

Contents

PREFACE ..... xiii

THE FUNCTIONALISTIC PERSPECTIVE OF LCA MODELLING AND  
APPLICATION - A FOREWORD .....xvii

PART I: INTRODUCTION

1. INTRODUCTION..... 3  
1.1 RISING OF THE DISQUIET: A RETROSPECTIVE ..... 4  
1.2 OBJECTIVITY AND SUBJECTIVE ELEMENTS IN LCA ..... 12  
1.3 FROM REAL WORLD TO MODELS AND BACK ..... 15  
1.4 IMPOSSIBILITY TO VALIDATE LCA-MODELS..... 18  
1.5 SCIENTIFIC APPROACH: THESES ..... 19  
1.6 STRUCTURE OF THE BOOK ..... 20

PART II: REQUIREMENTS OF PRODUCT SYSTEMS AND THEIR  
LCIS IN PRODUCT-RELATED DECISION-MAKING

2. LCA AS METHOD AND ITS MODELLING CHARACTERISTICS..... 27  
2.1 METHODOLOGICAL STRUCTURE OF LCA ..... 28  
2.2 SOME CHARACTERISTICS OF CURRENT LCA-METHODOLOGY ..... 29  
2.3 COMPLEXITY AS CHALLENGE FOR THE INVENTORY ANALYSIS ..... 31  
2.3.1 The attribution problem in defining the life cycle model  
of the product ..... 32  
2.3.2 Complexity reduction during the setting up of the life cycle  
model of a product..... 34

