

## Contents

### Preface *XI*

<b>1</b>	<b>Introduction</b>	<b>1</b>
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
<b>2</b>	<b>Goal and Scope Definition</b>	<b>27</b>
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
<b>3</b>	<b>Life Cycle Inventory Analysis</b>	<b>63</b>
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	
3.4.1	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	
3.7.2.1	Processes of the Production System	143
3.7.2.2	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
<b>4</b>	<b>Life Cycle Impact Assessment 181</b>
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
<b>5</b>	<b>Life Cycle Interpretation, Reporting and Critical Review</b>	<b>329</b>
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
<b>6</b>	<b>From LCA to Sustainability Assessment</b>	<b>357</b>
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
<b>Appendix A Solution of Exercises</b> 375		
<b>Appendix B Standard Report Sheet of Electricity Mix Germany (UBA 2000, Materials p. 179ff) Historic example, only for illustrative purposes</b> 381		
<b>Acronyms/Abbreviations</b> 385		
<b>Index</b> 391		