

Walter Klöpffer and Birgit Grahl

Life Cycle Assessment (LCA)

A Guide to Best Practice



*Walter Klöpffer and
Birgit Grahl*

Life Cycle Assessment (LCA)

Related Titles

Reniers, G. L. L., Sörensen, K., Vrancken, K. (eds.)

Management Principles of Sustainable Industrial Chemistry

Theories, Concepts and Industrial Examples for Achieving Sustainable Chemical Products and Processes from a Non-Technological Viewpoint

2013
ISBN: 978-3-527-33099-7 (Also available in digital formats)

Hessel, V., Kralisch, D., Kockmann, N.

Novel Process Windows Innovative Gates to Intensified and Sustainable Chemical Processes

2014
ISBN: 978-3-527-32858-1 (Also available in digital formats)

Houson, I. (ed.)

Process Understanding For Scale-Up and Manufacture of Active Ingredients

2011
ISBN: 978-3-527-32584-9 (Also available in digital formats)

Imhof, P., van der Waal, J. C. (eds.)

Catalytic Process Development for Renewable Materials

2013
ISBN: 978-3-527-33169-7 (Also available in digital formats)

Jansen, R. A.

Second Generation Biofuels and Biomass

Essential Guide for Investors, Scientists and Decision Makers

2013
ISBN: 978-3-527-33290-8

Hites, R. A., Raff, J. D.

Umweltchemie

Eine Einführung mit Aufgaben und Lösungen

2014
ISBN: 978-3-527-33523-7

Klöpper, W.

Verhalten und Abbau von Umweltchemikalien

Physikalisch-chemische Grundlagen
Zweite, vollständig überarbeitete Auflage

2012
ISBN: 978-3-527-32673-0

Hochheimer, N.

Das kleine QM-Lexikon

Begriffe des Qualitätsmanagements aus GLP, GCP, GMP und EN ISO 9000
Zweite, vollständig überarbeitete und erweiterte Auflage

2012
ISBN: 978-3-527-33076-8

*Walter Klöpffer and
Birgit Grahl*

Life Cycle Assessment (LCA)

A Guide to Best Practice

WILEY-VCH
Verlag GmbH & Co. KGaA

The Authors

Prof. Dr. Walter Klöpffer

LCA Consult & Review, Frankfurt, Germany
Am Dachsberg 56 E
60435 Frankfurt am Main
Germany

Prof. Dr. Birgit Grahl

Institut für Integrierte Umwelt
Forschung und Beratung
Schuhwiese 6
23858 Heidekamp
Germany

■ All books published by **Wiley-VCH** are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Print ISBN: 978-3-527-32986-1

ePDF ISBN: 978-3-527-65565-6

ePub ISBN: 978-3-527-65564-9

mobi ISBN: 978-3-527-65563-2

oBook ISBN: 978-3-527-65562-5

Cover-Design Formgeber, Mannheim, Germany

Typesetting Laserwords Private Limited, Chennai, India

Printing betz-druck GmbH, Darmstadt

Binding Litges & Dopf GmbH, Heppenheim

Printed on acid-free paper

Contents

Preface *XI*

1	Introduction	1
1.1	What Is Life Cycle Assessment (LCA)?	1
1.1.1	Definition and Limitations	1
1.1.2	Life Cycle of a Product	2
1.1.3	Functional Unit	3
1.1.4	LCA as System Analysis	4
1.1.5	LCA and Operational Input–Output Analysis (Gate-to-Gate)	5
1.2	History	6
1.2.1	Early LCAs	6
1.2.2	Environmental Policy Background	7
1.2.3	Energy Analysis	8
1.2.4	The 1980s	8
1.2.5	The Role of SETAC	9
1.3	The Structure of LCA	10
1.3.1	Structure According to SETAC	10
1.3.2	Structure of LCA According to ISO	11
1.3.3	Valuation – a Separate Phase?	12
1.4	Standardisation of LCA	14
1.4.1	Process of Formation	14
1.4.2	Status Quo	16
1.5	Literature and Information on LCA	17
	References	18
2	Goal and Scope Definition	27
2.1	Goal Definition	27
2.2	Scope	28
2.2.1	Product System	28
2.2.2	Technical System Boundary	29
2.2.2.1	Cut-Off Criteria	29
2.2.2.2	Demarcation towards System Surrounding	32
2.2.3	Geographical System Boundary	34

