## Contents

PrefacexiiiAbout the Companion Websitexv

Part I Introduction 1

1	Challenges and Perspectives of Applying Circular Economy in	
	Business and Engineering 3	
	Juliano Araujo, Henning Hinderer, Tobias Viere, Jörg Woidasky	
1.1	Introduction 3	
1.2	Strategic Approach for CE Implementation 4	
1.3	Comprehensive Evaluation of Business Circularity Readiness 7	
1.4	Overview of Current Progress in Business Circularity 9	
1.5	Innovation as a Key Driver for Business Circularity 10	
1.6	Conclusion and Structure of This Book 13	
	References 15	

Part II Materials (Selection, Properties) 19

2	Aluminum Alloys, Recycling, and the Circular Economy 21	
	Robert Sanders, Wilhelm Kiefer	
2.1	Introduction: The Importance of Recycling for the Aluminum	
	Industry 21	
2.2	Current State of the Circular Economy for Aluminum 22	
2.2.1	Challenges in Aluminum Recycling 22	
2.2.2	Aluminum Scrap Recycling Processes and Streams 28	
2.2.2.1	Generalized Aluminum Recycling 29	
2.2.2.2	Aluminum Remelting 30	
2.2.2.3	Aluminum Beverage Cans 31	
2.2.2.4	Foil and Packaging 33	
2.2.2.5	Aerospace 34	
2.2.2.6	Commercial Transportation 35	
2.2.2.7	Automotive 35	

2.3 Innovations in Scrap Processing Technologies 36

vi	Contents
----	----------

2.3.1	Laser-induced Breakdown Spectroscopy 36	
2.3.2	Optical AI 37	
2.3.3	Design for Recycling 38	
2.4	Summary and Conclusion 40	
	References 41	
3	Circular Economy of Polymers – Its Current State in	
	Germany and Beyond 43	
	Maximilian Auer, Jannick Schmidt, Jörg Woidasky	
3.1	Introduction 43	
3.2	State of the Art of Plastic Categories and Applications 44	
3.3	Polymer Production in Europe and Germany 46	
3.4	Polymer Waste in Europe and Germany 48	
3.5	Lightweight Packaging Waste Collection Systems 48	
3.6	Lightweight Packaging Sorting in Germany 50	
3.7	Plastic Waste Recycling 51	
3.8	Conclusion 53	
	Acknowledgements 54	
	Abbreviations 54	
	References 55	
4	Implementing Circular Value Creation in the Construction Sector 63	
	Franziska Struck, Celestin Stretz, Gotthard Walter,	
	Dirk Klöpper, Sabine Flamme	
4.1	Background 63	
4.2	Challenges for the Implementation of Circular Value Creation in the	
	Construction Sector 64	
4.3	Approaches for Increasing Circular Value Creation in the Construction	
	Sector 65	
4.3.1	Mapping of Regional Anthropogenic Material Deposits 66	
4.3.2	Evaluation Criteria for Circular Construction 68	
4.3.3	Digitalization to Support the Circular Economy 69	
4.3.4	Sustainable Business Models for Closing Product Cycles 71	
4.3.5	Resource Efficiency in Civil Engineering 73	
4.4	Outlook/Perspectives 75	
	References 75	
	Part III Products (Design, Servitization) 79	
_		
5	Circular Process Implementation for Electric Drives – Experiences	

### and Examples 81

- Jürgen Miller
- 5.1 Introduction 81
- 5.1.1 Circulation Strategy 81
- 5.1.2 The Business Model: Product Variance and Safety Thinking vs. Circularity Realization *83*

Contents vii

- 5.2 Environmentally Friendly Product Design: New Challenges 85
- 5.3 Closing the Loop Circular Return 90
- 5.4 Disassembly, Treatment, and Reuse 92
- 5.5 Industrial Examples 92
- 5.5.1 Sustainable Inverter for Simple Conveyor Applications 92
- 5.5.2 Magnetic Body of a Spring-operated Brake for Electric Motors 93
- 5.6 Conclusion and Outlook 94 References 95

6 Circularity in the Healthcare Industry	97
--	----

Marcel Kern, Jörg Woidasky

- 6.1 Current Challenges in the Healthcare Sector 97
- 6.2 Handling Clinical Waste 98
- 6.3 Waste Production in Hospitals 100
- 6.4 Medical Devices 101
- 6.4.1 Life Cycle Steps of Medical Devices 101
- 6.4.2 Typical Materials in Medical Devices 102
- 6.4.3 Developments in Single-use Medical Devices 103
- 6.5 Circular Economy in Medical Technology 104
- 6.6 Conclusion 106 References 106
- 7 Circular Economy Indicators for Product Design Calculation and Applicability 111

Paula Kuhn, Juliano Bezerra de Araujo, Annika Pruhs, Anina Kusch, Frank Bertagnolli, Tobias Viere

