning, R&D and design, introducing a product into the market, producing, selling, leasing, etc. until the product is taken out of the market. This definition can also be used for goods and services where a functional unit can be defined. In an environmental LCA it is hard to confuse the two related terms. If, however, a Life Cycle Costing—LCC[1] is to be added

[1] A pre-guideline or framework of LCSA was published by UNEP/SETAC at the end of 2011. The final version has been published in 2012 at: http://lcinitiative.unep.fr. It contains the three-pillar equation:

LCSA = LCA + LCC + SLCA
(SLCA = Social LCA).

to the LCA, great care has to be taken in order to avoid confusion. The type of LCC compatible with LCA should better be called 'Environmental LCC' to show that it adheres to the physical life cycle (Hunkeler et al. 2008, Klöpffer 2008, Swarr et al. 2011).

The 'functional unit' is the basis of comparison of product systems (goods *and* services) if they provide the same or a very similar function (hence the name). It describes quantitatively the function of the product systems to be compared, e.g. the packaging of 1000 L of a beverage and its transport to the point of sale, recycling and waste removal (Klöpffer and Grahl 2009, 2014). It is usual praxis in LCA to neglect small differences of products (e.g. aesthetic ones), as long as they have no or only minor influence on the environmental impacts of the product system. A clear definition of the product systems to be investigated, including their boundaries with the environment and the rest of the technosphere, is of paramount importance; it has to be provided in the Goal and Scope Definition.

Underpinning all terms introduced so far means understanding that products in the sense of LCA are product *systems* rather than the material product we may use or the service we may hire. Behind these obvious aspects of products to be observed in daily life there is a multitude of upstream and downstream processes[2], intermediate products, transport processes, packaging and energy use, to name just a few. Downstream from the use phase[3] starts the end-of-life (EOL) phase (waste management and recycling). In general, even experienced life cycle practitioners, if confronted with a new problem, are not aware of the full complexity of the 'product tree'[4], the 'supply chain'[5] and the EOL. This has two consequences: first, the construction of the product tree has to be done on the basis of best available information and may require some research; and, second, the system has to be tailored, and small amounts of residual inputs and outputs have to be cut off. Metaphorically speaking, the product tree has to be cut out of the dense network of the technosphere. In comparing two or more products, their system boundaries[6] have to be defined in a similar way.

To bring together all product-related terms, we may call LCA (to be precise: the Life Cycle Inventory—LCI) a simplified system analysis. To visualize such systems, the smallest units for which data are available—the unit processes—are shown as boxes which are connected to other unit processes from which they obtain inputs and to which they transfer substances, materials and energy. Releases into the environment (emissions) leave the system. There are also imports from

[2] Upstream processes: toward the 'cradle', downstream processes: toward the 'grave'.

[3] Use phase: e.g. driving a car for a certain time; the use phase is the centre of most life cycles defined in LCA.

[4] Product tree: the most common form of graphical presentation of product life cycles.

[5] Supply chain: usual, but misleading (since suggesting linearity) designation of the upper part of a product tree or branches thereof; modern economies are characterised by a high degree of work-sharing.

[6] The system boundary separates the system to be studied from the rest of the technosphere and the environment.

the environment in the form of oil and coal, gases, minerals, water, radiation from the sun, etc. The systems studied in LCI are part of the technosphere, whereas the environment is receiving the releases and provides inputs at the interface between the two spheres. Specific interactions between environment and technosphere are quantified in an LCA-phase called Life Cycle Impact Assessment—LCIA and discussed in the final phase Interpretation.

The success of LCA as an environmental assessment tool lies in its broad applicability, to all product systems for which data can be generated and the possibility to compare the results with competing (or improved) systems. This offers a great opportunity for improving products and the technosphere (thus improving the environment), but it has also led to producing false or at least exaggerated environmental product claims. The misuse potential was especially high in the time of the 'proto-LCAs' (see Sect. 2) and led to the harmonisation of the different early methods by SETAC and finally to the standardisation by ISO (Klöpffer 2006, 2012).

2 LCA—How it Came About

2.1 The Early Time

The first LCAs—the author called them 'proto-LCAs' (Klöpffer 2006)—were performed between about 1970 and 1990, when the harmonisation of the early life cycle methods developed in North America and Europe started (Fava et al. 1991). Even these proto-LCAs presented the two most important features discussed in Sect. 1: system comparison by functional unit and cradle-to-grave analysis. They consisted of a life cycle inventory (LCI) and sometimes a rudimentary form of impact analysis. The emphasis of the early LCAs was on energy saving and resource conservation rather than on pollution. This can be seen in the designation of the proto-LCAs chosen by Franklin Associates Ltd (FAL): Resource and Energy Profile Analysis (REPA) (Hunt et al. 1992). The history of this method dates back to the late 1960s when Franklin and Hunt worked at Midwestern Research Institute (MRI), as related by the two pioneers in an invited personal account in the first issue of Int J Life Cycle Assess (Hunt and Franklin 1996). According to this story, the first REPA study was performed for the Coca Cola Company; the commissioner of the study, Harry Teasley, evidently contributed to the method development with ideas of his own. FAL has performed hundreds of REPAs in the following decades and still exists as division of a larger consultancy (ERG).