2.2.4	Temporal System Boundary/Time Horizon	35
2.2.5	The Functional Unit	37
2.2.5.1	Definition of a Suitable Functional Unit and a Reference Flow	37
2.2.5.2	Impairment Factors on Comparison – Negligible Added Value	40
2.2.5.3	Procedure for Non-negligible Added Value	41
2.2.6	Data Availability and Depth of Study	43
2.2.7	Further Definitions	44
2.2.7.1	Type of Impact Assessment	44
2.2.7.2	Valuation (Weighting), Assumptions and Notions of Value	45
2.2.7.3	Critical Review	46
2.2.8	Further Definitions to the Scope	47
2.3	Illustration of the Component ‘Definition of Goal and Scope’ Using an Example of Practice	47
2.3.1	Goal Definition	48
2.3.2	Scope	50
2.3.2.1	Product Systems	50
2.3.2.2	Technical System Boundaries and Cut-Off Criteria	53
2.3.2.3	Demarcation to the System Surrounding	53
2.3.2.4	Geographical System Boundary	54
2.3.2.5	Temporal System Boundary	55
2.3.2.6	Functional Unit and Reference Flow	55
2.3.2.7	Data Availability and Depth of Study	55
2.3.2.8	Type of Life Cycle Impact Assessment	56
2.3.2.9	Methods of Interpretation	57
2.3.2.10	Critical Review	57
	References	57
3	Life Cycle Inventory Analysis	63
3.1	Basics	63
3.1.1	Scientific Principles	63
3.1.2	Literature on Fundamentals of the Inventory Analysis	64
3.1.3	The Unit Process as the Smallest Cell of LCI	65
3.1.3.1	Integration into the System Flow Chart	65
3.1.3.2	Balancing	67
3.1.4	Flow Charts	69
3.1.5	Reference Values	72
3.2	Energy Analysis	74
3.2.1	Introduction	74
3.2.2	Cumulative Energy Demand (CED)	77
3.2.2.1	Definition	77
3.2.2.2	Partial Amounts	77
3.2.2.3	Balancing Boundaries	79
3.2.3	Energy Content of Inflammable Materials	81
3.2.3.1	Fossil Fuels	81
3.2.3.2	Quantification	81

3.2.3.3	Infrastructure	84
3.2.4	Supply of Electricity	85
3.2.5	Transports	88
3.3	Allocation	92
3.3.1	Fundamentals of Allocation	92
3.3.2	Allocation by the Example of Co-production	92
3.3.2.1	Definition of Co-production	92
3.3.2.2	'Fair' Allocation?	93
3.3.2.3	Proposed Solutions	98
3.3.2.4	Further Approaches to the Allocation of Co-products	101
3.3.2.5	System Expansion	102
3.3.3	Allocation and Recycling in Closed-Loops and Re-use	105
3.3.4	Allocation and Recycling for Open-Loop Recycling (COLR)	107
3.3.4.1	Definition of the Problem	107
3.3.4.2	Allocation per Equal Parts	109
3.3.4.3	Cut-off Rule	111
3.3.4.4	Overall Load to System B	113
3.3.5	Allocation within Waste-LCAs	113
3.3.5.1	Modelling of Waste Disposal of a Product	114
3.3.5.2	Comparison of Different Options of Waste Disposal	116
3.3.6	Summary on Allocation	117
3.4	Procurement, Origin and Quality of Data	118
3.4.1	Refining the System Flow Chart and Preparing Data Procurement	118
3.4.2	Procurement of Specific Data	119
3.4.3	Generic Data and Partial LCIs	127
3.4.3.1	Which Data are 'Generic'?	127
3.4.3.2	Reports, Publications, Web Sites	129
3.4.3.3	Purchasable Data Bases and Software Systems	131
3.4.4	Estimations	132
3.4.5	Data Quality and Documentation	133
3.5	Data Aggregation and Units	134
3.6	Presentation of Inventory Results	136
3.7	Illustration of the Inventory Phase by an Example	137
3.7.1	Differentiated Description of the Examined Product Systems	138
3.7.1.1	Materials in the Product System	138
3.7.1.2	Mass Flows of the Product after Use Phase	140
3.7.1.3	Handling of Sorting Residues and Mixed Plastics Fraction	142
3.7.1.4	Recovery of Transport Packaging	143
3.7.2	Analysis of Production, Recovery Technologies and Other Relevant Processes of the Production System	143
3.7.2.1	Production Procedures of the Materials	143
3.7.2.2	Production by Materials	146
3.7.2.3	Distribution	148
3.7.2.4	Collection and Sorting of Used Packaging	148

