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Modeling Framework for Integrated, Model-based Development of Product-Service Systems

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Abstract

Product-service systems (PSS) are seen as the 21st-century solution for direct delivery of value to customers under the requirements of high availability, quality, and reduced risks. With mutual benefits for customers, manufacturers, service providers and often the environment, PSS represent a promising approach to sustainable development. This paper addresses the integrated development of product-service systems consisting of physical products/systems and services and proposes an integrated modeling framework that utilizes the Systems Modeling Language. A use case from Lenze, a German automation company, demonstrates the applicability of the integrated modeling framework in practice.

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1. Introduction

In recent years, focus has shifted from owning technical products that deliver certain functionality towards the availability of the material or non-material value they provide to the client, both in the industrial and private sectors. This change in the market makes manufacturers rethink their business models and consider alternative ways to sustain profitability. Typical product-centric enterprises have started experimenting with different business models, mostly by offering services which extend their products' functionalities or provide additional value. Further, the ownership of the product was reconsidered – moving away from the customer – allowing for far more sophisticated offerings [1]. Products are, thereby, not in the center of enterprises' business models anymore, rather is the whole system, arising from the seamless integration of complex, cyber-capable products with different service units. The technical elaboration of such business models are product-service systems (PSS) or industrial products-service systems (IPSS). They mostly integrate multiple stakeholders apart from the customer and the manufacturer, forming partnerships with certain responsibilities and thereby creating so-called extended value-creation networks [2].

The development and integration of products and services into product-service systems adds further complexity to the development process with new aspects to be considered, such as broader partnership networks, state-aware service logic with executional responsibilities, data management, and supporting IT infrastructure. Regardless of whether the product-service system under development is based on already existing or newly developed products, an integrated development approach is necessary from the very beginning in order to ensure the success of the project, maximize value extraction and sustain in the long term.

This contribution presents a model-based approach for support of the integrated development of product-service systems in the early design phases – from stakeholder requirements to

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full system specification. It follows the Model-Based System Engineering concepts and utilizes the Systems Modeling Language (SysML) as an interdisciplinary specification instrument, allowing formal, single-model specification of the whole system. The single, managed model serves as a single source of truth in the PSS development process allowing for seamless traceability cross-linking between product and service subsystems and advanced 1D simulations.

The paper is structured as follows: In the second section, the research background and gap is given. In section three, the developed framework for integrated modeling of PSS is theoretically introduced. Section four shows the application of the framework in a case study from a publicly funded research project. Section five concludes the paper and points out areas for further research and development.

2. Product-service systems design – background and gap

Product-service systems are bundles consisting of technical products or systems and additional service units integrated together to deliver value to the customer rather than just functionalities [3]. PSS shift the risks, responsibilities and cost associated with the ownership of traditional products away from the customer and – in the same time – allow manufacturers to improve competitiveness through increased value extraction from their products due to retained ownership enhancing utilization, reliability, design, and protection [4]. Many authors see product-service systems as an embracement of sustainability owing to the possibly reduced overall resource consumption and environmental impacts, which result from better utilization, maintenance, and adaptation to changing needs and market conditions compared to traditional offerings [3–9], and thereby, a way for a shift to a more sustainable economy.

Services, as part of PSS, are activities with economic value performed for others [8]. Typical characteristics of services are their immateriality, the inseparability of the service production from the service consumption and their perishability [15]. With the increasing need to deliver services of constant high quality and ensure high availability, service engineering emerged in the mid-1990s in Germany as an approach aiming at adapting traditional engineering methods from the product development to the service sector. Earlier marketing-driven and customer-integration focused approaches for development and design of services are know from the USA. [15,16] Au fond, service engineering can be defined as the systematic development and design of services using suitable models, methods and tools as well the management of the service development process, aiming at intensifying, improving and automating the whole process of service development, design and realization [15,17,18]. In the mid-2000s as Service Engineering was already established as an engineering discipline, further aspects such as the integration of services with products started to be considered [23]. At this time, product-service systems began gaining considerable attention [24] and multiple design approaches and methods for integrated development of PSS such as Extended Product Service Blueprint [25,26], PSS Layer Method [19], Integrated Life Cycle [7,27], Functional Hierarchy Modeling [28] PSS Multi-Views Modeling [29], Extended Functional Analysis [29], IPS² Metadata Model [31] as well as combinations of existing modeling approaches [30,33] were proposed by different authors [32]. Despite an increased interest in research, widely accepted and industrially practiced approaches to the PSS design are still missing. A possible reason for that can be found in the lack of practical methods with adequate IT-tool support for the early, multi-disciplinary design and specification of systems consisting of interdependent products and services.