The first Franklin-type proto-LCA in Europe was performed in the early 1970s at Battelle Institut e.V. (Frankfurt am Main) about the comparative assessment of beverage containers (Oberbacher et al. 1996; Oberbacher 1975). The inventory ('proto-LCI') was already well developed, and even an economic analysis, a kind of life cycle costing (LCC) was added to this life cycle study which was classified by the authors as a system analysis without a name of its own. The importance of this work was recognised at once but did not immediately lead to additional research contracts … until 1988 when it helped the author, who was only marginally involved in the original study, to get his first LCA project (Klöpffer 1989). It finally opened the door to an international cooperation with Battelle Memorial Institute (Columbus, Ohio, USA) and the Society of Environmental Toxicology and Chemistry (SETAC).

It should be noted that the first LCA PhD dissertation in Germany was performed at the Technical University Berlin (Franke 1983), later to become one of the centres of LCA research. Related activities occurred and are still going on at the University of Stuttgart which can be considered the cradle of PE International.

In England, Ian Boustead started related life cycle work in the early 1970's (Boustead 1996), again using bottles for liquids (milk) as first study objects. His work rapidly extended into industrial systems, where the scarcity of data soon turned out as a bottle neck. He started a huge data collection effort which culminated in a first book (Boustead and Hancock 1979) on data useful for extending Life Cycle Thinking into a quantitative analysis. Another lasting result of this pioneering work has been the creation of a vast commercial data bank for LCA practitioners. With the advent of modern LCA (Sects. 2.2 and 2.3), numerous LCI data collections for commodities, especially for polymers, were created by Boustead (e.g. Boustead 1993). Similar to other pioneers who approached LCA from an engineering perspective, he never supported or practiced life cycle impact assessment methodology.

The role of Switzerland as a leading LCA power was also founded in the 1970's (Fink 1997). The leading organisations at that time were EMPA[7] and the University of St. Gallen. The proto-LCAs were called 'Ökobilanz' and this is still the official German name for LCA. As in the UK, data collection for the most important packaging materials was initiated by the Swiss Federal Office for the Environment (BUS 1984). The update (Habersatter and Widmer 1991) was of great influence in the whole German-speaking LCA community. It already contained a rudimentary impact assessment.

Ruedi Müller-Wenk tried to improve the industrial praxis (economy) by inclusion of environmental protection and life cycle thinking (Müller-Wenk 1978). The combination of the different strings of thought and practice ultimately led to the typical Swiss ecobalance method in which the different weighted impacts of product systems are expressed in one figure (Ahbe et al. 1990). This method is still used, after some modifications, in Switzerland (Frischknecht et al. 2009).

The early time of LCA in France is nicely presented by (Blouet and Rivoire 1995). The leading consultant, Écobilan in Paris, contributed early and significantly to the big problem of most inventories: allocation (Heintz and Baisnée 1992; Huppes and Schneider 1994; Ekvall and Tillman 1997; Heijungs and Frischknecht 1998; Curran 2008).

Japan entered the LCA arena around 1990 (Finkbeiner and Matsuno 2000a, b). A biannual series of 'Ecobalance conferences' made the LCA research and praxis done in this country known in the world. As in other countries, a national data bank

[7] Eidgenössische Materialprüfungs- und -forschungsanstalt.

was created as a fundament for the steep increase of the use of LCA around the year 2000.

Last, but not least, two pioneers from Scandinavia have to be mentioned: Gustav Sundström and Allan Astrup Jensen. The former, a civil engineer from Malmö (SE), pioneered the early LCAs of carton packaging (Tetra Pak) (Lundholm and Sundström 1985). Jensen (DK) was strongly involved in the transition from the proto-LCA phase to the harmonised and later standardised LCA. Being convinced that the application of LCAs in industry is more important than academic research about it, he later became the founder of Life Cycle Management—LCM (see Sect. 4.3) as a discipline of its own (Jensen 2007).

James A. (Jim) Fava of the United States has played a leadership role in LCA development at the global level. He was a key promoter of the work conducted under the auspices of SETAC and the early technical workshops on LCA, primarily in the years 1990 through 1993. Later, he was instrumental in forging the UNEP and SETAC alliance to build the UNEP/SETAC Life Cycle Initiative (2002).

