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Implementation and Assessment of a Comprehensive Model-Based Systems Engineering Methodology with Regard to User Acceptance in Practice

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Abstract

Model-Based Systems Engineering (MBSE) is becoming increasingly popular, not only in research but also in industrial companies. However, MBSE approaches (i.e. methods, frameworks, ontologies, and tools) are usually developed at a scientific level, so that they are too generic and formal for a company's internal use leading to acceptance issues in industrial practice. Against this background, this contribution presents a comprehensive user-oriented MBSE methodology tackling this lack of acceptance in industrial practice. Based on ten previously derived fields of action for individual and organizational acceptance of MBSE approaches, a first positive evaluation of the MBSE methodology has been received. In this contribution, a further developed MBSE methodology is presented, which is created in cooperation of partners from research and industry. Assessment of this further developed MBSE methodology with six companies across different industries shows a positive impact on acceptance in comparison to existing MBSE approaches across the identified fields of action. Major improvements are seen regarding the perceived performance and benefit of MBSE, the usability of the modeling tool, and the communication within a development team. Smaller improvements are noted regarding the establishment of a clear target picture and modeling process, as well as in tackling ambiguity when modeling in a development team. In addition, research at one of the industrial partners shows that company-specific tailoring and implementation of the developed MBSE methodology can be performed in a fast and straightforward way.

Keywords: Model-Based Systems Engineering, modeling, product development, user-orientation, evaluation

1. Introduction and Motivation

Model-Based Systems Engineering (MBSE) is gaining increasing popularity across different industrial applications [1]. MBSE primarily offers the possibility of making diverse information from product development accessible to various stakeholders in a targeted and transparent manner and across projects. While at the moment a consistent use of MBSE is only seen in individual pioneering companies, several companies report that they are introducing MBSE in their work [1, 2]. A multitude of MBSE approaches have been proposed in literature (see e.g. [3]). However, surveys with representatives from industry state, that often these approaches cannot be directly transferred to company practice [2]. In addition, many users nowadays have little to no experience in creating and analyzing system models. The MBSE approaches developed at the scientific level are often too generic and formal for the company's internal use case and must be tailored to individual needs. Thus, new flexible and user-oriented MBSE approaches that are easily adaptable to the specific needs of a company are required. In this contribution, a MBSE methodology aiming at addressing factors for user acceptance of MBSE in industrial applications is introduced and initially evaluated. The research builds on existing descriptions of the IPEK MBSE

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methodology [4]. This methodology is applied and further developed with partners from industry and research in the Federal Ministry of Education and Research Germany (BMBF)-funded research Project MoSyS – Human Oriented Design of Complex Systems of Systems. To assess the impact of the resulting MoSyS MBSE methodology on user acceptance of MBSE, interviews are conducted with six partner companies. For the company HARTING Applied Technologies (HARTING AT), a tailored application is introduced.

2. State of Research

2.1. Advanced Systems Engineering (ASE) and Model-Based Systems Engineering (MBSE)

Increasing interconnectedness and system complexity characterize today's product engineering [5, 6]. Advanced Systems Engineering (ASE) provides a context for the integration of approaches and tools of modern engineering. ASE integrates three pillars: Advanced Systems, Advanced Engineering, and Systems Engineering [2].

Advanced Systems are characterized as intelligent, cyber-physical systems with a high degree of autonomy, interconnectedness, and socio-technical interaction. They often constitute a part of a larger so-called System of Systems (SoS). Advanced Engineering represents new technical and organizational approaches to engineering that enrich methods, processes, tools, and work organizations with creative, agile, and digital aspects. Systems Engineering is an approach that supports the collaboration of different disciplines and the handling of the associated complexity in projects and organizations. [2]

According to INCOSE, MBSE forms the future of Systems Engineering [6]. MBSE describes a formalized approach to the creation of cross-domain system models. Such an MBSE-system model may contain (but is not limited to) elements to support the technical processes of the INCOSE Systems Engineering Handbook/ISO 15288 [7]. To create such a system model, three essential “pillars” are needed: a modeling language, a modeling tool, and a method and/or an architecture framework to use the language [8]. According to Holt and Perry, the modeling language should be based on an ontology that is implemented using a standard formal language such as SysML [9]. In addition, viewpoints, arranged in an architecture framework, describe filters on the system model, focusing on sub-sets of the ontology [9]. For this contribution, the term “comprehensive” in the methodology description denotes the integrated and mutually harmonized consideration and development of a modeling language, a modeling method, tool customization to support modeling as well as an architecture framework for the models to be created.