A promising paradigm to support the integrated development of PSS is the Model-Based Systems Engineering (MBSE). With its roots in the North-American aerospace and defense industries, Systems Engineering – the predecessor of MBSE, so to say – is a general-purpose approach to provide system solutions to technologically challenging and project-critical problems [10]. Nowadays, Systems Engineering is being applied in industrial and public sectors, where solutions to complex problems are to be worked out or complex systems are to be developed. Some examples are found in the automotive, healthcare, logistics and material handling, resource and infrastructure management branches [11]. For many years, a model-based approach has been standard practice in mechanical, electrical, and software engineering. The same model-based approach is becoming prevalent in systems engineering as well. [10] MBSE is a interdisciplinary engineering paradigm propagating the use of formal models instead of documents to support requirements generation, analysis, specification, design, verification and validation of the system under development – in the early conceptual phase but also continuing throughout the development and later life cycle phases [10,12]. As a result, enhanced specification and design quality, reuse of system specifications and design artifacts, and communication within interdisciplinary design teams is achieved. [10]

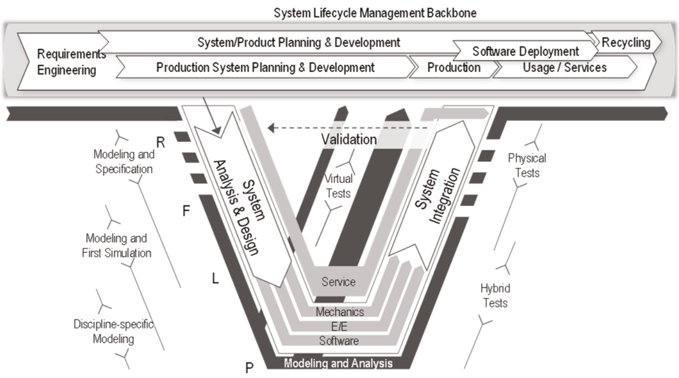

Fig.1. V-model for multi-disciplinary PSS development (after [16,32])

The output of the systems engineering activities utilizing the model-based approach is a consistent system model [10], which serves as a starting point for the discipline-specific development, i.e. mechanic, electric/electronic, software. MBSE methods can be very well applied to the design of product-service systems. Furthermore, supported by formal languages such as the SysML, MBSE can be practiced in an efficient and well-supported way. Thereby, the design of services can be integrated in the early system development as suggested by Eigner et al. (fig.1) [12,21]

In order to facilitate this, a newly developed modeling framework for specification of product-service system with special focus on the service aspect of the system is presented in the following section. The inclusion of the service aspect into the interdisciplinary, model-based engineering of systems would allow for an integrated specification of product-service systems, better understanding of the overall-system under development by all stakeholder, clear definition of responsibilities within the extended value-creation network, and also new possibilities in early behavior simulation, validation and verification of the PSS design.

3. Modeling framework for integrated PSS design

In this section, a framework for the integrated design of product-service systems is proposed. It is based on a single model, which facilitates the specification of the whole PSS and supports decision making in the design process. This integrated system model of the PSS is a formal, computer-interpretable specification of interdisciplinary knowledge about the system under development and a record of decisions made in the early design stage. It is also the object based on which the stakeholders in the extended value-creation network can find a common ground to exchange ideas and synchronize their knowledge about the system. The system model is expressed in a modeling language, created according to certain methodology using a modeling tool and is preferably contained in a model repository [10,14], which provides model management capabilities, cross-model element traceability and integration with other tools [12,13].