2.2 Harmonisation by SETAC

The role of SETAC in the development of LCA is described by Jim Fava in this volume, Chapter 2, and was dealt with earlier by the author to honour Helias Udo de Haes on the occasion of his retirement from CML Leiden (Klöpffer 2006). Although the SETAC structure was slightly modified during the standardisation by ISO, the basic discussions occurred in this scientific society in a relatively short period between 1990 and 1993. The author called this time the 'heroic time of SETAC' (with regard to LCA; see also Jensen and Postlethwaite 2008). SETAC has continued to offer a discussion forum for LCA and related life cycle methods. Together with the United Nations Environment Programme (UNEP), a joint project, the 'UNEP/SETAC Life Cycle Initiative' was founded 2002 (Töpfer 2002) leading to a globalisation of the life cycle methods, above all LCA, Life Cycle Management—LCM (Remmen et al. 2007) and most recently Life Cycle Sustainability Assessment—LCSA (Valdivia et al. 2011). The UNEP/SETAC Life Cycle Initiative is presented in this volume, Chapter 4.

Whereas the proto-LCAs essentially consisted of a life cycle inventory and—frequently, but not always—a rudimentary impact assessment, modern LCAs consist of four components. The first attempt to find a suitable structure was done during the SETAC workshop 'A Technical Framework for Life Cycle Assessments' in August 1990, Smugglers Notch, Vermont (Fava et al. 1991).

This structure, the famous 'SETAC triangle' (Fig. 1.1) consisted of three components:

- Inventory
- Impact Analysis
- Improvement Analysis

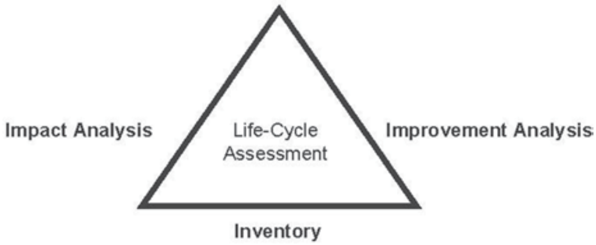

Fig. 1.1 The famous 'SETAC triangle' 1991 (Fava et al. 1991, p. 1)

As stated in the text, most LCAs at that time (typical 'proto-LCAs', see Sects. 1 and 2.1) consisted of inventories only. The component 'Improvement Analysis' was invented during the workshop and experienced a stormy fate in the years to come.

The naming of the 'new' method resulted in Life-Cycle Assessment (LCA). This designation superseded different names used for the proto-LCAs such as life cycle analysis (Ciambrone 1997), ecobalance, REPA (Sect. 2.1) and was taken over by the International Standard Organisation—ISO[8] and The International Journal of Life Cycle Assessment (Sect. 3). The book by Ciambrone, an industry manager and consultant, nicely describes the proto-LCA, many basic techniques of which are still valid today, but neglects any new developments brought about by the harmonisation pioneered by SETAC (Klöpffer 1998a). The book appeared at about the same time when the first modern books on LCA were printed (Curran 1996; Wenzel et al. 1997; Hauschild and Wenzel 1998).

SETAC finally came up with a revised structure during the Sesimbra workshop, immediately after the first SETAC World Conference in Lisbon March/April 1993. The little fishing and recreation village south of Lisbon was to become the birthplace of standardised Life Cycle Assessment: already in August 1993, the 'Guidelines for Life-Cycle Assessment: A Code of Practice' (SETAC 1993) appeared based on the input by 47 invited experts.

The LCA structure, again a triangle (Fig. 1.2), now included four components:

1. Goal Definition and Scoping
2. Inventory Analysis (Materials and Energy Acquisition; Manufacturing; Use; Waste management)
3. Impact Assessment (Ecological Health; Human Health; Resource depletion)
4. Improvement Assessment

How important the inclusion of the (new) first component was, turned out during the ISO process (Sect. 2.3) and after considering the scientific standing of LCA (Sect. 7). Since the second component 'Inventory Analysis' was already well developed in the pre-SETAC time, the new structure focused on 'Impact Assessment' that defined three steps:

- Classification (assigning the data from the inventory table to impact categories)
- Characterisation (aggregation of impacts within the impact categories)

[8] Without hyphen (ISO 1997, 2006a).

