Proceedings of the International MultiConference of Engineers and Computer Scientists 2019
IMECS 2019, March 13-15, 2019, Hong Kong

A Methodical Approach for Using SysML to Optimize Product Architectures for Industrie 4.0

Yübo Wang, Philipp Richard Zingel, Reiner Anderl

***Abstract*—The research initiative Industrie 4.0 offers wide potential for the enhancement of industrial productivity. Besides the optimization of value-chains, there are also new challenges for product development. Products in the form of cyber-physical systems are characterized as highly customer individual and technologically diverse. In this context, the methods of systems engineering provide an interdisciplinary approach for handling these complex systems. This is enabled by modeling of systems for analysis and optimization. Model-based systems engineering (MBSE) helps to formalize system models with the aid of the graphical modeling language SysML. This facilitates the creation of highly integrated product models, which can be utilized throughout the engineering process. However, the practical implementation of MBSE is regarded as challenging, particularly because of the lack of discipline-specific methodology. In this paper we introduce a methodology that aims at leveraging existing product documentation by extending and transferring it to a system model. This is achieved by the customization of the SysML to the specific needs from the domain of mechanical engineering. Furthermore, we demonstrate how the resulting models may be used for improvements in an environment of mass-customization.**

***Index Terms*—Industrie 4.0, virtual product development, mass-customization, complexity management, SysML, MBSE**

I. Introduction

INDUSTRIE 4.0 is a strategic research initiative aiming at taking advantage of the high potential that is provided by the digitalization of manufacturing. Though Industrie 4.0 started as a German project, similar efforts can be found around the globe, following the trend of digitalization in manufacturing [1]. The basis for the so-called fourth industrial revolution is formed by cyber-physical-systems (CPS) [2]. According to Lee, CPS "are integrations of computation with physical processes" [3]. In practice CPS are highly integrated systems with communication interfaces connecting them directly to the Internet. This also enables new business models around the product which are often characterized by high customer individuality [4]. A multitude of products and production equipment in the form of CPS make for a decentralized production network - a cyber-physical-production-system (CPPS) [5]. Also known as industrial Internet of things (IIOT), these production systems are envisioned to be capable of a product-driven, highly flexible and self-optimizing production flow [2]. This is again motivated by the increase of customer-individuality in products. Initial examples of such production systems have been shown by industry and research in recent years. The ultimate goal is being able to manufacture 'batch size 1' at the same efficiency of a rigid mass production [4]. This demand of flexibility poses unanswered questions to product development, since flexibility in manufacturing depends on its anticipation in the early stages of design. Consequently, the challenges for product development can be summarized as:

- Short product lifecycles
- High customer individuality
- Interdisciplinarity

From the perspective of product development, these are typical challenges of complexity in a product. Hence, the field of engineering design has developed a set of methods which can be used for optimizing product structures in order to be suitable for mass-customization. Modularization as a common approach to product architecture of this type relies on an optimized physical-to-functional mapping [6]. This is enabled by creating a solution-neutral functional architecture of a product alongside the physical structure. The physical structure implements the functional description of what the product is expected to do. Diagrams such as the design structure matrix (DSM) are used to visualize product architecture for the purpose of optimization [7]. Additionally, a high flexibility in product development requires a high traceability from customer requirements over design specification to the components of a product. Only then the impact of changing customer requirements can be anticipated prior to the production process. Traceability in the development phase is also demanded in highly regulated fields such as the medical devices industry. In order to fulfill the regulations from 21 CFR 820 and ISO 13485 for quality management systems of medical devices, traceability matrices have to be created as part of the product documentation [8].

A. Model-based Systems Engineering

A broad approach to managing complexity is given by the discipline of systems engineering which can be traced back to the challenges of early astronautics [9]. Systems engineering is an approach to manage complexity in technical problems through an interdisciplinary way. This is typically done by using modeling techniques in a top-down development process. A specialized form of systems