SysML was chosen as a modeling language for the presented framework. The language supports analysis, specification, design, verification and validation of various multidisciplinary systems. This decision was made because of the universality of the language, its suitability for specification of interdisciplinary systems and its extendibility through profiling. [10,14] Further reasons were the relatively easy understanding of models expressed in SysML even by non–system-engineers and its wide adoption in the model-based systems engineering field. Another important factor was the aim to be able to generate an integrated model of the overall product-service system, which includes both the material product part as well as the immaterial service part of the system.

Along with the language and the tool to perform the modeling with, a methodological approach – defining what is to be done and how the language and tool are to be used – is needed to ensure system models of consistent breath, depth, and fidelity. The modeling methodology defines a specific set of tasks and certain techniques, with the help of which these tasks are to be performed, in order to create a complete, consistent, redundancy-free system specification. [14,22] Methodical approaches of the MBSE field available today vary in their specification target, abstraction level of specification, and coverage of the system development process.

The modeling framework proposed hereafter targets especially the service and IT infrastructure part of product-service systems. It serves as an extension of the Kaiserslautern System Concretization Model (KSCM) [21], which deals with the specification of complex, cybertronic systems and is integrated in the process model for Model-based Virtual Product Engineering (MVPE) (see fig. 1) [21]. The development of the framework follows the CASE research cycle (clarification – analysis – synthesis – evaluation) [19] and is still ongoing. The following parts of this contribution provide insight in the current state of the framework's synthesis and its initial evaluation through a case study.

3.1. PSS modeling framework

The PSS specification according to the framework takes place on four different abstraction levels (fig. 2): the context, functional solution, logical solution, and physical solution levels. Requirement and verification/validation spaces spans over all abstraction levels. These contain requirements respectively tests cases associated with system elements at all abstraction levels. The space between the requirement and validation rooms is the solution space, which facilitates the creative engineering design work. The framework is developed from the beginning with the SysML in mind, which allows for formal, coherent and inter-traceable specification of both product and service parts in a single, integrated model.

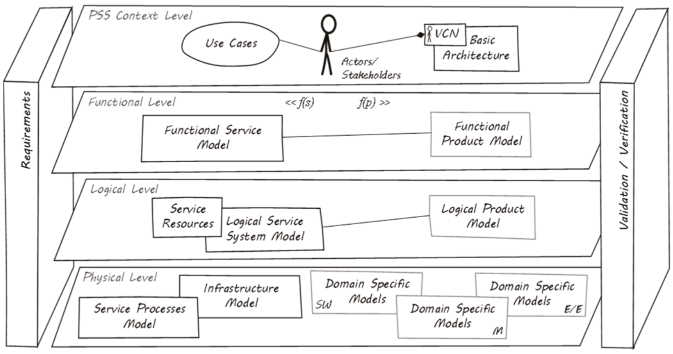

Fig. 2. General structure of the integrated PSS modeling framework

3.2. PSS context level

As a first step in the development of the PSS, business requirements are collected and documented in the systems model. This takes place in the requirement space. Out of those requirements, the goal and aimed functionality of the product-service system is identified and described through the definition of service-relevant use cases, which extend the functionality of the physical systems to a product-service system. The context, in which the PSS is to be realized, is analysed and the PSS is separated from its environment by the system border. Following, the envisioned basic architecture of the PSS along with the extended value-creation network is defined.

3.3. Functional level

As a first task at the functional level, system requirements defining specific functions to be realized by the PSS are derived from the business requirements and documented as part of the requirement space. The use cases defined at the previous abstraction level are further detailed by means of activities. Alternatives for provision of functionalities of the PSS are considered and decisions, whether they are to be realized by products or services or combination of both, are being made and documented through the allocation of activities to the product or service subsystems. In the verification space, test cases specifying how the fulfilment of the requirements respectively the implementation of the functions is to be tested are defined.