3.7.2.5	Recovery Technologies (Recycling)	149
3.7.2.6	Recycling of Transport Packagings	151
3.7.2.7	Transportation by Truck	152
3.7.2.8	Electricity Supply	152
3.7.3	Elaboration of a Differentiated System Flow Chart with Reference Flows	153
3.7.4	Allocation	153
3.7.4.1	Definition of Allocation Rules on Process Level	153
3.7.4.2	Definition of Allocation Rules on System Level for Open-Loop Recycling	157
3.7.5	Modelling of the System	157
3.7.6	Calculation of the Life Cycle Inventory	158
3.7.6.1	Input	159
3.7.6.2	Output	165
	References	170
4	Life Cycle Impact Assessment	181
4.1	Basic Principle of Life Cycle Impact Assessment	181
4.2	Method of Critical Volumes	183
4.2.1	Interpretation	184
4.2.2	Criticism	185
4.3	Structure of Impact Assessment according to ISO 14040 and 14044	187
4.3.1	Mandatory and Optional Elements	187
4.3.2	Mandatory Elements	187
4.3.2.1	Selection of Impact Categories – Indicators and Characterisation Factors	187
4.3.2.2	Classification	190
4.3.2.3	Characterisation	191
4.3.3	Optional Elements of LCIA	192
4.3.3.1	Normalisation	192
4.3.3.2	Grouping	197
4.3.3.3	Weighting	200
4.3.3.4	Additional Analysis of Data Quality	201
4.4	Method of Impact Categories (Environmental Problem Fields)	201
4.4.1	Introduction	201
4.4.2	First ('Historical') Lists of the Environmental Problem Fields	202
4.4.3	Stressor-Effect Relationships and Indicators	206
4.4.3.1	Hierarchy of Impacts	207
4.4.3.2	Potential versus Actual Impacts	209
4.5	Impact Categories, Impact Indicators and Characterisation Factors	212
4.5.1	Input-Related Impact Categories	212
4.5.1.1	Overview	212
4.5.1.2	Consumption of Abiotic Resources	214

4.5.1.3	Cumulative Energy and Exergy Demand	220
4.5.1.4	Consumption of Biotic Resources	222
4.5.1.5	Use of (Fresh) Water	224
4.5.1.6	Land Use	227
4.5.2	Output-Based Impact Categories (Global and Regional Impacts)	233
4.5.2.1	Overview	233
4.5.2.2	Climate Change	234
4.5.2.3	Stratospheric Ozone Depletion	240
4.5.2.4	Formation of Photo Oxidants (Summer Smog)	246
4.5.2.5	Acidification	254
4.5.2.6	Eutrophication	261
4.5.3	Toxicity-Related Impact Categories	268
4.5.3.1	Introduction	268
4.5.3.2	Human Toxicity	269
4.5.3.3	Ecotoxicity	279
4.5.3.4	Concluding Remark on the Toxicity Categories	285
4.5.4	Nuisances by Chemical and Physical Emissions	286
4.5.4.1	Introduction	286
4.5.4.2	Smell	286
4.5.4.3	Noise	287
4.5.5	Accidents and Radioactivity	289
4.5.5.1	Casualties	289
4.5.5.2	Radioactivity	290
4.6	Illustration of the Phase Impact Assessment by Practical Example	291
4.6.1	Selection of Impact Categories – Indicators and Characterisation Factors	293
4.6.1.1	(Greenhouse) Global Warming Potential	294
4.6.1.2	Photo-Oxidant Formation (Photo Smog or Summer Smog Potential)	295
4.6.1.3	Eutrophication Potential	296
4.6.1.4	Acidification Potential	297
4.6.1.5	Resource Demand	298
4.6.2	Classification	300
4.6.3	Characterisation	300
4.6.4	Normalisation	305
4.6.5	Grouping	310
4.6.6	Weighting	311
	References	311
5	Life Cycle Interpretation, Reporting and Critical Review	329
5.1	Development and Rank of the Interpretation Phase	329
5.2	The Phase Interpretation According to ISO	331
5.2.1	Interpretation in ISO 14040	331
5.2.2	Interpretation in ISO 14044	331