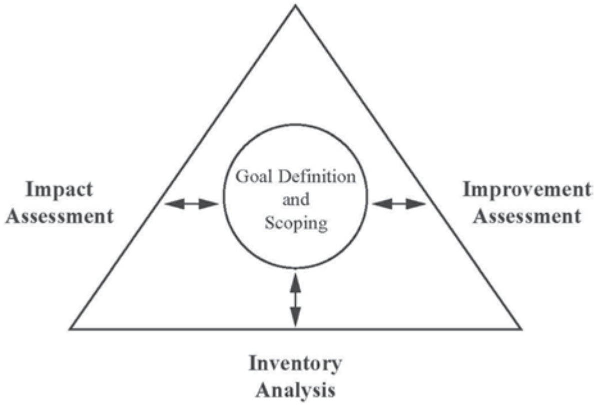

Fig. 1.2 LCA structure in the SETAC 'Code of Practice' of 1993. p 11

- Valuation (weighting of impact results in case of unclear situations, e.g. no clear 'winner' in a comparative LCA)

The terminology used had its origin in a very influential Dutch report which appeared in English in Spring 1993 (Heijungs et al. 1993). Further workshops between Smugglers Notch (1990) and Sesimbra (1993) formed the structure and, of course, the content of LCA.

With commendable foresight, the workshop attendants and editors included the description of a 'peer review' process which should be performed for each LCA:

1. "The peer review process enhances the scientific and technical quality of LCAs; and
2. the process helps to focus study goals, data collection, and provides a critical screening of study conclusions, thereby enhancing study credibility".

Furthermore, an interactive and accompanying peer review was preferred to an 'a posteriori' review for good reasons (Klöpffer 2012).

The success of the 'code of practice' was immediate, and it is not exaggerated to say that it served as 'blue print' for the standardisation by ISO.

2.3 Standardisation by ISO

After harmonisation of LCA by SETAC, the international standardisation process was soon initiated (Autumn 1993 in Paris)[9], but it took seven years until the first series of LCA standards was finished (ISO 1997, 1998, 2000a, 2000b). During that time, the Scandinavian countries prepared LCA guidelines by the 'Nordic Council'

[9] Personal communication by Dr. Manfred Marsmann, chair of ISO/TC 207 'Environmental Management', SC 5 'Life Cycle Assessment', see also (Marsmann 2000).

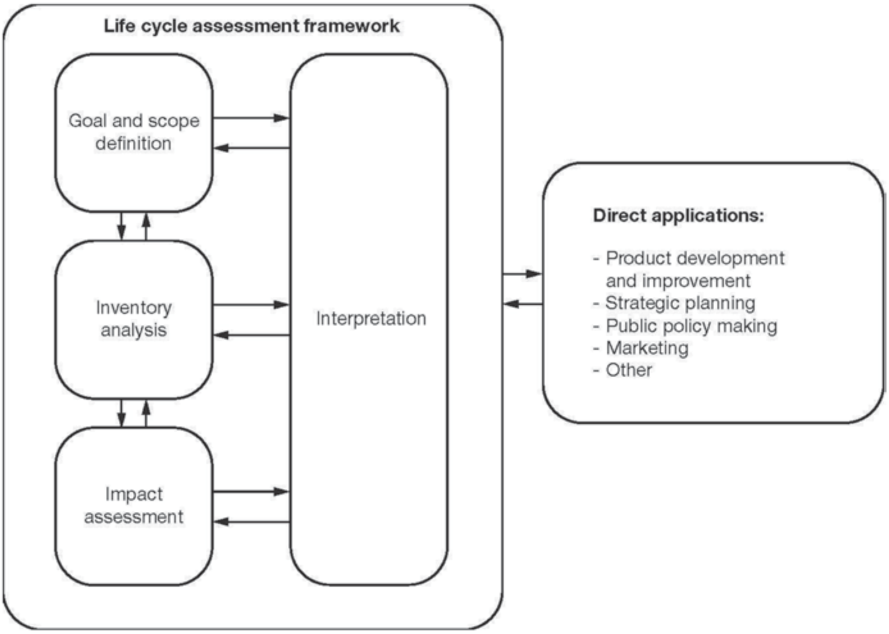

Fig. 1.3 Phases of an LCA (ISO 14040, Fig. 1)

(Lindfors et al. 1995). This and continuing LCA activities by SETAC provided input into the standardisation process.

Fortunately for the LCA community, the first international standard (ISO 14040) dealing with the principles and framework appeared in print already in 1997 (Marsmann 1997). It is this basic LCA standard, later slightly updated (ISO 2006a), which became the 'mother' of all life-cycle based standards and defined the now generally accepted structure of LCA (Fig. 1.3).