Manuscript received January 08, 2019; revised February 14, 2019.
This publication has been supported by SHL Medical, a company of SHL Group. SHL Medical is a global leader in design, development and manufacturing of advanced drug delivery systems, such as auto injectors and pen injectors. Most recently, SHL has expanded its R&D profile to support ongoing innovations in drug development and digital healthcare.
This work was supported by the Hessian LOEWE initiative within the Software-Factory 4.0 project.
Mr. Yübo Wang is with the Department of Computer Integrated Design of the TU Darmstadt, Otto-Berdt-Str. 2, 64287 Darmstadt, Germany (phone: +49 (0) 6151-16-21845; email: y.wang@dik.tu-darmstadt.de)
Mr. Philipp Richard Zingel is with the Technische Universität Darmstadt, Nieder-Ramstaedter-Str. 183a, 64285 Darmstadt, Germany (phone: +49-160-9538-4607; email: philipp.zingel@googlemail.com)
Prof. Dr.-Ing. Reiner Anderl is Head of the Department of Computer Integrated Design of the Technische Universität Darmstadt, Otto-Berdt-Str. 2, 64287 Darmstadt, Germany

engineering is provided with model-based systems engineering (MBSE). MBSE makes use of the Systems Modeling Language (SysML) to transform systems specification from a document-based form to a formalized, model-based form [10]. SysML is a graphical modeling language based on the Unified Modeling Language (UML). It is designed to provide a language for integrating specifications of multiple disciplines into a single system model. This can be achieved by a multitude of diagrams representing the view on a system's structure, behavior and requirements [11]. By integrating these aspects into a single data model, MBSE offers the possibility to depict the relations between different modeling elements such as requirements and functions of a system. Those relationships can be analyzed with the help of SysML modeling tools to achieve a multi-domain traceability which can be visualized as graphs or matrices.

From a few specialized companies in the aerospace and defense industry using MBSE, its application has recently extended to multiple industrial branches. Especially for Industrie 4.0, MBSE is regarded as a key enabling technique [12].

B. Challenges

As the use of UML is very common in software engineering, engineers of this domain are likely to adopt the concept of MBSE. However, engineers from the mechanical domain are typically not familiar with graphical modeling languages. This poses an obstacle to the multi-domain integration intended with MBSE. Moreover, SysML is a generic language providing an abundance of modeling options, which can overstrain new users [13].

The methods for optimizing product architectures which are used in engineering design are commonly applied with the help of spreadsheets or specialized software. From the perspective of data integration along the entire product lifecycle this results in an isolation from existing product data. Maisenbacher et al. have shown an example for creating DSM with the help of SysML and pointed out the benefit of this technique for a better understanding of complex systems [14]. However there is still a lack of concrete procedures leading to system models, that can be used for further analysis such as DSM and provide a comprehensive traceability.

II. State of the Art

Since the SysML is a generic language, every MBSE approach needs be supported by a specific development process which determines the aspects of systems that have to be modeled in the particular development stages. The approach shown in this paper is based on the approaches introduced in the following paragraphs.

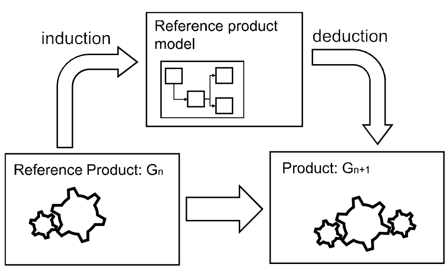

Fig. 1. MBSE development approach. Own representation based on [15]

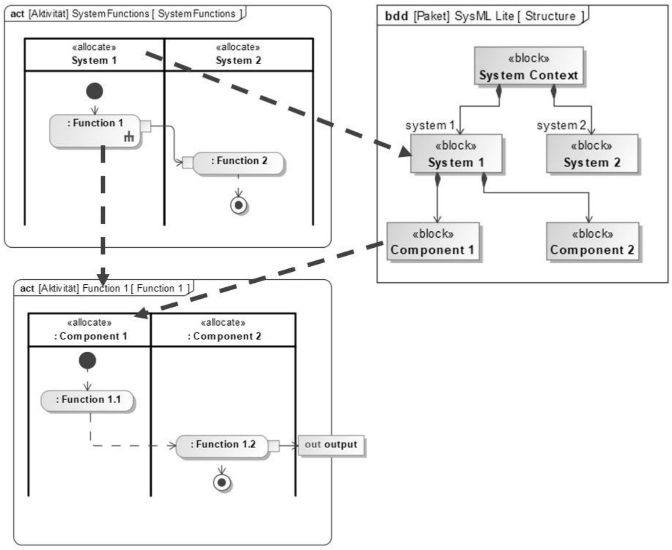

Fig. 2. Physical and functional modeling in SysML-Lite. Own representation based on [18]

A. General Approach

According to Maurer, "most development projects can be classified as change and adaption projects, as they are largely based upon existing products" [7]. Following this conclusion, Bursac suggests an approach to use MBSE for gathering information from existing Products using it for the development of new variants and generations (Fig. 1) [15]. The bi-directional approach describes the induction of information into the SysML-Model on one side and the deduction of information from the model to the new generation on the other side. This procedure ensures that insights from previous product generations are incoporated into the new design.