2.3.3 System boundaries as source of systematic errors in input-output models..... 37

3. REQUIREMENTS OF LCIS IN PRODUCT DESIGN-RELATED DECISION-MAKING.....41

3.1 REQUIREMENTS FROM THE USE OF LCA IN PRODUCT-RELATED DECISION-MAKING..... 41

3.1.1 Use of LCA as a decision support tool..... 41

3.1.2 Experiences with LCA in product-related decision-making..... 44

3.1.3 Requirements of LCA in product-related decision-making..... 49

3.2 REQUIREMENTS DERIVED FROM DECISION THEORY..... 49

3.2.1 Requirements of decision support tools derived from decision theory ..... 50

3.2.2 Introduction to normative decision analysis..... 52

3.2.3 Mental models and values in LCA ..... 55

3.2.4 Whose values and mental models are to be depicted in LCA?..... 64

3.3 DESCRIPTIVE POWER OF LCA AND CONSEQUENCES FOR THE LIFE CYCLE INVENTORY ANALYSIS..... 65

3.3.1 Sustainable development as overall target direction ..... 66

3.3.2 Normative basis of sustainable development ..... 67

3.3.3 Management rules for sustainable development ..... 73

3.3.4 Descriptive power of LCA in view of the management rules of sustainable development..... 76

3.3.5 Consequences for the attribution of material and energy flows to a product..... 79

3.4 SUMMARY: REQUIREMENTS OF PRODUCT SYSTEMS AND THEIR LCIS ..... 81

**PART III: MENTAL MODELS AND VALUE CHOICES IN THE LIFE CYCLE INVENTORY ANALYSIS**

4. INTRODUCTION..... 85

5. ANALYSIS OF ISO 14041 FOR MENTAL MODELS AND VALUES .....87

5.1 REFERENCE ISO 14040: CURRENT STATUS..... 87

5.2 LIFE CYCLE INVENTORY ANALYSIS..... 88

5.3 AIMS OF THE LIFE CYCLE INVENTORY ANALYSIS: MODEL REPRESENTING THE LIFE CYCLE OF A PRODUCT ..... 91

5.4 THEORETICAL CONSTRUCT ‘LIFE CYCLE OF A PRODUCT’ ..... 92

5.4.1 Goal and scope dependency ..... 92

5.4.2 The product system as a list of possible processes to select..... 92

5.5 SETTING OF SYSTEM BOUNDARIES BASED ON RELATIVE EFFECTS..... 93

|       |                                                                                                                                           |     |
|-------|-------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.6   | MULTIFUNCTIONAL PROCESSES AND ALLOCATION BASED ON 'CAUSAL RELATIONSHIP' .....                                                             | 94  |
| 5.6.1 | Definition of the allocation problem .....                                                                                                | 94  |
| 5.6.2 | Allocation principles .....                                                                                                               | 95  |
| 5.6.3 | Identification of multifunctional processes .....                                                                                         | 96  |
| 5.6.4 | Step 1: Can allocation be avoided? .....                                                                                                  | 97  |
| 5.6.5 | Step 2: Physical relationship for unavoidable allocation.....                                                                             | 99  |
| 5.6.6 | Step 3: 'Causal relationship' in other cases.....                                                                                         | 102 |
| 5.6.7 | Remarks on the three-step procedure of ISO/EN 14041 .....                                                                                 | 104 |
| 5.7   | MENTAL MODELS OF THE CAUSAL RELATIONSHIP OF MATERIAL AND ENERGY FLOWS .....                                                               | 105 |
| 5.7.1 | Physical/chemical causation.....                                                                                                          | 106 |
| 5.7.2 | Economic causation.....                                                                                                                   | 107 |
| 5.7.3 | Physical/chemical and economic causation.....                                                                                             | 110 |
| 5.7.4 | Economic and environmental costs .....                                                                                                    | 112 |
| 5.7.5 | Socio-economic causation.....                                                                                                             | 113 |
| 5.7.6 | Consequences for the definition of the product system.....                                                                                | 114 |
| 5.8   | ALLOCATION FOR REUSE & RECYCLING .....                                                                                                    | 114 |
| 5.8.1 | Some allocation principles for reuse & recycling.....                                                                                     | 115 |
| 5.8.2 | Setting of system boundaries for reuse & recycling.....                                                                                   | 115 |
| 5.8.3 | Identification of multifunctional processes related to reuse & recycling .....                                                            | 117 |
| 5.8.4 | Open-loop recycling and closed-loop recycling.....                                                                                        | 122 |
| 5.8.5 | Temporal changes and the decision-maker's attitude towards risk .....                                                                     | 124 |
| 5.8.6 | Excursus: allocation for reuse & recycling in ISO/TR 14049:2000 .....                                                                     | 132 |
| 6.    | ALLOCATION PROCEDURES FOR OPEN-LOOP RECYCLING .....                                                                                       | 135 |
| 6.1   | INTRODUCTION.....                                                                                                                         | 135 |
| 6.2   | APPROACHING RECYCLING ON THE PROCESS LEVEL.....                                                                                           | 139 |
| 6.3   | APPROACHING RECYCLING ON PRODUCT SYSTEM LEVEL .....                                                                                       | 141 |
| 6.4   | APPROACHING RECYCLING INCLUDING ALL PRODUCT SYSTEMS IN A CASCADE .....                                                                    | 145 |
| 6.5   | DESCRIPTION OF ALLOCATION PROCEDURES FOR OPEN-LOOP RECYCLING.....                                                                         | 146 |
| 6.5.1 | Two product systems without the import of primary material into the second product system .....                                           | 148 |
| 6.5.2 | Three product system with a single import of primary material into the first product system and final waste disposal after the last ..... | 149 |
| 6.5.3 | Three product system with importation of primary material and waste disposal in all product systems of the cascade.....                   | 153 |

