

# Contents

|                                                                         |             |
|-------------------------------------------------------------------------|-------------|
| <b>Acknowledgments .....</b>                                            | <b>III</b>  |
| <b>Abstract .....</b>                                                   | <b>V</b>    |
| <b>Kurzfassung.....</b>                                                 | <b>VII</b>  |
| <b>Резюме.....</b>                                                      | <b>IX</b>   |
| <b>Resumen.....</b>                                                     | <b>XI</b>   |
| <b>Contents .....</b>                                                   | <b>XIII</b> |
| <b>1 Introduction .....</b>                                             | <b>1</b>    |
| 1.1 Thesis scope.....                                                   | 1           |
| 1.2 Design research approach.....                                       | 2           |
| 1.3 Thesis structure.....                                               | 4           |
| <b>2 Problem statement and intended contributions .....</b>             | <b>7</b>    |
| 2.1 Problem formulation.....                                            | 7           |
| 2.2 Intended contribution .....                                         | 9           |
| <b>3 Fundamental terms and state of the art .....</b>                   | <b>11</b>   |
| 3.1 (Smart) Product-Service System .....                                | 11          |
| 3.1.1 The Product .....                                                 | 13          |
| 3.1.2 The Service.....                                                  | 14          |
| 3.1.3 The System .....                                                  | 15          |
| 3.1.4 Variations of Product-Service Systems.....                        | 17          |
| 3.2 Systems Engineering .....                                           | 18          |
| 3.2.1 Essentials of the Systems Engineering.....                        | 19          |
| 3.2.2 Essentials of the Model-Based System Engineering.....             | 21          |
| The system model .....                                                  | 21          |
| Modeling language.....                                                  | 23          |
| Modeling tool.....                                                      | 24          |
| Modeling method .....                                                   | 25          |
| 3.3 State of the art in the interdisciplinary product development ..... | 25          |
| VDI guideline 2206.....                                                 | 26          |

|                                                                                                             |           |
|-------------------------------------------------------------------------------------------------------------|-----------|
| 4-cycle-model by Gausemeier .....                                                                           | 28        |
| Systems Engineering and Model-Based Systems Engineering Approaches....                                      | 30        |
| Harmony for System Engineering .....                                                                        | 31        |
| Object-Oriented Systems Engineering Method (OOSEM) .....                                                    | 33        |
| SPES Engineering Methodology .....                                                                          | 35        |
| Further approaches.....                                                                                     | 36        |
| 3.4 State of the art in developing Product-Service Systems .....                                            | 37        |
| 3.4.1 Modular process for technical PSS design by Aurich et al.....                                         | 38        |
| 3.4.2 Service Engineering by Sakao, Shimomura, et al. ....                                                  | 39        |
| 3.4.3 Model-oriented conceptual development of industrial Product-Service-<br>Systems after Hassanein ..... | 42        |
| 3.4.4 Industrial PSS modeling based on Systems Engineering by Maleki et<br>al. ....                         | 44        |
| 3.4.5 Integrated PSS design method by Boucher, Medini, Andriankaja, et al.<br>.....                         | 46        |
| 3.4.6 PSS design methodology by Kim, Lee, et al.....                                                        | 49        |
| 3.4.7 Methodology for model-based planning of product-service systems by<br>Kammerl .....                   | 53        |
| 3.4.8 Modeling framework for integrated PSS design by Trevisan, Brissaud<br>et al. ....                     | 55        |
| 3.4.9 ‘Layer-based’ PSS development methodology by Müller .....                                             | 57        |
| 3.5 Analysis of PSS design approaches .....                                                                 | 61        |
| 3.5.1 Analysis method .....                                                                                 | 61        |
| 3.5.2 Results discussion and conclusion .....                                                               | 64        |
| <b>4 Requirements for the integrative model-based PSS design methodology. 69</b>                            |           |
| 4.1 General requirements .....                                                                              | 71        |
| 4.2 PSS and MBSE-specific requirements.....                                                                 | 71        |
| <b>5 Methodology for integrative, model-based design of Product-Service<br/>Systems.....</b>                | <b>75</b> |
| 5.1 Earlier relevant work – the <i>VPE System Development Methodology (VPE-<br/>SDM)</i> .....              | 75        |
| MVPE process model for interdisciplinary system development.....                                            | 76        |