B. Complexity management in Engineering Design

Approaches for managing complexity as a result of high individuality are successfully applied in engineering design. Fundamentally this is based on the optimization of a product's architecture containing its physical as well as its functional structure [6]. Modular structures are regarded as particularly suitable for mass-customization [16]. Regarding the product's architecture, modules are characterized as functionally and physically independent from each other [6].

1) Structural complexity management: Structural complexity management is a discipline of engineering design for optimizing complex structures. As a means of visualizing dependencies between components, matrices are used. A specialized form of these matrices is the DSM which "represents a subset of a single domain, for example the geometrical relations between components of a structure" [14]. DSM can also be optimized with the help of computer algorithms as shown by [17].

C. MBSE Methodology

The 'V-Model' is an interdisciplinary development process commonly used to apply systems engineering. It combines a

ISBN: 978-988-14048-5-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

'top-down' system design process with a 'bottom-up' system integration of discipline specific systems [19]. The MVPE process model is a specialized V-Model for MBSE. Adopting product architectures used in engineering design, the MVPE-Model also distinguishes between functional and physical structures. These are extended to the following modeling artifacts, which are established subsequently in the design phase [20]:

- Requirements (R)
- Functional (F)
- Logical (L)
- Physical (P)

The artifacts, also called R-F-L-P, allow for discipline-neutral system descriptions in early development stages [20]. Yet, the concrete relationships are not defined in the MVPE-Model. Moreover, functional modeling is not integrated into SysML by default. Thus, methods for functional modeling techniques such as functional architectures for system (FAS) have been developed [21]. Such modeling techniques are usually supported by customizations of the SysML. This can be achieved by SysML-Profile in which additional, more specific elements are specified based on the existing objects. An approach to simplify the SysML is given by the Friedenthal et al. with the 'SysML-Lite'. In SysML-Lite, the number of diagrams is reduced significantly and functional modeling is realized by using the SysML activity diagrams [18]. The scheme of functional modeling in relation to physical components is shown in Fig. 2. Functions are represented by the 'activity' element in SysML. The allocation to the physical components is achieved by activity partitions. As a result, both functions and their related components can be shown in a single diagram.

III. Objective

The aim of this paper is to show a generic approach using SysML to increase the understanding of complex products as they can be found in Industrie 4.0. This shall be done with a particular focus on the mechanical domain. The models created shall enable the traceability of customer requirements down to the component level. Furthermore, the model shall facilitate the application of methods and tools from engineering design such as DSM and modular architectures. This shall be done with a particular focus on simplifying the given tools and providing a framework for intuitive application.

IV. A method for optimizing product architectures using SysML

The method for making existing products accessible for SysML-based optimization and analysis consists of a high-level macro cycle, a SysML-Profile and a reference model. In the macro cycle, the overall approach with the modeling artifacts is determined. The SysML-Profile provides a customization of the SysML for more intuitive modeling of objects in mechanical designs. With the reference model, a generic framework for modeling is given, showing the possible relations between elements.

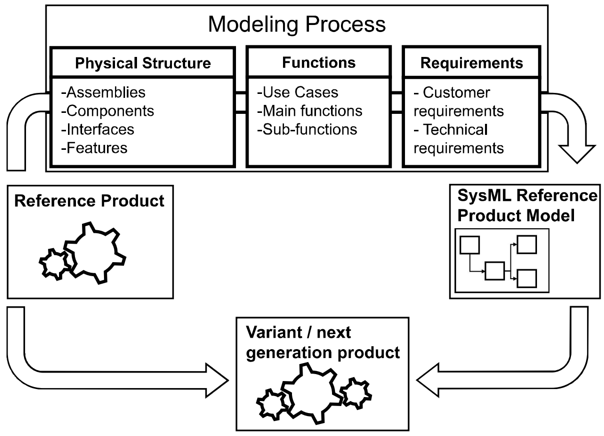

Fig. 3. Macro cycle of the methodology

A. Macro Cycle

The macro cycle of the methodology (Fig. 3) resembles the generic procedure of modeling with its key modeling artifacts. Herein, an existing reference product is used to create a reference system model in SysML. This is done by transferring the existing physical product structure to SysML. Additionally, the model is extended by a functional structure and a requirements model. Together the modeling artifacts form a reference model, which can be used for creating new product variants or generations.