|                                                                                                |                                                                                  |     |
|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|-----|
| 6.5.4                                                                                          | Some more allocation procedures for marginal LCA.....                            | 157 |
| 6.6                                                                                            | CHOICE OF AN ALLOCATION PROCEDURE FOR REUSE & RECYCLING..                        | 158 |
| 7.                                                                                             | THE DECISION-MAKER’S MENTAL MODELS AND VALUES IN<br>INVENTORY ANALYSIS.....      | 161 |
| <b>CASE STUDY I: DEVELOPMENT OF THE VALUE-CORRECTED<br/>SUBSTITUTION FOR ALUMINIUM WINDOWS</b> |                                                                                  |     |
| 8.                                                                                             | INTRODUCTION.....                                                                | 167 |
| 9.                                                                                             | MATERIAL AND MARKET CHARACTERISTICS OF ALUMINIUM .....                           | 169 |
| 9.1                                                                                            | CHARACTERISTICS OF ALUMINIUM AS MATERIAL.....                                    | 169 |
| 9.2                                                                                            | CHARACTERISTICS OF THE SUPPLY SIDE OF PRIMARY ALUMINIUM....                      | 170 |
| 9.3                                                                                            | CHARACTERISTICS OF THE SUPPLY SIDE OF SECONDARY MATERIAL..                       | 171 |
| 9.4                                                                                            | DEMAND OF ALUMINIUM .....                                                        | 172 |
| 9.5                                                                                            | PRINCIPLES OF A MORE SUSTAINABLE USE OF ALUMINIUM.....                           | 173 |
| 9.5.1                                                                                          | Paradigm: value preservation.....                                                | 173 |
| 9.5.2                                                                                          | Approach I: the material cascade model .....                                     | 176 |
| 9.5.3                                                                                          | Approach II: the material pools model.....                                       | 177 |
| 9.5.4                                                                                          | Defining material value.....                                                     | 178 |
| 9.6                                                                                            | REQUIREMENTS OF ALLOCATION PROCEDURES FOR<br>REUSE & RECYCLING OF ALUMINIUM..... | 180 |
| 10.                                                                                            | DEVELOPMENT OF THE VALUE-CORRECTED SUBSTITUTION<br>FOR ALUMINIUM WINDOWS.....    | 181 |
| 10.1                                                                                           | PRINCIPLES.....                                                                  | 181 |
| 10.2                                                                                           | OPERATIONALISATION FOR THE RECYCLING OF ALUMINIUM .....                          | 183 |
| 10.3                                                                                           | LME QUOTATIONS AS REFERENCE POINTS FOR THE PRICE<br>FORMATION OF ALUMINIUM.....  | 187 |
| 10.3.1                                                                                         | Primary aluminium and alloyed (secondary) aluminium<br>contracts .....           | 187 |
| 10.3.2                                                                                         | Influence of speculation on price formation.....                                 | 188 |
| 10.3.3                                                                                         | Statistical analysis of LME quotations.....                                      | 189 |
| 10.3.4                                                                                         | LME-quotations as allocation factors in LCA.....                                 | 192 |
| 10.4                                                                                           | TIME DEPENDENCY IN THE VALUE-CORRECTED SUBSTITUTION ....                         | 193 |
| 10.5                                                                                           | ‘FINAL DISPOSAL’ OF ALUMINIUM.....                                               | 195 |
| 11.                                                                                            | SELECTED ALLOCATION PROCEDURES FOR COMPARISON .....                              | 199 |
| 11.1                                                                                           | CUT-OFF PROCEDURE.....                                                           | 200 |
| 11.1.1                                                                                         | Principles.....                                                                  | 200 |
| 11.1.2                                                                                         | Operationalisation for the recycling of aluminium.....                           | 201 |
| 11.2                                                                                           | CLOSED-LOOP PROCEDURE WITH MATERIAL POOLS MODEL .....                            | 202 |