The only major change compared to the last scheme by SETAC (see Fig. 1.2) consists in the replacement of 'Improvement Assessment' by 'Interpretation' (see Fig. 1.3). One reason of this retreat behind the ambitious SETAC aim was certainly the fear by industry that an improvement assessment may become obligatory for all LCAs. Another reason for the change is the fact that an LCA may indeed serve different purposes, not only product improvement. Some uses of LCA are given outside the LCA frame in a non-exhaustive list of 'Direct applications':

- Product development and improvement
- Strategic planning
- Public policy making
- Marketing
- Other

The author would add 'teaching and learning' (about environmental burdens connected with product systems) high up in the list as a most useful application of LCA.

A further much commented feature of the ISO framework (already indicated in Fig. 1.2, but only with regard to G&SD) consists in the double arrows symbolizing that the phases may be modified if new aspects emerge during the performance of an LCA. Clearly, a new impact category in LCIA may require a more detailed LCI. Even the goal and scope definition (G&SD) can be altered, but only in written form. This gives the necessary flexibility in performing LCAs and hinders, at the same time, arbitrary changes in G&SD.

Two other aspects have to be considered with regard to the structure of LCA:

- An LCA has to consist of *all* stages. An LC study without Life Cycle Impact Assessment (remember the proto-LCAs!) is a Life cycle inventory study and consists of G&SD, LCI and Interpretation.
- An LCIA has to consist of a *set* of impact categories, one is *not* enough. This means that so called 'Carbon footprint' and other 'footprint' studies with only one impact category are *not* LCAs. Actually they contradict the spirit of LCA fundamentally.
- The norm 14040 has to (*"shall"*) be used in conjunction with ISO 14044, not stand alone and not with another set of requirements (Finkbeiner et al. 2006).
- A 'critical review' (this term superseded the 'peer review' proposed by SETAC) is obligatory for LCA studies to be used for 'comparative assertions' and is recommended, but voluntary, for all other LCAs. The prevention of misuse of the method is high up in the agenda of ISO 14040 ff (Klöpffer 2012).

The very successful first series of ISO LCA standards (ISO 1997, 1998, 2000a, b) superseded the SETAC 'Code of practice' (SETAC 1993), the Nordic guidelines and several national standards as well and became the uncontested model of an environmental life cycle standard. The series 14040 ff was revised once and condensed into two standards 14040 (ISO 2006a) and 14044 (ISO 2006b). The structure, which is our main interest in this chapter, was not altered. Furthermore, the two new standards dealing with the principles and framework of LCA (14040:2006) and with the requirements and guidelines (14044:2006) are coupled together with one "shall" so that the more open standard 14040 cannot be used together with a less demanding set of requirements and still claims to be performed according to ISO. This is extremely important—together with the critical review—for the prevention of misuse of the standards.

2.4 Recent Trends

Whereas the structure of LCA as a science-based method for environmental assessments (presented in Sect. 3) is unchallenged, new developments occurred in recent years (or older ones were rediscovered, as in the case of sustainability assessment) requiring more flexibility and/or detailed requirements than ISO 14040+44 can offer. The changes suggested—and partly are enacted in separate ISO norms (this volume, Chap. 3[10]) or other guidelines—can be classified as belonging to one of the following trends:

- Make it simpler and more flexible
- Reduce the life cycle impact assessment to one impact category
- Expand the environmental LCA to a life-cycle based sustainability assessment

The *first* tendency is as old as modern LCAs; e.g. a SETAC Europe working on simplified LCA came out with definitions and proposals of how to perform such studies—either as a first step to a full LCA or as a stand-alone study (Christiansen 1997). Other studies and workshops also dealt with the problem of 'streamlining' LCA (Curran and Young 1996; Weitz et al. 1996; Hunt et al. 1998; Hochschorner and Finnveden 2003). It seems that the advent of Life Cycle Management—LCM offering a broader palette of methods—the so-called 'tool box' (Wrisberg and Udo de Haes 2002)—took some pressure out of the simplified LCA debate. Furthermore, recent improvements of data bases and LCA software made simplified LCAs feasible at short notice (unfortunately often at the price of a thorough understanding of the systems investigated).

Clearly, any simplified/streamlined LCA studies should be used internally only and upgraded to a full, critically reviewed LCA if a broader public is to be informed (e.g. in marketing) or a scientific publication is planned.