B. SysML Profile

The SysML profile shown in Fig. 4 customizes the SysML for modeling physical product structures. In SysML, 'blocks' are commonly used as modeling elements to represent such structures. Yet a block is an unspecific element, which may represent a system, sub-system or any other object of interest [22].

Therefore, with the profile, specialized blocks are defined in relation to typical physical structures of a product. As a result, the composition of a product as defined in the bill of material (BOM) can be represented. This is achieved by introducing new blocks of the type 'product', 'assembly' and 'component'. For further specification, attributes such as item- and material number can be assigned to the blocks.

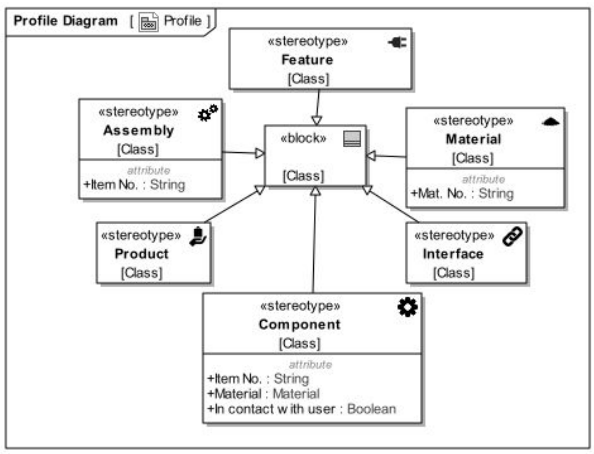

Fig. 4. SysML Profile

ISBN: 978-988-14048-5-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

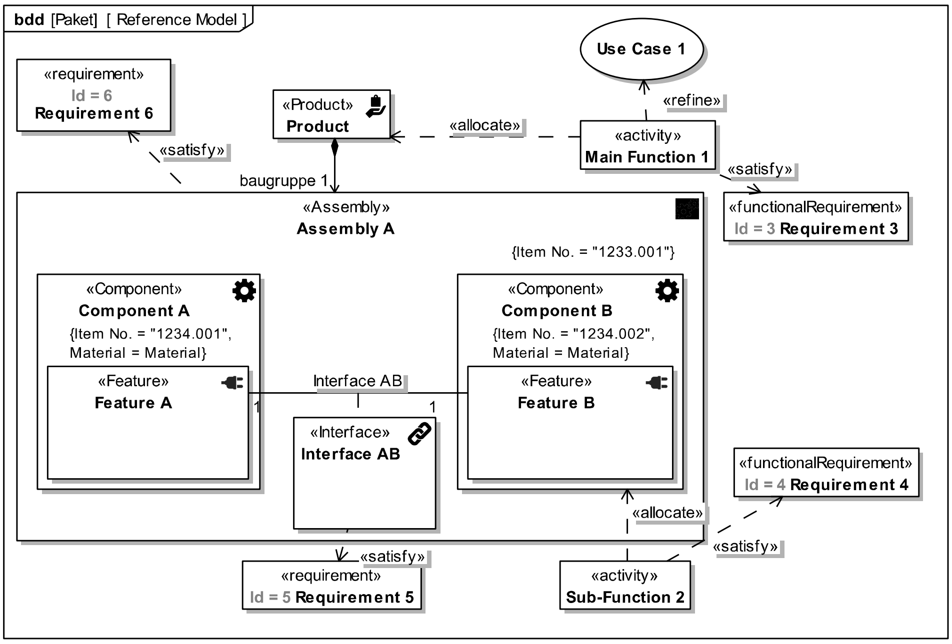

Fig. 5. Reference Model

The hierarchy in the BOM, however, lacks the relations between components which are necessary for analysis. For this reason, 'features' and 'interfaces' are defined in the profile. The 'feature block' shall represent mechanical joints as part of an interface between two components. Such features may be all kinds of mechanical design features such as latches, grooves, etc. Interfaces are modeled as association classes, which allows for further specification and allocation. Interfaces may be either dynamic or rigid connections that can occur between two components.