- 7.1 Introduction 111
- 7.2 Methodology 114
- 7.2.1 Researching Indicators 114
- 7.2.2 Generating a Catalog of Indicator Evaluation Criteria 115
- 7.2.3 Evaluating the Indicators 116
- 7.3 Results and Discussion *117*
- 7.3.1 Selected Circularity Indicators 117
- 7.3.2 Calculation Scheme for the Set of Circularity Indicators 121
- 7.3.3 Evaluation of Circularity Indicator Applicability 122
- 7.4 Conclusion and Perspectives 126
  Funding 127
  Author Contributions 127
  Appendix 128
  References 128
- 8 Makigami of an Industrial Product Development Process: Use of a Lean Methodology to Integrate Sustainable and Circular Product Design 133 Annika Pruhs, Anina Kusch, Frank Bertagnolli, Tobias Viere, Jörg Woidasky
- 8.1 Introduction 133
- 8.2 Analysis and Visualization Through the Makigami Methodology 134

# viii Contents

8.3 8.4 8.5 8.6 8.7	Product Development Process in Practice 134 Current State: Recording of the PDP 135 Target State: Integration of the EDA into the PDP 137 Implementation of a Circularity-oriented PDP 141 Conclusion 141 Acknowledgments 142 References 142		
	Part IV Technology (Production and Business Processes) 145		
9	Single-stage Sorting and Marker Technology for a Circular		
	Economy of Polymers 147		
	Guojun Gao, Dirk Wacker, Beate Kummer, Robin Just, Reiner Just,		
	Markus Reisacher, Christof Strohhoefer, Jochen Moesslein		
9.1	Introduction 147		
9.1.1	Plastic Waste Generation in the European Union 147		
9.1.2	Regulatory Framework 149		
9.1.2.1	EU Packaging Regulation (Draft 2022) 149		
9.1.2.2	Plastics Recycling Regulation (EU/2022/1616) 149		
9.2	Problems with Existing Conventional Sorting Technology 150		
9.2.1	The Functional Principle of Sort4Circle <sup>®</sup> and Tracer-based Sorting 151		
9.2.2	Sort4Circle <sup>®</sup> : Single-step Sorting and Combined Detection 151		
9.3 9.3.1	Sort4Circle® Innovations Compared to the Competition 153		
	Automated Singulation and Controlled Handling of Waste Objects 153 Closed Detector with Laser Safety 153		
9.3.2 9.3.3	Technology-open Combined Detection in One Single Stage 154		
9.3.3 9.3.4	Fluorescent Markers and TBS 154		
9.3.4	Background-free Upconversion Fluorescence and Sorting Codes 155		
9.3.6	Error-free Storage at a Flexible Number of End Points 155		
9.3.7	Machine-readable Product Tracking with TrackByStars <sup>®</sup> 155		
9.4	Conclusion 156		
J. <del>T</del>	References 156		
10	Embracing Entomophagy: Insects as Catalysts for Sustainable Circular		
-	Economies 159		
	Gia Tien Ngo		
10.1	Introduction 159		
10.2	Back to the Roots Can Also Drive Innovations 159		
10.3	Advantages of Insects as Food and Feed 161		
10.3.1	Nutritional Benefits 161		
10.3.1.1	Proteins 161		
10.3.1.2	Fatty Acids 162		
10.3.1.3	Minerals 162		
10.3.1.4	Vitamins 162		
10.3.1.5	Dietary Fiber Content 162		
10.3.1.6	Specific Advantages for Livestock 162		

- 10.3.2 Environmental Benefits 163
- 10.3.2.1 Reduced Greenhouse Gas and Ammonia Emission 164
- 10.3.2.2 Higher Feed Conversion 164
- 10.3.2.3 Enabled Use of Organic Side Streams 164
- 10.3.2.4 Reduced Water Use 164
- 10.3.2.5 Less Required Land 165
- 10.3.2.6 Lower Risk of Zoonotic Infections 165
- 10.3.2.7 Technical Maturity 165
- 10.4 Case Study Alpha-protein 165
- 10.5 Industrial Automation as the Key to Sustainability 167
- 10.6 The Promising Future of the Insect Industry: A Beacon of Sustainability 168 References 169

# 11 Digital Technologies for Enabling and Engineering the Circular Economy 171

- Heiko Thimm
- 11.1 Introduction 171
- 11.2 CE Principles in the Context of Collaborative Business and the Internet Evolution *172*
- 11.3 Transition Toward the CE ICT-specific Barriers and Challenges *175*
- 11.4 The Concept of the Circular Economy Digital Machine Room 177
- 11.4.1 Supporting Technologies: BDA, IoT, and AI 179
- 11.4.1.1 Internet of Things 180
- 11.4.1.2 Big Data Analytics 180
- 11.4.1.3 Artificial Intelligence 181
- 11.4.2 Implementation Issues: Digital Product Pass and Data Spaces 181
- 11.4.2.1 Digital Product Pass 181
- 11.4.2.2 Data Spaces 182
- 11.5 Use Cases 183
- 11.5.1 CE-oriented Product Design and Manufacturing 184
- 11.5.2 Life-time Extension of Products and their Parts 185
- 11.5.3 Effective Reuse of Materials 187
- 11.6 Conclusion 188
  - References 189

