

# Contents

- 1 Introduction** ..... 1
  - 1.1 Present Situation and Problem Statement ..... 1
  - 1.2 Research Objective and Structure of Thesis ..... 5
- 2 Theoretical Background and Technical Overview** ..... 9
  - 2.1 Modularity of Product Systems and Product System Fleets ..... 9
    - 2.1.1 Modular Product System Architectures ..... 9
    - 2.1.2 Multiple Product Systems and Population Fleets ..... 18
  - 2.2 Life Cycle Thinking ..... 20
    - 2.2.1 Environmental Life Cycle Assessment ..... 22
    - 2.2.2 Life Cycle Costing ..... 28
  - 2.3 Sustainable Development and Corresponding Legislation ..... 33
    - 2.3.1 Environmental Impacts and Impact Assessment ..... 33
    - 2.3.2 Sustainability and Sustainable Development ..... 36
    - 2.3.3 General Environmental Legislation ..... 41
    - 2.3.4 Environmental Regulations for  
the Automotive Industry ..... 43
  - 2.4 Life Cycle Engineering and Mathematical Optimization ..... 51
    - 2.4.1 Life Cycle Engineering ..... 51
    - 2.4.2 Optimization Approaches for Decision Support ..... 57
  - 2.5 Conclusions Regarding the Theoretical Background ..... 60
- 3 State of Research and Identification of the Research Gap** ..... 63
  - 3.1 Criteria and Requirements for Optimizing  
the Eco-effectiveness of Product Systems ..... 63
    - 3.1.1 Criteria to Handle Product System Modularity ..... 64
    - 3.1.2 Criteria to Handle Use Case Specific Requirements ..... 65

---

3.1.3	Criteria for Optimization Approach .....	66
3.1.4	Additional Requirements to Obtain Useful Results .....	67
3.2	Current Approaches and State of Research .....	68
3.2.1	Product Modularity .....	70
3.2.2	Modular Life Cycle Assessments .....	72
3.2.3	Optimization of LCA and LCC .....	75
3.3	Identification of the Research Gap .....	83
<b>4</b>	<b>Concept for the Optimization of Eco-effectiveness of Product Systems</b> .....	<b>91</b>
4.1	Concept Requirements .....	91
4.2	Framework for the Optimization Concept .....	93
4.2.1	General Framework .....	93
4.2.2	Selection of Graph Theory as Optimization Approach ...	96
4.3	Modelling the Product System's Structure in a Network .....	103
4.3.1	Transformation of Modular Product Systems into Networks .....	103
4.3.2	Product System Networks Including Interdependencies .....	106
4.3.3	Network Reduction Strategies for Interdependency Modelling .....	110
4.3.4	Strategy Adaption to Reduce the Data Demand of LCA Values and LCC Values .....	115
4.4	Data Management of the Input Data .....	122
4.5	Adaption of Shortest Path Algorithms to the Problem Statement .....	124
4.6	Visualization and Interpretation of Results .....	132
<b>5</b>	<b>Prototypical Implementation and Application of the Methodology</b> .....	<b>137</b>
5.1	Prototypical Implementation of the Optimization Approach ...	137
5.2	Exemplary Application Cycle of the Optimization Approach ...	141
<b>6</b>	<b>Application of the Optimization Approach to a Case Study of the Automotive Industry</b> .....	<b>145</b>
6.1	Life Cycle Perspectives of a Vehicle .....	146
6.1.1	Product Life Cycle of a Vehicle .....	146
6.1.2	Environmental Assessment of a Vehicle's Life Cycle ...	148
6.1.3	Total Cost of Ownership along a Vehicle's Life Cycle .....	151

---

6.2	Selection of Measures for the Reduction of Greenhouse Gas Emissions .....	155
6.2.1	Selection of Measures and Module Alternatives .....	156
6.2.2	Measure Analysis Regarding LCA, LCC and Availability .....	161
6.3	Data Input for the Vehicle and Fleet Optimization .....	168
6.4	Results of Optimization for Different Scenarios .....	171
6.4.1	Analysis of the Results for a Single Vehicle Optimization .....	174
6.4.2	Analysis of Results for Vehicle Fleet Optimization .....	177
6.4.3	Sensitivity Analysis of Results .....	184
6.5	Findings for Further Vehicle Development and Fleet Planning .....	187
<b>7</b>	<b>Summary, Critical Appraisal and Outlook .....</b>	<b>193</b>
7.1	Summary .....	193
7.2	Critical Appraisal .....	195
7.3	Outlook .....	196
	<b>Appendix .....</b>	<b>199</b>
	<b>Literature .....</b>	<b>203</b>