C. Reference Model

The reference model shown in Fig. 5 provides a framework for establishing product architectures in SysML. The left side shows an assembly as part of a product. The assembly in this case consists of two components. Each of these components has a feature, linked with an interface.

For representing a physical-to-functional mapping, the 'allocate' relationship is used. This relationship can either exist between the product and 'main functions' or components and 'sub-functions'. Each of the sub-functions must be part of a main-function. The 'main-functions' allocated to the product are generally independent from each other and determined by the interaction with the user. User interaction with the product is first defined in use case diagrams and refined later on in activity diagrams showing more detailed flows of functions. Functional flows are modeled separately in activity diagrams according to Fig. 2.

In order to establish relationships between the products architecture and requirements, the 'satisfy' relation is used. Since requirements can be adressed to either product functionality or directly to physical properties, requirements are distinguished in functional and non-functional requirements [23]. Consequently, a non-functional requirement can be satisfied by the product, its assemblies, components or interfaces. Functional requirements may be satisfied by functions allocated to the physical structure. The reference model is designed to provide a general purpose framework for modeling by limiting the relations between the modeling artifacts. This leads to a consistent model which enables analysis later on.

V. RESULTS

As a result of the consistent modeling on the basis of the reference model, various forms of analysis can be performed. As an example, a DSM which shows the dependencies between two components can be generated automatically from the model (Fig. 6). These dependencies shown in the DSM are given by the specific interfaces between components. This information can be used for further evaluation of adaption. Additionally, the physical-to-functional mapping can be visualized in the form of matrices. Through this, products may be optimized towards modular or integral architectures. The

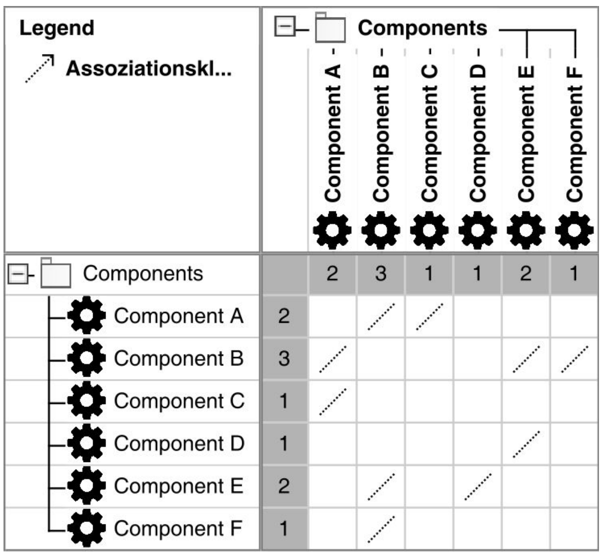

Fig. 6. DSM showing the dependencies of components in a product

ISBN: 978-988-14048-5-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

practical application of the modeling procedure has shown advantages when single components have to be changed according to the customer's demand. In this case, the impact of the change of one component on other components could be anticipated saving time in development. The enhanced traceability inherently provided by the system model has also shown significant advantages of the model-based approach in comparison to conventional methods. Thus, the approach helped to overcome the hurdles given by regulatory constrains for medical devices.

VI. Conclusion and Outlook

This paper has shown a generic methodology for transferring existing product structures to a SysML-Model. With the modeling artifacts of functions and requirements, the physical structure of products could be extended for further analysis. This has shown to be a suitable approach to managing the high individuality in products that is demanded by the vision of Industrie 4.0. It has been shown that limiting the modeling elements and providing a framework assists users with adopting MBSE in their workflows.

Despite the performed customization of the SysML, the language still remains complex and intuitiveness of the modeling process has yet to be improved. Since the demonstrated approach focuses on the mechanical domain, the successful application in interdisciplinary projects has still to be proven. Using the SysML as discipline-neutral language generally offers the ability to integrate the introduced model into an interdisciplinary product specification.

Sate-of-the-art product lifecycle management systems (PLM) provide interfaces for the exchange of product data created by computer aided design (CAD) to SysML models. This offers the possibility to automatically transfer physical structures to SysML which could reduce modeling efforts. Hence, further research is needed to investigate the potential of the method introduced in this paper in combination with PLM-Systems.