The *second* tendency has become *en vogue* recently, mostly under the name 'footprint', a reminder of a simplified impact assessment long before SETAC defined LCIA. The basic idea was to estimate the area of forest needed to provide the same service as a certain amount of fossil energy. The advantage of such simple parameters is being pictorial. This advantage is lost in modern footprints, the most used being the 'carbon footprint' (CF) which is just another name for the Global Warming Potential (GWP) caused by the Green House Gas (GHG) emissions, mainly carbon dioxide (CO_2), methane (CH_4) and dinitrogen oxide (N_2O). As can be seen, the third gas of this infamous troika does not contain the element carbon (C), and the same is true for sulphur hexafluoride (SF_6), one of the strongest GHG. Despite all deficiencies of the CF concept, we have to deal with it seriously (Finkbeiner 2009) in order to prevent inaccurate calculations of the GWP. An international standard ISO DIS 14067 for CF has been elaborated (ISO 2013), and a British pre-standard PAS 2050 has been available since 2008 (BSI 2008; Sinden 2009). These standards refer to ISO 14040 as basis document and describe in detail how the GWP of products is calculated and how it should be communicated. This goes beyond ISO 14040+44, since the LCA standards do not prescribe for any impact category how the indicators chosen should be determined. So, in the end, CF may enrich LCA, although a stand-alone CF study is not and never will be an environmental LCA.

The same may be true for another 'footprint' which is more innovative and concerns the use of water, especially in countries where water is a scarce resource (Pfister et al. 2009; Berger and Finkbeiner 2010). Water use has been on the list

[10] The international standards as the constitution of LCA: the ISO 14040 series and its offspring by Matthias Finkbeiner.

of life cycle impact categories since the time of LCA harmonisation (Sect. 2.2), but concrete indicators and characterisation factors have not been worked out until recently. This may be due to the fact that LCA has been developed in countries (e.g. Switzerland) in which water scarcity is—in general—no problem at all. The global approach of the UNEP/SETAC Life Cycle Initiative brought water on the LCA agenda. The term 'water footprint' is much used and can be integrated into LCIA—as an impact category belonging to resource use. Water is a renewable abiotic resource and the basis of life on earth; it therefore has many other aspects than as resource for human use.

An 'Ecological footprint' has recently been suggested (SETAC Europe 2011) and may be seen as counterweight against the preponderance of energy—and resource-related impacts in classical LCIAs. This predominance was much more overwhelming, however, in the time of the proto-LCAs (see, e.g., REPA), and the input given by CML[11] in the early 1990s was seen as breakthrough of the environmental sciences in LCA (Gabathuler 1997).

The **third** trend is a come-back of sustainability as the ultimate assessment goal (World Commission on Environment and Development 1987). In the 'three pillar' interpretation of sustainability, environmental, economic and social aspects have to be considered and weighted against each other. In life cycle product assessment, LCA deals with the environmental aspects only (ISO 1997, 2006a). In order to give the full picture, however, an economic and a social life cycle assessment have to be considered with the environmental one (Klöpffer 2003, 2008; Finkbeiner et al. 2010; Valdivia et al. 2012). This concept has been represented as the following non-numerical 'equation':

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA}$$

LCSA: Life Cycle Sustainability Assessment
LCA: (environmental) Life Cycle Assessment
LCC: (environmental) Life Cycle Costing
SLCA: Social Life Cycle Assessment

In order to apply this 'equation' properly, it is essential that the system boundaries of the three life cycle assessments are compatible, ideally equal.

With regard to harmonisation and standardisation, (environmental) LCA is most advanced (ISO 2006a, b) and LCSA has been recognised by UNEP/SETAC only recently (Valdivia et al. 2011), albeit after a long discussion at working group level.

The (environmental) LCC[12] has been defined in a 'SETAC Code of practice' (Swarr et al. 2011), based on a more comprehensive treatise relating to the results of a SETAC Europe LCC working group (Hunkeler et al. 2008).

[11] Centrum voor Milieukunde Leiden.

[12] Stand-alone LCC as a purely economic method is older than LCA and has been used to calculate the true costs of long lived products—including the costs of the use and end-of-life phases in addition to the purchase.

The various approaches to Social Life Cycle Assessment (SLCA) are described in a global guideline (UNEP/SETAC 2009; Benoît et al. 2010). It remains to be seen which approach fits best to LCA and LCC. A quantitative approach based on LCI data and statistics (a kind of poorness index) has been proposed by one of the pioneers of sustainability assessment (Hunkeler 2006). Poorness is at the heart of most social problems and seems to play a similar role in SLCA as energy in LCA: as the common root of several impacts.

3 The Structure of LCA According to ISO 14040 and 14044

The structure of LCA, as defined by the international standards, follows the scheme in Fig. 1.3 (Sect. 2.3). It consists of the four phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

3.1 Goal and Scope Definition

The importance of the Goal and scope definition—G&SD cannot be overestimated. Of course, the goal of an LCA study has to be presented at the beginning of any study as an introduction and gives some information about the background, etc. The far greater role of G&SD in LCA (ISO 2006a, b) rests in the standards which are strict in some items (structure, origin of data, reporting, reviewing) but very loose and open in others, even important ones. In LCIA, for instance, no impact categories, indicators and characterisation factors are prescribed, not even a recommended default list is given. But any LCA study has to include a (well-founded) list of impact categories, one is (for good reasons) not enough, see the ‘footprint’ discussion in Sect. 2.4.