5.2.3	Identification of Significant Issues	332
5.2.4	Evaluation	333
5.3	Techniques for Result Analysis	334
5.3.1	Scientific Background	334
5.3.2	Mathematical Methods	335
5.3.3	Non-numerical Methods	338
5.4	Reporting	338
5.5	Critical Review	340
5.5.1	Outlook	342
5.6	Illustration of the Component Interpretation Using an Example of Practice	343
5.6.1	Comparison Based on Impact Indicator Results	343
5.6.2	Comparison Based on Normalisation Results	344
5.6.3	Sectoral Analysis	344
5.6.4	Completeness, Consistency and Data Quality	346
5.6.5	Significance of Differences	347
5.6.6	Sensitivity Analyses	348
5.6.7	Restrictions	350
5.6.8	Conclusions and Recommendations	351
5.6.9	Critical Review	351
	References	352

6	From LCA to Sustainability Assessment	357
6.1	Sustainability	357
6.2	The Three Dimensions of Sustainability	358
6.3	State of the Art of Methods	361
6.3.1	Life Cycle Assessment – LCA	361
6.3.2	Life Cycle Costing – LCC	364
6.3.3	Product-Related Social Life Cycle Assessment – SLCA	366
6.4	One Life Cycle Assessment or Three?	368
6.4.1	Option 1	368
6.4.2	Option 2	369
6.5	Conclusions	370
	References	371

Appendix A Solution of Exercises 375

Appendix B Standard Report Sheet of Electricity Mix Germany (UBA 2000, Materials p. 179ff) Historic example, only for illustrative purposes 381

Acronyms/Abbreviations 385

Index 391

Preface

This book is the updated translation of a textbook and monograph written in German language by the same authors.¹⁾ The first version emerged from lectures at the University of Mainz.

The topic of the book, life cycle assessment (LCA), developed from modest seeds in the 1970s and 1980s to become the only internationally standardised method of ecological product assessment. The development entered its decisive phase when the Society of Environmental Toxicology and Chemistry (SETAC) began to harmonise diverse older methods ('proto-LCAs'). This process culminated in 1993 in the publication of the *Guidelines for Life Cycle Assessment: A Code of Practice*, a result of the SETAC Workshop in Sesimbra, Portugal. In the same year started the standardisation by the International Standard Organization (ISO) involving 40 nations, resulting in the famous series of ISO LCA standards 14040ff (1997–2006). The authors of this book followed this development as members of the German mirror group 'Deutsches Institut für Normung-Normenausschuss Grundlagen des Umweltschutzes (DIN NAGUS)', discussing and commenting on the drafts developed by ISO/TC 207/SC 5 (TC, Technical Committee; SC, Sub Committee). In addition, German translations of the standards were checked and improved.

The topic 'valuation' caused heated discussions and turned out to be not consensual – surviving today as an optional element 'weighting' within the phase Life Cycle Impact Assessment (LCIA), and not as originally planned as an LCA phase of its own. Moreover, 'weighting' is strictly prohibited for comparative LCA studies intended to be made available to the public.

The revision of the LCA standards 2006 even enforced this, so that now the intention to use a comparative LCA publicly is sufficient for banning the 'weighting' of results and requiring strict regulations regarding publishing, documentation and critical review (panel method).