#### Part V Organization (Management, Business Models) 197

- **12** Finding Ideas for Sustainability-oriented Innovations: Using Circular Business Models for Innovation 199 Claus Lang-Koetz, Philipp Wichert, Leon Deterding
- 12.1 Introduction 199
- 12.2 Business Models and CE 202
- 12.3 Sustainability-oriented Innovation Management 206
- 12.4 Creative Search for New Ideas 207

12.5	Practical Approach on How to Use CBMs in Innovation		
12.6	Management 208 Conclusion and Outlook 212		
	References 212		
13	Circular Economy Business Models and Ecodesign Approaches in Practice – A Case Study Literature Review 219		
	Liz Fohrenkamm, Juliano de Araujo, Tobias Viere		
13.1	Introduction 219		
13.2	Methods 220		
13.2.1	Systematic Literature Research 220		
13.2.2	Qualitative Research and Analysis 221		
13.3	Results 224		
13.3.1	Case Studies' Review 224		
13.3.2	Prevalence of CBMs 225		
13.3.3	Prevalence of EDAs 227		
13.3.4	Correlation Between CBMs and EDAs 228		
13.4	Discussion 230		
13.5	Conclusion 232		
	References 232		
	The IRMa Approach – Integrative Resource Efficiency Management in		
14	The IRMa Approach – Integrative Resource Efficiency Management in		
14	The IRMa Approach – Integrative Resource Efficiency Management in Small and Medium-sized Enterprises 235		
14			
14	Small and Medium-sized Enterprises 235		
<b>14</b> 14.1	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235		
	<b>Small and Medium-sized Enterprises</b> 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth		
14.1	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency		
14.1 14.2	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237		
14.1 14.2 14.3	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239		
14.1 14.2 14.3 14.4	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239		
14.1 14.2 14.3 14.4 14.4.1	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240		
14.1 14.2 14.3 14.4 14.4.1 14.4.2	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240 Indicators and Multi-criteria Decision Making 242		
14.1 14.2 14.3 14.4 14.4.1 14.4.2 14.4.3	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240 Indicators and Multi-criteria Decision Making 242 IRMa Platform 242 Technology Scouting 244 Application 246		
14.1 14.2 14.3 14.4 14.4.1 14.4.2 14.4.3 14.4.4	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240 Indicators and Multi-criteria Decision Making 242 IRMa Platform 242 Technology Scouting 244 Application 246 Conclusion and Outlook 247		
14.1 14.2 14.3 14.4 14.4.1 14.4.2 14.4.3 14.4.4 14.5	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240 Indicators and Multi-criteria Decision Making 242 IRMa Platform 242 Technology Scouting 244 Application 246		
14.1 14.2 14.3 14.4 14.4.1 14.4.2 14.4.3 14.4.4 14.5	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240 Indicators and Multi-criteria Decision Making 242 IRMa Platform 242 Technology Scouting 244 Application 246 Conclusion and Outlook 247		
14.1 14.2 14.3 14.4 14.4.1 14.4.2 14.4.3 14.4.4 14.5	Small and Medium-sized Enterprises 235 Alexandra Vogt, Ingela Tietze, Philipp Preiss, Claus Lang-Koetz, Heidi Hottenroth Introduction 235 State of the Art: Conceptual Frameworks for SMEs in Resource Efficiency and Circular Economy 237 Methodology 239 IRMa Approach 239 PDCAC-cycle Phases 240 Indicators and Multi-criteria Decision Making 242 IRMa Platform 242 Technology Scouting 244 Application 246 Conclusion and Outlook 247 Acknowledgement 248		

15	Cultural and Cross-Cultural Requirements of Circular Economy		
	Engineering: Addressing Issues of Global Responsibility, Social		
	Sustainability, and Ethics	255	
	Jasmin Mahadevan		

15.1 Introduction 255

#### Contents xi

- 15.2 Essential Concepts 256
- 15.3 Three Properties of Culture and Ensuring Requirements 257
- 15.3.1 Property 1: The Implicit Normalities of Culture 257
- 15.3.2 Property 2: The Diversity of Culture 259
- 15.3.3 Property 3: The Complexities of Culture 261
- 15.4 The Systemic Challenge of Culture and How to Address It 264
- 15.4.1 Step 1: From Shareholder to Stakeholder Value 265
- 15.4.2 Step 2: Acknowledging Systemic Responsibility on More and More All-encompassing Levels 266
- 15.4.3 Step 3: Shaping a Corporate Climate of Sustainability, Ethics, and Responsibility *268*
- 15.5 The Engineering Dimension of Culture and Its Implications 270
- 15.6 Towards an Interculturally Competent Circular Economy Engineering 273
- 15.7 Summary and Conclusion 274 About the Author 275 References 275

### 16 The Actual Goals and Limits of Circular Economy – A Critical Perspective 277

Mario Schmidt

- 16.1 Introduction 277
- 16.2 Review of Common Premises 278
- 16.3 Circularity as an Overall Goal? 279
- 16.4 Lack of Proper Assessments and Indicators 281
- 16.5 Holistic Approaches Needed 282
- 16.6 Concluding Remarks 283 References 283

Index 287