|                                                                                                                      |     |
|----------------------------------------------------------------------------------------------------------------------|-----|
| Kaiserslautern System Concretization Model (KSCM) .....                                                              | 77  |
| Five-layer IT Architecture Concept.....                                                                              | 79  |
| 5.2 Methodology for integrative, model-based design of Product-Service Systems .....                                 | 82  |
| 5.2.1 Motivation .....                                                                                               | 82  |
| 5.2.2 Fields of action .....                                                                                         | 83  |
| 5.2.3 The <i>VPE System Development Methodology for Product-Service Systems</i> — <i>VPE-SDM<sup>PSS</sup></i> ..... | 84  |
| MVPE <sup>PSS</sup> Process Model .....                                                                              | 84  |
| KSCM <sup>PSS</sup> —Kaiserslautern System Concretization Model for Product-Service Systems .....                    | 86  |
| 5.2.4 The VPE Service Development Methodology— <sup>VPE</sup> ServDM.....                                            | 89  |
| ServDM Design Process .....                                                                                          | 90  |
| Specify business model and business requirements.....                                                                | 91  |
| Analyze the system context.....                                                                                      | 93  |
| Design functional system architecture .....                                                                          | 95  |
| Partition functional system architecture.....                                                                        | 97  |
| Design logical service system architecture .....                                                                     | 98  |
| Physical System Design .....                                                                                         | 103 |
| ServDM Design Method.....                                                                                            | 105 |
| PSS Business Analysis .....                                                                                          | 108 |
| System Context Analysis.....                                                                                         | 111 |
| Functional Architecture Design .....                                                                                 | 114 |
| Logical Architecture Design .....                                                                                    | 121 |
| Physical PSS Design .....                                                                                            | 126 |
| Synchronization between Service and Product Design.....                                                              | 128 |
| ServDM Tool Integrations .....                                                                                       | 130 |
| Business Model Canvas and Value Proposition Canvas Modeling Solution in CIM Database PLM .....                       | 131 |
| SysML Profile for Cameo Systems Modeler .....                                                                        | 132 |

|          |                                                                        |              |
|----------|------------------------------------------------------------------------|--------------|
| <b>6</b> | <b>Prototypical application and evaluation of KSCM<sup>PSS</sup></b>   | <b>141</b>   |
| 6.1      | Scenario and scope of the demonstration                                | 141          |
| 6.2      | PSS modeling according to <i><sup>VPE</sup>ServDM</i>                  | 142          |
| 6.2.1    | Business Model Design                                                  | 142          |
| 6.2.2    | System Context Analysis                                                | 146          |
| 6.2.3    | Functional Architecture Design                                         | 153          |
| 6.2.4    | Functional to Logical System Architecture Design – System Partitioning | 162          |
| 6.2.5    | Logical System Architecture Design                                     | 163          |
| 6.2.6    | Physical Service System Design and Implementation                      | 177          |
|          | Generic Technical Service Design                                       | 177          |
|          | Instantiation and Implementation                                       | 179          |
| 6.3      | Requirements evaluation                                                | 187          |
| <b>7</b> | <b>Summary and Outlook</b>                                             | <b>190</b>   |
| 7.1      | Summary                                                                | 190          |
| 7.2      | Outlook                                                                | 191          |
|          | <b>Appendix</b>                                                        | <b>XIX</b>   |
|          | <b>Bibliography</b>                                                    | <b>XXI</b>   |
|          | <b>List of Figures</b>                                                 | <b>41</b>    |
|          | <b>List of Tables</b>                                                  | <b>47</b>    |
|          | <b>List of Abbreviations</b>                                           | <b>XLIX</b>  |
|          | <b>Betreute studentische Arbeiten</b>                                  | <b>LI</b>    |
|          | <b>Lebenslauf</b>                                                      | <b>LXI</b>   |
|          | <b>Curriculum vitae</b>                                                | <b>LXIII</b> |