The authors have performed several critical reviews together and necessarily studied the standards in greater detail than possibly necessary for academic lectures alone. Most standards use cumbersome wording to some extent, which is why they are not ideally suited as teaching and learning material – a good reason to write this book that is expected to help beginners entering the field of LCA and

1) Klöpffer and Grahl (2009).

also offering advanced readers something new. The LCA standards are written in a spirit which shall prevent any misuse of the method, especially in marketing and advertisement. As a consequence, frequently we read what shall not be done and less details on how a real LCA is to be done correctly. To give an example, in the phase LCIA there is no list of impact categories, not even a default list, not to speak of indicators and characterisation factors. Therefore, LCIA is treated extensively in this book. Even so, no complete picture could be presented since several methods are still in development, cited in many references.

Equally important as reporting the mere facts seemed relating a deeper understanding of the LCA methodology including its limits. The same is true for the environmental problems forming the basis of the impact categories. The most important application of LCA is learning and understanding of environmental problems caused by product systems 'from cradle to grave', that is, from the raw materials to recycling and waste removal, respectively. This learning process cannot start without a good understanding of the processes and can be even worsened by thoughtlessly using software. The modern software offers great help in performing LCAs (hardly to dream of 10 years ago); it should not, however, replace the collection of original ('foreground') data, thorough system analysis, or selection and explanation of the impact categories.

There can be no doubt that LCA as an applied (simplified) system analysis offers much material for theoretical work, enriching the methodology. It is not, however, 'art pour l'art', but should rather achieve the learning effect mentioned above, the results of which should enter decision finding. Ecologically correct decisions during product development will lead to better products in the long range. The application of LCA is therefore of decisive importance. In order to demonstrate this point, the authors divided a 'real' LCA study into four parts, which were assigned to the four phases according to ISO 14040.

1. Goal and scope definition (Chapter 2)
2. Life cycle inventory analysis (Chapter 3)
3. Life cycle impact assessment (Chapter 4)
4. Interpretation (Chapter 5).

This 'real-life' LCA study in German has been provided by the Institut für Energie- und Umweltforschung (IFEU), Heidelberg, by courtesy of the commissioner Fachverband Getränkekarton (FKN), Wiesbaden. The translation of the recorded textual passages has been carried out by the authors of this book. We would like to point out explicitly that this specific LCA study was chosen as example for purely didactic reasons. A specific product system is always more descriptive compared to a theoretically constructed one. Specific conclusions included in the example LCA do not belong to the learning goal set by the authors of this book.

Textbooks on LCA are rare in any language, but even in English we remember only one, originating from Sweden.²⁾ We hope that this book will contribute

2) Baugmann and Tillmann (2004).

to academic lecturing as well as private studies and be of use in industry and governmental organisations.

We owe great thanks to Andreas Detzel (IFEU), who not only provided the example study but also carefully read and commented on the whole manuscript of the German version. Martina Krüger (IFEU) was a great help in adapting the example study to the didactic presentation needed in a textbook. Many of our friends in the LCA community contributed to the development of LCA and thus, finally, also to this book. To mention only few of them, Harald Neitzel (then at Umweltbundesamt (UBA), Berlin), the unforgettable chairman of DIN NAGUS in the 1990s; Isa Renner, main LCA practitioner at Battelle Frankfurt, later at C.A.U. Ltd. Dreieich; and Eva Schmincke, longstanding discussion partner, centrally involved in the development of environmental product declarations (EPDs) according to the ISO Type III declaration system. At the international level, the LCA-related activities of SETAC and the UNEP (United Nations Environmental Programme)/SETAC Life Cycle Initiative were of great help.

Almut B. Heinrich, the managing editor of the book series 'LCA Compendium – The whole world of Life Cycle Assessment' helped us with the translation of the German book doing final corrections in all chapters. She was managing editor of The International Journal of Life Cycle Assessment from 1996 to 2009 and contributed in that position to the proliferation of LCA world-wide.³⁾

Last, but not least, we thank the editorial managers at Wiley-VCH for their patience and competence during the creation of this book.