On the other hand, the standards contain many “do not” orders out of the old—and not unfounded—fear of misuse. G&SD defines which rules—under the umbrella of the standards—are applied for a specific study. It is interesting to note that some other standards referencing ISO 14040 as the base standard require a collective G&SD for a group of related products in the form of so-called product category rules (PCR). This is the case for environmental product declaration (EPD), also called ‘Level 3 labelling’ in standard 14025 (ISO 2006c).

Standards are conventions, not laws, although many standards become *de facto* laws, especially in ordinances which explain how a law has to be used in practice. With regard to LCA, methods that deviate from the ISO standards or national standards related to the ISO norms can, of course, be used. It would be unlawful, however, to claim that a specific study has been performed according to ISO and actually was not. This problem is related to the need of critical reviews to be discussed again in Sect. 3.4. The type of critical review (if there is any) should be declared in G&SD including the names of the reviewers, if already known.

3.2 Life Cycle Inventory Analysis

Life Cycle Inventory Analysis—LCI forms the 'core' of any LCA study. It is also considered to be the most quantitative and scientific component (but see Sect. 7). The following steps are a minimum requirement to be fulfilled in comparative LCAs for all systems studied:

- System definition(s) including graphical presentation of the product trees
- Definition of the functional unit and the reference flow(s)[13]
- Data collection (input and output)
- Implementation of the data into the system, applying a predetermined cut-off rule and allocation rules, if appropriate
- Performing the calculations

The first two items refer to the individual study to be performed, either as a stand-alone LCA or—more frequently and interesting—in the form of a comparative LCA. In most cases the practitioners will already have produced rough schemes during the G&SD or even before (e.g. writing a research proposal). Frequently, any commercial or home-made software is used to help in this phase. The definition of the functional unit—needs thinking and cannot be delegated to the computer. What is the main function of the system(s) to be studied and compared? Which details (e.g. purely aesthetic ones) are unlikely to influence the final result and can be neglected in defining the fu? Such are the questions to be answered. Chemical, physical and biological/(eco-)toxicological knowledge is necessary in this phase and, of course, information about the production and waste management/recycling technology has to be collected in a systematic way. Multi-use systems need reliable data about average trip-numbers (e.g. in the case of refillable bottles). Questions about the lifetime of products and duration of services have to be answered.

The third item (data) is split, in most cases, into foreground data (to be supplied by the producer) and background data (mostly provided by generic data, e.g. from public and private data banks). It is essential that the data are representative for the reference-year or -period and for the region in which the processes occur. Rules for establishing data collections have recently been published (Sonnemann and Vigon 2011). Foreground data should be requested from producers (e.g. by using data collection sheets, for example see ISO 2006, annex A) and may be made unidentifiable

[13] The 'reference flow' is the translation of the verbally defined functional unit into technical terms.

for reasons of confidentiality (at least three producers are necessary). In this working phase it should already be known which data are essential for the LCIA stage. Possible data asymmetries should already be known or removed in a following update/correction step (see the double arrow discussion above in Sect. 2.3). A data quality discussion is indispensable.

The last item can be performed by excel-sheet calculations, using commercial software or applying the matrix method (Heijungs and Suh 2002, 2006) which can deal with loops in the product tree. In a recent development of the last method, even LCC can be combined with LCI paving the way to the calculation of LCSA (Heijungs et al. 2012).

The main result of LCI is the inventory table listing all inputs and outputs per unit process and aggregated per fu. For partial LCIs (e.g. cradle-to-factory gate or cradle-to-point of sale instead of cradle-to-grave) in the case of a tangible product (good) the results can also be related to a mass unit (mostly per kg or t = 1000 kg).

3.3 Life Cycle Impact Assessment

The somewhat loose content of Life Cycle Impact Assessment—LCIA mentioned in Sect. 3.1 is not—or not only—the result of the openness of the authors of ISO 14042 (ISO 2000a), the first international standard on LCIA. It was also caused by the fact that the European delegates, advised by SETAC Europe and its LCA steering committee (Udo de Haes et al. 1999a, b, 2002) and the US delegates, also advised by a SETAC (US) working group (Barnthouse et al. 1998) had substantially different ideas about impact assessment in LCA. Essentially the Europeans relied more on the precautionary principle, 'less is better' and 'beyond compliance' (Udo de Haes et al. 1999a, b), whereas the Americans favoured risk assessment and compliance with existing legislation (Barnthouse et al. 1998). The solomonic compromise consisted in accepting the European form, but not the recommended list of impact categories (essentially Heijungs et al. 1993).