|                                                                                             |     |
|---------------------------------------------------------------------------------------------|-----|
| 11.2.1 Principles.....                                                                      | 202 |
| 11.2.2 Operationalisation for the recycling of aluminium.....                               | 203 |
| 11.3 STRICT COPRODUCT ALLOCATION .....                                                      | 204 |
| 11.3.1 Principles.....                                                                      | 204 |
| 11.3.2 Operationalisation for the recycling of aluminium.....                               | 205 |
| 12. APPLICATION IN AN LCA OF ALUMINIUM WINDOWS.....                                         | 207 |
| 12.1 GOAL AND SCOPE DEFINITION.....                                                         | 207 |
| 12.2 FUNCTIONAL UNIT .....                                                                  | 208 |
| 12.3 SCENARIOS CONSIDERED SYSTEM BOUNDARIES .....                                           | 208 |
| 12.4 MODEL OF THE REFERENCE FLOW.....                                                       | 209 |
| 12.5 DATA QUALITY .....                                                                     | 218 |
| 12.6 INVENTORY ANALYSIS .....                                                               | 219 |
| 12.7 IMPACT ASSESSMENT .....                                                                | 219 |
| 12.8 INTERPRETATION.....                                                                    | 225 |
| 12.8.1 General remark.....                                                                  | 225 |
| 12.8.2 Interpretation focusing on methodological considerations.....                        | 225 |
| 12.8.3 Data quality and sensitivity .....                                                   | 227 |
| 13. METHODOLOGICAL CONCLUSIONS .....                                                        | 229 |
| 13.1 CUT-OFF PROCEDURE.....                                                                 | 229 |
| 13.2 CLOSED-LOOP PROCEDURE BASED ON A MATERIAL POOL MODEL.....                              | 232 |
| 13.3 STRICT COPRODUCT ALLOCATION .....                                                      | 234 |
| 13.4 VALUE-CORRECTED SUBSTITUTION .....                                                     | 236 |
| <br><b>CASE STUDY II: MODELLING END-OF-LIFE OPTIONS FOR<br/>BEECH WOOD RAILWAY SLEEPERS</b> |     |
| 14. INTRODUCTION.....                                                                       | 245 |
| 15. MATERIAL AND MARKET CHARACTERISTICS OF WOOD .....                                       | 247 |
| 15.1 WOOD AS MATERIAL.....                                                                  | 247 |
| 15.2 SOME CHARACTERISTICS OF WOOD INDUSTRY .....                                            | 248 |
| 15.3 UTILISATION OPTIONS OF POST-CONSUMER WOOD .....                                        | 249 |
| 15.3.1 Options for material re-utilisation of post-consumer wood.....                       | 250 |
| 15.3.2 Thermal utilisation .....                                                            | 253 |
| 15.3.3 Further end-of-life options .....                                                    | 254 |
| 15.3.4 Economics of wood residuals and post-consumer wood.....                              | 254 |
| 15.4 POST-CONSUMER WOOD MARKET IN SWITZERLAND .....                                         | 255 |
| 16. SUSTAINABLE WOOD FLOW MANAGEMENT.....                                                   | 259 |
| 16.1 FORESTRY .....                                                                         | 259 |
| 16.2 USE OF WOOD .....                                                                      | 261 |

|        |                                                                                   |     |
|--------|-----------------------------------------------------------------------------------|-----|
| 16.3   | POST-CONSUMER WOOD .....                                                          | 263 |
| 16.4   | WOOD IN THE INTERNATIONAL DISCUSSION ON CLIMATE CHANGE ....                       | 265 |
| 16.5   | LEGAL FRAMEWORK FOR A SUSTAINABLE UTILISATION<br>OF POST-CONSUMER WOOD .....      | 266 |
| 16.6   | RULES FOR A SUSTAINABLE UTILISATION OF WOOD .....                                 | 267 |
| 17.    | WOOD PROCESSING CHAIN AND ATTRIBUTION IN LCA .....                                | 269 |
| 17.1   | ATTRIBUTION AND ALLOCATION IN LCA OF WOOD<br>AND WOOD PRODUCTS .....              | 269 |
| 17.2   | OVERVIEW OF LCA METHODOLOGIES RELATED TO WOOD .....                               | 270 |
| 17.2.1 | Life Cycle Inventory Analysis by the American<br>Forest & Paper Association ..... | 270 |
| 17.2.2 | Methodological Appendix of the Life-Sys Wood project .....                        | 272 |
| 17.2.3 | Conclusions .....                                                                 | 274 |
| 18.    | MODELLING END-OF-LIFE OPTIONS OF BEECH WOOD RAILWAY<br>SLEEPERS .....             | 275 |
| 18.1   | GOAL AND SCOPE DEFINITION .....                                                   | 275 |
| 18.2   | FUNCTIONAL UNIT .....                                                             | 276 |
| 18.3   | MODEL OF THE REFERENCE FLOW .....                                                 | 277 |
| 18.4   | ALLOCATION PROBLEM I: TECHNICAL WOOD PRODUCTION .....                             | 279 |
| 18.4.1 | Allocation problems and scenarios considered .....                                | 282 |
| 18.4.2 | Inventory analysis .....                                                          | 286 |
| 18.4.3 | Impact assessment .....                                                           | 286 |
| 18.4.4 | Interpretation focusing on methodological considerations .....                    | 287 |
| 18.4.5 | Conclusions .....                                                                 | 290 |
| 18.4.6 | Data quality and sensitivity .....                                                | 292 |
| 18.5   | ALLOCATION PROBLEM II: TRANSPORT FROM FOREST TO<br>PRODUCTION SITE .....          | 293 |
| 18.6   | ALLOCATION PROBLEM III: PRODUCTION PROCESSES FOR THE<br>SLEEPER PRODUCTION .....  | 295 |
| 18.6.1 | Allocation problems and scenarios considered .....                                | 295 |
| 18.6.2 | Inventory analysis .....                                                          | 297 |
| 18.6.3 | Impact assessment .....                                                           | 297 |
| 18.6.4 | Interpretation focusing on methodological considerations .....                    | 298 |
| 18.6.5 | Conclusions .....                                                                 | 300 |
| 18.6.6 | Data quality and sensitivity .....                                                | 301 |
| 18.7   | ALLOCATION PROBLEM IV: RECYCLING OR INCINERATION WITH<br>ENERGY RECOVERY .....    | 301 |
| 18.7.1 | Allocation problems and scenarios considered .....                                | 302 |
| 18.7.2 | Inventory analysis .....                                                          | 307 |
| 18.7.3 | Impact assessment .....                                                           | 307 |
| 18.7.4 | Interpretation focusing on methodological considerations .....                    | 309 |