3.4. Logical level

At the logical level, the architecture of the product-service system is further detailed making decisions about the elements to be used to provide the defined functions. The activities specified on the previous level are broken down to operations allocated to the logical elements of the system that will perform them during operation. These logical units might be components of the products, supporting IT infrastructure or personnel. The object and information flows between those units as well as to other (sub-)systems or users outside the PSS are defined and their interfaces are specified. The general information model to be used within the PSS is developed. Test cases specifying how the proper functioning of the infrastructure is to be assessed are defined in the verification space at this level.

3.5. Physical level

At the physical level, the maximum concretization of the service subsystem within the PSS is achieved. Here, the operational procedures of the activities within the service units are defined. All resources necessary for fulfillment of the activities are specified – material and personnel. The documentation necessary for conduction of the activities by personnel is defined. At this level, the decisions about particular software solutions to be used in or developed for the supporting IT infrastructure are made and their implementation/development begins.

4. Case study

In this section, the modeling method of the framework is demonstrated based on a case study from a German governmentally funded research project named "InnoServPro".

4.1. Scenario of the case study

The PSS modeling framework is exemplarily applied in a use case from Lenze, a company of the German automation industry. With focus fields in the automotive, intralogistics and packaging industries as well as robotics applications, Lenze provides main automation components like motors, gearboxes, inverters and controllers. The use case is based on an availability-oriented business model, whereby the high availability of a production system is to be ensured. Therefore, intelligent maintenance policies for the company's components that are essential for the production system's functioning are to be applied. Virtual representation of the components, machines supported by asset and base management are central for intelligent maintenance [20]. Special focus is put on smart services such as condition monitoring and predictive maintenance. Thereby, not only the company's own components are to be regarded, but also their interplay with other components within the whole production systems. Real-time sensor data is combined with lifetime models to provide detailed information about the condition of components. This condition information needs to be assigned to asset information from the company's Enterprise Resource Planning (ERP) or Manufacturing Execution systems (MES). In case of replacing components during maintenance activities, all necessary information should be available at a central point. Thereby downtimes of machines can be reduced significantly. All services and workflows should be digital recorded and assigned to corresponding components.

Parts of the PSS modeled along the presented framework are shown in the following example. A real prototype including typically used components in intralogistics applications as well as services will be built within the InnoServPro project to demonstrate the integrated PSS.

4.2. Exemplarily application of the modeling framework

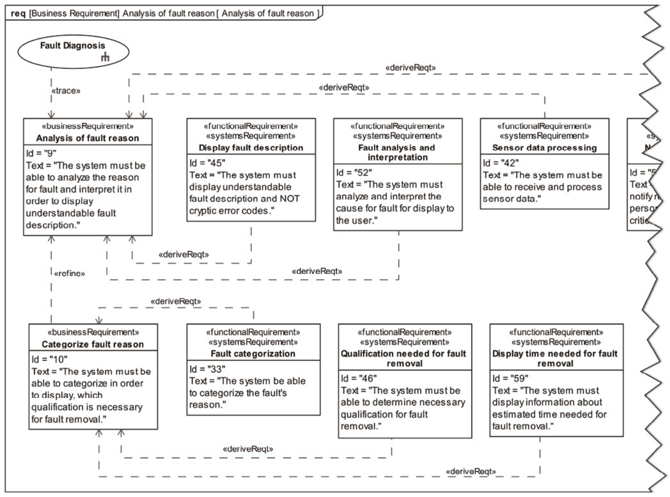

Fig. 3. Requirements diagram of the business requirement "Analysis of fault reason" displaying associated system requirements and use case (excerpt).