The form of LCIA is given by the revised ISO 14040 (ISO 2006a) in a list of mandatory and optional elements:

A—Mandatory elements

- Selection of impact categories, category indicators and characterisation models
- Assignment of LCI results (classification)
- Calculation of category indicator results (characterisation)
- **Category indicator results** (LCIA results, LCIA profile)

B—Optional elements

- Calculation of the magnitude of category indicator results relative to reference information (normalisation)
- Grouping
- Weighting

The first mandatory element should already exist in G&SD, but has to be refined now. Also the LCI results should have been produced in the second stage with regard to the impact categories selected (classified), again final decisions to be taken now. The characterization is a genuine impact assessment element and requires knowledge of the interrelation between releases into the environment or extractions out of the environment and the potential impacts of the releases and extractions. In praxis, however, well established methods are selected by the practitioners, many being available in the software. The methods should be accepted internationally.

Among the optional elements 'normalization' is most frequently used. The results of this element allow discarding impacts contributing only marginally to the environmental damage in the region concerned.

The element 'weighting' *shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public* (ISO 2006b § 4.4.5, Finkbeiner et al. 2006) (see also 'critical review' in Sect. 3.4). In contrast to 'grouping' according to (qualitative) similarities in the pattern of results (UBA 1999), weighting aims at quantitative aggregation of results using weighting factors. The result may be a single number which could be misused, hence the verdict by ISO.

3.4 Interpretation

Interpretation replaced older concepts such as improvement assessment (Sect. 2.2) and/or valuation (much discussed in Germany, see Klöpffer and Grahl 2009, 2014). The reason for declining the latter by ISO was that 'subjective' elements should be avoided in the otherwise scientific (as far as possible objective, see Sect. 6) LCA. Although "subjective is not (necessarily) arbitrary" (Klöpffer 1998b), since international conventions have another weight than opinions held by individuals, the last stage of LCA had to be profoundly changed (ISO 2000b; Lecouls 1999). Interpretation is now the counterpart of G&SD and essentially has to secure that the first three phases of an LCA study are well tuned in and consistent with each other. In addition, the plausibility and accuracy of the results have to be checked with suitable methods, such as sensitivity analyses and/or error calculations.

A critical review by independent experts should be performed for each LCA (optional) (ISO 14044, Sect. 6.2) but has to be done if the study is "intended to be used in comparative assertions intended to be disclosed to the public". In that case, the review has to be performed in the strongest form according to the panel method (ISO 14044, Sect. 6.3).

The structure of the final stage Interpretation is described in ISO 14044, Sect. 4.5 as follows:

- Identification of significant issues
- Evaluation with the elements Completeness check, Sensitivity check and Consistency check
- Conclusions, limitations and recommendations

Reporting (ISO 14044 Sect. 5) and Critical review report (ISO 14044 Sect. 6) are separate items outside of interpretation, but evidently belong to the final phase of any LCA study. The performance of the critical review should preferably be done in the interactive or accompanying mode, as proposed by (SETAC 1993). According to ISO 14040 + 44, it can also be performed 'a posteriori' in most cases, if the draft final report is available (Klöpffer 2012).

4 The Structure of LCA Beyond ISO 14040

A structure beyond the standard which defines the method seems at first sight to be an oxymoron. For this work, however, we need some structure for the elements and methods not (yet) or not fully covered by ISO 14040 ff. The following considerations may serve as guidance to such a structure.

4.1 Applications of Life Cycle Assessment

The applications of LCA lie outside the framework of LCA, see Fig. 2.3. The applications named explicitly in DIN 14040 are:

- Product development and improvement
- Strategic planning
- Public policy making
- Marketing

Actual LCA studies on these and other important topics certainly belong to this field of applied research. In addition to industry with an obvious interest in environmental assessment, also governments and related bodies (e.g. the European Commission) use increasingly LCA for policy making.

Marketing with environmental arguments and claims, based on environmental labels and product declarations (EPDs), is also regulated by the international standard series ISO 14020 ff. The most demanding standard 14025 (ISO 2006c) is firmly based on LCA (ISO 2006a, b) and product category rules (PCR), a kind of common G&SD for groups of similar products.

4.2 Beyond the Classical ISO LCA

In recent years, several methodological developments took place which go beyond the classical LCA, but are considered by the majority of LCA scientists as developments within Life Cycle Assessment. Such developments are, e.g., the consequential LCA (Weidema 2000) and the Input/Output (I/O) LCA and the I/O hybrid LCA (Suh 2003).