Frankfurt am Main und Lübeck
October 2013

Walter Klöpffer and Birgit Grahl

References

- | | |
|---|---|
| <p>Baumann, H. and Tillman, A.-M. (2004) <i>The Hitch Hiker's Guide to LCA. An Orientation in Life Cycle Assessment Methodology and Application</i>, Studentlitteratur, Lund. ISBN: 91-44-02364-2.</p> <p>Klöpffer, W. and Grahl, B. (2009) <i>Ökobilanz (LCA) – Ein Leitfaden für Ausbildung</i></p> | <p><i>und Beruf</i>, Wiley-VCH Verlag GmbH, Weinheim. ISBN: 978-3-527-32043-1.</p> <p>Klöpffer, W. and Curran, M.A. (2014) <i>LCA Compendium – The Whole World of Life Cycle Assessment</i>, Springer, Dordrecht.</p> |
|---|---|

3) Klöpffer and Curran 2014.

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 14040¹⁾ 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 of⁴⁾ 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 quantify⁶⁾ 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).

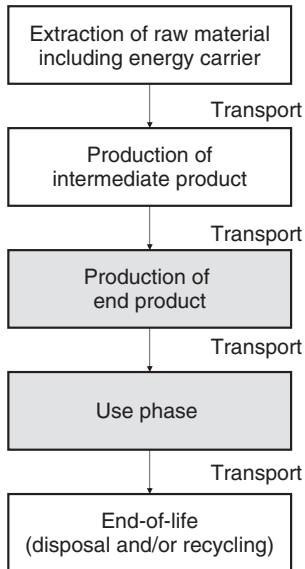


Figure 1.1 Simplified life cycle of a tangible product.

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 l¹¹⁾ 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 dm³.

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 starch¹⁴⁾ 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 salubrity 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) BfA/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 Germany²¹⁾ 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 Kingdom²³⁾ 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 LCI²⁸⁾ (see Chapter 3). In Germany, this development was mainly promoted by Professor Schäfer at the Technical University Munich²⁹⁾ 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 Berlin³³⁾ 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:

$$\text{PLA} = \text{NA} + \text{LCA} + \text{SA} + \text{EA}$$

with $\text{LCA} = \text{inventory} + \text{environmental impact assessment}$.

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).

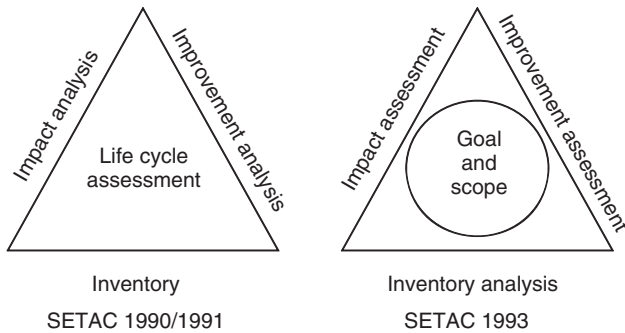


Figure 1.2 The SETAC-triangle in LCA guidelines ('code of practice').³⁵⁾

PLA therefore comprises all three aspects of sustainability according to the Brundtland Commission³⁶⁾ (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 development³⁸⁾:

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 persifflaged 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 reports⁴⁰⁾ 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).

States⁴⁵⁾ and in Japan⁴⁶⁾ 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 Gabathuler⁴⁷⁾ 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 land⁵⁰⁾ (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: Umweltbundesamt (UBA).

52) ISO (1997).

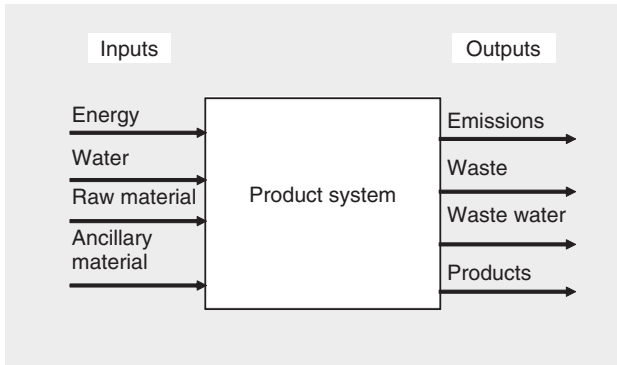


Figure 1.3 Analysis of matter and energy of a product system.