References

[1] U. Sendler, *Industrie 4.0 grenzenlos*. Berlin, Heidelberg: Springer, 2016.
[2] W. Dorst, *Umsetzungsstrategie Industrie 4.0: Ergebnisbericht der Plattform Industrie 4.0*. Berlin and Frankfurt/Main: Bitkom and VDMA and ZVEI, 2015.
[3] E. A. Lee, "Computing foundations and practice for cyber-physical systems: A preliminary report," Berkeley, CA. [Online]. Available: http://www2.eecs.berkeley.edu/Pubs/TechRpts/2007/EECS-2007-72.html
[4] R. Anderl, *Leitfaden Industrie 4.0: Orientierungshilfe zur Einführung in den Mittelstand*. Frankfurt am Main: VDMA-Verl., 2015.
[5] T. Bauernhansl, M. ten Hompel, and B. Vogel-Heuser, *Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration*. Wiesbaden: Springer Vieweg, 2014.
[6] J. Feldhusen and K.-H. Grote, Eds., *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung*, 8th ed. Berlin and Heidelberg: Springer Vieweg, 2013.
[7] M. Maurer, *Complexity management in engineering design - a primer*. Berlin, Heidelberg: Springer, 2017.
[8] Regulatory Compliance Associates Inc, "Correspondence between iso 13485:2016 and 21 cfr part 820 qms requirements," Pleasant Prairie, WI. [Online]. Available: https://www.rcainc.com/wp-content/uploads/2017/06/ISO-Comparison-Matrix-jw-mp.pdf.
[9] T. Weilkiens and R. M. Soley, *Systems Engineering mit SysML/UML: Anforderungen, Analyse, Architektur*, 3rd ed. Heidelberg: dpunkt.verl., 2014.
[10] D. D. Walden, G. J. Roedler, K. Forsberg, R. D. Hamelin, and T. M. Shortell, Eds., *Systems engineering handbook: A guide for system life cycle processes and activities ; INCOSE-TP-2003-002-04, 2015*, 4th ed. Hoboken, NJ: Wiley, 2015.
[11] O. Alt, *Modellbasierte Systementwicklung mit SysML*. München: Hanser, 2012.
[12] J. Gausemeier, A. Czaja, and O. Wiederkehr, "Studie: Systems engineering in der industriellen praxis," in *Tag des Systems Engineering*, M. Maurer and S.-O. Schulze, Eds. München: Hanser, 2013.
[13] J. C. Zingel, *Basisdefinition einer gemeinsamen Sprache der Produktentwicklung im Kontext der Modellbildung technischer Systeme und einer Modellierungstechnik für Zielsystem und Objektsystem technischer Systeme in SysML auf Grundlage des ZHO-Prinzips*, ser. Forschungsberichte: IPEK, Karlsruhe, 2013, vol. 70.
[14] S. Maisenbacher and K. Kernschmidt, "Using dsm and mdm methodologies to analyze structural sysml models," in *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2013*, IEEE, Ed. Piscataway, NJ: IEEE, 2013.
[15] N. Bursac, *Model Based Systems Engineering zur Unterstützung der Baukastenentwicklung im Kontext der Frühen Phase der Produktgenerationsentwicklung*, ser. Forschungsberichte: IPEK, Karlsruhe, 2016, vol. 93.
[16] M. Kratochvíl and C. Carson., *Growing Modular: Mass Customization of Complex Products, Services and Software*, 1st ed. Berlin, Heidelberg: Springer-Verlag, 2005.
[17] M. Maurer, N.-O. Boesch, G. Sheng, and B. Tzonev, "A tool for modelling flexible product structures–mofleps," in *DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 15.-18.08. 2005*, 2005.
[18] S. Friedenthal, *A practical guide to SysML: The systems modeling language*, third edition ed. Waltham, MA: Morgan Kaufman, 2015.
[19] R. Haberfellner, Ed., *Systems Engineering: Grundlagen und Anwendung*, 12nd ed. Zürich: Orell Füssli, 2012.
[20] M. Eigner, D. Roubanov, and R. Zafirov, Eds., *Modellbasierte virtuelle Produktentwicklung*. Berlin: Springer Vieweg, 2014.
[21] J. G. Lamm and T. Weilkiens, Eds., *Functional Architectures in SysML*. München: Carl Hanser Verlag, 2010.
[22] C. Rupp and S. Queins, *UML 2 glasklar: Praxiswissen für die UML-Modellierung*, 4th ed. München: Hanser, 2012.
[23] I. Baumgart, "Requirements engineering," in *Handbuch Produktentwicklung*, U. Lindemann, Ed. München: Hanser, 2016.