As described in the previous section, at the beginning of the PSS development process stakeholder requirements are collected per usual systems engineering practices. Those requirements are documented – stereotyped as business requirements – in the SysML model as shown in fig. 3 through a requirement diagram. An analysis with the aim to bundle them in accordance to their subject or similarities about required functionality or

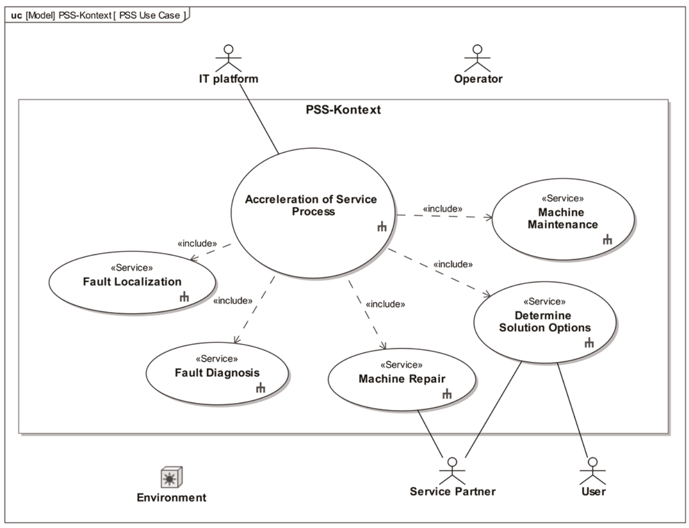

Fig. 4. Definition of the PSS goal and service units

property is performed. The bundling is done by means of stereotyped, traceable associations, e.g. «derive», «refine». It is important to note, that diagrams are views on parts of the model from a certain perspective and do not depict the full set of properties of and dependencies between the elements of the model.

After a thorough requirement analysis, the goal and context of the PSS is clarified and defined, while the PSS itself is still considered as a black box. First functional breakdown is performed through the definition of service units to be implemented within PSS. These are modeled as stereotyped use case elements included or extending of the base use case – the goal of the PSS – as depicted in fig. 4. The use cases are associated with actors involved in the particular service units.

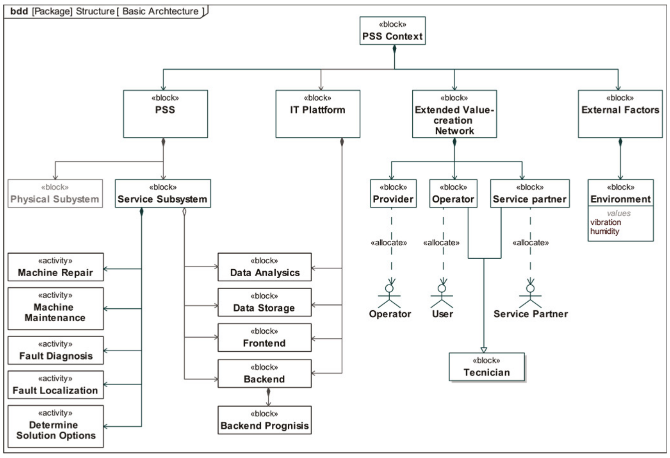

Fig. 5: Basic structure of the PSS in its context

In a next step, the basic architecture of the PSS as well as its context in terms of the extended value-creation network and external factors are defined in a SysML block definition diagram. Thereby, the product-service system is subdivided into physical and service subsystems. In this example, the physical subsystem is regarded as a black box of which only the interfaces to service units through the supporting IT infrastructure or personnel are defined. In the case of new development of the product subsystem, the Kaiserslautern System Concretization Model [21] for development of cybertronic/mechatronic systems is used. The service subsystem is composed of service units and supporting IT infrastructure. In the present case, the IT infrastructure is a subset of components of a bigger IT platform, which can be used to support further PSS. In case of the InnoServPro project for example, three product-service systems are supported by the same IT platform. In the system model (fig. 5), this is expressed by composition respectively aggregation relations between the IT components and the IT platform respectively the service subsystem. The extended value-creation network, especially the actors actively participating in the service units, is defined by means of blocks allocated to the actual SysML actors known from the use case definition. This is done in order to be able to allocate activities to those blocks in the further detailing of the service units.