|                                                                                              |     |
|----------------------------------------------------------------------------------------------|-----|
| 18.7.5 Conclusions .....                                                                     | 315 |
| 18.7.6 Data quality and sensitivity .....                                                    | 316 |
| 18.8 MODELLING WHOLE LIFE CYCLES .....                                                       | 317 |
| 18.8.1 Scenarios selected .....                                                              | 317 |
| 18.8.2 Inventory analysis .....                                                              | 319 |
| 18.8.3 Impact assessment .....                                                               | 319 |
| 18.8.4 Interpretation focusing on methodological considerations .....                        | 320 |
| 19. CONCLUSIONS .....                                                                        | 325 |
| 19.1 WOOD-SPECIFIC METHODOLOGICAL CONCLUSIONS .....                                          | 325 |
| 19.2 GENERAL METHODOLOGICAL CONCLUSIONS .....                                                | 326 |
| <br>PART VI: CONCLUSIONS AND OUTLOOK                                                         |     |
| 20. REVIEW OF THE THESES .....                                                               | 331 |
| 21. CONSEQUENCES FOR LCA AS A DECISION SUPPORT TOOL .....                                    | 335 |
| 22. CONSEQUENCES FOR A REVISION OF ISO/EN 14041 .....                                        | 339 |
| 22.1 CRITICAL POINTS IN ISO/EN 14041 .....                                                   | 339 |
| 22.2 OUTLINE OF ATTRIBUTION RULES IN INVENTORY ANALYSIS<br>FOR A REVISION OF ISO 14041 ..... | 341 |
| 23. TOWARD A GROUP-MODEL BUILDING PROCESS IN LCA .....                                       | 347 |
| 23.1 STAKEHOLDERS OF AN LCA .....                                                            | 348 |
| 23.2 KNOWLEDGE INVOLVED IN LCA .....                                                         | 351 |
| 23.3 LCA AS GROUP MODEL-BUILDING PROCESS .....                                               | 353 |
| 23.4 PITFALLS OF PARTICIPATORY PROCESSES .....                                               | 361 |
| 23.5 EVALUATION OF LCA AS GROUP MODEL-BUILDING PROCESS .....                                 | 361 |
| 23.6 FINAL REMARKS .....                                                                     | 362 |
| 24. FUTURE RESEARCH NEEDS .....                                                              | 365 |
| ACRONYMS .....                                                                               | 369 |
| GLOSSARY .....                                                                               | 371 |
| APPENDIX .....                                                                               | 375 |
| REFERENCES .....                                                                             | 387 |
| INDEX .....                                                                                  | 415 |