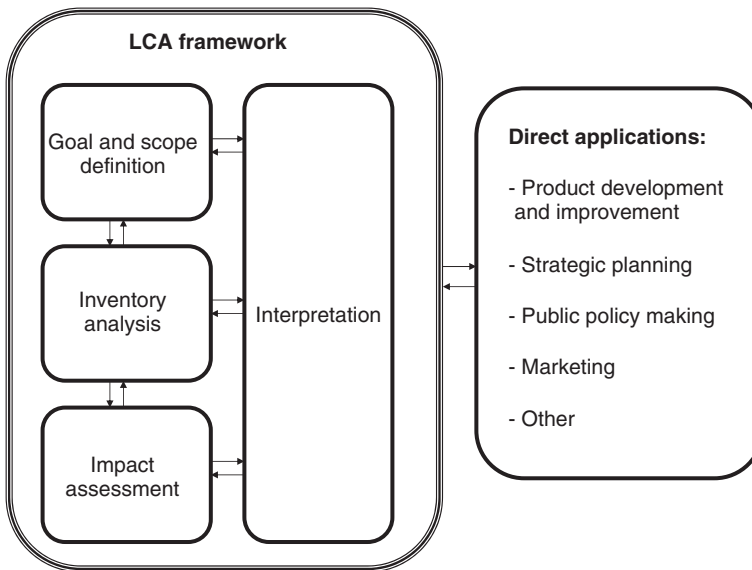


Figure 1.4 LCA phases according to ISO 14040:1997/2006.

1.3.2

Structure of LCA According to ISO

To date, the structure developed by SETAC has essentially been maintained by ISO⁵³⁾ 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 1991⁵⁶⁾ to introduce *valuation* as a component of its own. This proposition was seized by UBA Berlin⁵⁷⁾ and by DIN-NAGUS⁵⁸⁾ 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 conclusion⁶¹⁾ 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
Comparison of products	Integrated product policy	EuP directive ^g
	Surfactants	ECOSOL LCAs ^h
	Beverage packaging	Comparison of packagings ⁱ
	Food packaging	Comparison of packagings ^j
Communication	Floor coverings	ERFMI survey ^k
	Insulating materials	Insulation of buildings ^l
	Consumer consultation	ISO type III declaration ^m
	Chain management	PCR ⁿ : electricity, steam, water ^o
Waste management	Ecological building	EPD ^p : building products ^q
	Carbon footprint	PCR: product declaration ^r
		Carbon-neutral enterprise ^s
Enterprise	Concepts of disposal	Graphic papers ^t
	Recycling	Plastics ^u
	Ecological valuation of business lines	Environmental achievement of an enterprise ^v

^aSchmitz *et al.* (1995) and UBA (2000b, 2002).^bUBA (2000a)^cKlöpffer *et al.* (1999).^dIFEU/SLFA (1998).^eTukker Kleijn and van Oers (1996).^fRüdenauer *et al.* (2007).^gKemna *et al.* (2005).^hStalmans *et al.* (1995) and Janzen (1995).ⁱIFEU (2002, 2004, 2007) and Detzel and Böß (2006).^jIFEU (2006) and Humbert *et al.* (2008).^kGünther and Langowski (1997, 1998).^lSchmidt *et al.* (2004).^mSchmincke and Grahl (2006).ⁿProduct category rules.^oVattenfall (2007).^pEnvironmental product declaration.^qDeutsches Institut für Bauen und Umwelt (2007).^rSvenska Miljöstyvningsrådet (2006) and BSI (2008).^sGensch (2008).^tTiedemann (2000).^uHeyde and Kremer (1999).^vWright *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 brief⁶⁴⁾ 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 organisations⁶⁷⁾ 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).