Further, the mentioned detailing of the service units takes place. This is done in activity diagrams with swimlane representations of actors and system components so that the responsibilities within the service unit can be unambiguously specified, as exemplarily shown in fig. 6 for the unit 'Fault localization'. The logical order of the activity execution in the service unit as well as the object flows between them are defined.

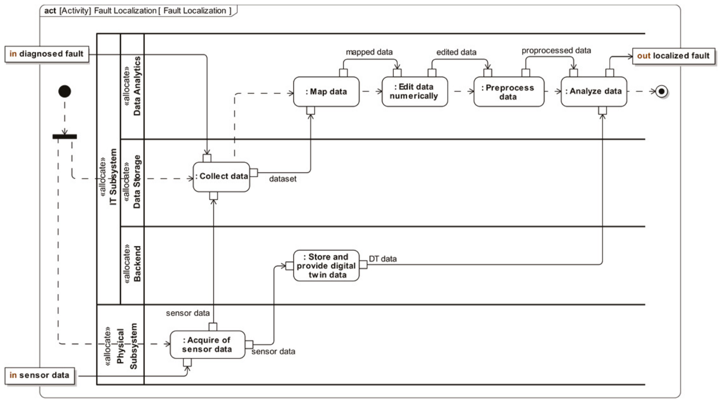

Fig. 6. Activity specification of the service unit 'Fault localization'

With the specification of the object flows in the activity diagrams, the interface between actors and IT components are indirectly defined. These interfaces as well as the objects flowing through them – objects of the general information model – are now explicitly specified in an internal block diagram. This is exemplarily shown in fig. 7 for the supporting infrastructure of the service subsystem.

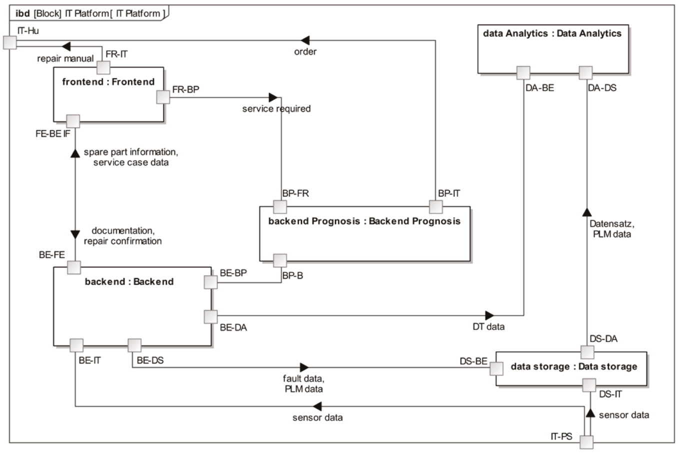

Fig. 7. Internal structure of the supporting IT infrastructure of the service subsystem

The tool independent general information model and its components – the required information objects and the relations between them – are specified by means of a block definition diagram. Information objects representing standard product data are linked to objects representing service steps and processes as well as objects that realise the condition monitoring aspects. As a result, sensor data and status information as well as specific service processes can be linked to the corresponding life time models and assemblies or components itself at any level in the hierarchical product structure.

5. Conclusion and outlook

The increasing complexity of modern industrial and consumer systems and the new business models made possible by connectivity and increased capabilities in data processing nowadays call for new design methodologies, which not only integrate the development processes of the three classical disciplines – mechanics, electric/electronics and software – but also include the service domain in the process. A grand challenge nowadays for the early PSS design, but also for the early engineering design in generals, is transition from the document-based way of working practiced today to such that utilizes formal, computer-interpretable models instead. The presented modeling framework provides a basis for an early inclusion of the service discipline in the model-based systems engineering of PSS. It can be applied by its own or in addition to the Kaiserslautern System Concretization Model and is integrated in the MVPE process model [21]. Future work related to the framework includes its further development and documentation as well as the provision of a guide for the joint application of it and the KSCM within the MVPE process model.

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