2.2. Fields of action to address the acceptance of MBSE approaches in practice

The evaluation of the acceptance of Systems Engineering and in particular MBSE in practice is a subject of research from different perspectives. Lohmeyer et al. describe six evaluation criteria to assess the acceptance of MBSE approaches [10]. Furthermore, the authors discern between acceptance by individuals (individual acceptance) and on an organizational level (organizational acceptance). Bretz et al. investigate barriers to the introduction of Systems Engineering [11]. While this research investigates rather the introduction process, conclusions can be drawn regarding the acceptance of MBSE approaches in particular. Several studies from the last years investigate the current state of Systems Engineering in practice (see e.g. [2, 12]). Therein, challenges for the use of (MB)SE described by interviewees from industry and research are analyzed and consolidated. Based on this existing research, Mandel et al. derive ten fields of action for the acceptance of MBSE approaches (see Table 1, [4]). As for Lohmeyer et al. [10], those fields of action are discerned between individual (I) and organizational (O) acceptance. The fields of action can on the one hand serve to derive objectives and requirements for the development of MBSE approaches to support their acceptance. On the other hand, the fields of action can be used to structure the evaluation of MBSE approaches e.g., in the form of semi-structured interviews or surveys.

Table 1: Fields of action for the acceptance of MBSE approaches [4]

Individual Acceptance	Organizational Acceptance
I1: Perceived performance of individual users	O1: (Monetary) benefit-effort ratio
I2: Intuitiveness of applicability	O2: Teach and learnability
I3: Flexibility and adaptability	O3: Reusability and extendibility
I4: Usability of the modeling tool	O4: Problem orientation
I5: Target vision and modeling procedure clear for users	
I5: Appropriate level of formalization	

Mandel et al. further describe the development and assessment of the acceptance of an MBSE methodology along those fields of action [4]. By structuring the interviews along them, the analysis of strengths and areas for further improvement of the developed MBSE methodology regarding its acceptance can be specified.

2.3. Existing MBSE approaches

In industry and research, various MBSE approaches, covering different pillars of MBSE, are described (see e.g. [3]). In order to support the placement of the research described in this paper, a non-exhaustive overview of popular MBSE approaches is given in this paragraph.

A first category of MBSE approaches focuses on method descriptions. The Object-Oriented Systems Engineering Method (OOSEM) is a modeling method developed within the INCOSE OOSEM Working Group to support the specification, analysis, and design as well as the verification of a system [5]. The FAS (Functional Architectures for Systems) method aims at supporting the development of the functional system architecture based on use cases and detailed activities [13]. Unlike other modeling methods, SYSMOD (System Modeling Process) does not require a fixed sequence of activities to be followed but serves as a toolbox for covering different aspects of the creation of an MBSE system model [14].

Other MBSE approaches integrate the description of modeling methods with customized modeling languages. CONSENS (CONceptual design Specification technique for the Engineering of mechatronic Systems) aims at enabling a holistic and interdisciplinary, engineering-oriented description of the system model [15]. Even another step further, for the ARCADIA method, including language specifications, a customized tool called Capella is developed and provided as open-source software [16].

Further MBSE approaches follow the description of Holt and Perry [9] and establish architecture frameworks consisting of a set of viewpoints to create system models. The Software Platform Embedded Systems (SPES) is a two-axis framework for structuring a system model [17]. The vertical axis describes the abstraction levels (system, sub-system, etc.) and the horizontal axis describes the four different viewpoints: Requirements, Functional, Logical, and Technical. This allows to visualize model information on a desired granularity level and in a desired viewpoint for different stakeholders. Similarly, MagicGrid is Dassault Systèmes' approach based on the SysML modeling language that combines a modeling method and an architecture framework [18]. The MagicGrid framework is also represented as a two-dimensional matrix of viewpoints and is available as a template for the modeling tool Cameo Systems Modeler [18].

As a comprehensive methodology covering all the pillars of MBSE, Mandel et al. present the IPEK MBSE methodology. It combines a reusable model structure, presented in the form of an architecture framework, with targeted modeling activities. In doing so, identified fields of action for an improved organizational and individual acceptance of MBSE approaches are addressed. In the presented methodology, agile modeling of product, reference- and validation systems is supported. The used framework can be extended by further layers, e.g. for engineering change management, as needed. [4]

3. Research gap and research questions

The use of MBSE to support the development of complex systems is widely regarded to be beneficial if not essential in today's product development. However, studies show that MBSE approaches appear to lack acceptance in practice. In existing research, we identified fields of action to address barriers to acceptance. We developed the IPEK MBSE methodology, addressing those fields of action. Studies in an innovation project of students and an industry partner indicate a positive impact of the IPEK MBSE methodology for individual and organizational acceptance [4].

In this contribution, further development and assessment of the developed MBSE methodology with partners from industry are presented. The goal of the research is to analyze the impact of the MBSE methodology regarding the fields of action with practitioners from different industries and with different backgrounds. Therefore, we first describe the further development of the MBSE methodology in cooperation and based on continuous feedback from the industry partners in a project context. We aim at investigating, if and how the further developed MBSE methodology impacts the assessment of the fields of action in comparison to existing MBSE approaches known and used by the industry partners. In addition, the further developed MBSE methodology aims at being easily applicable to the context of industrial applications. Therefore, we describe the first insights from a company-specific implementation of the methodology. For the research, we formulate three research questions (RQ):

- RQ 1: How can the existing IPEK-MBSE methodology be further developed to fit demands gained from the industry partners?
- RQ 2: How and to what extent does the (further) developed MBSE methodology impact the assessment of the fields of action in comparison to the MBSE approaches known by the partners?
- RQ 3: How may a tailored (i. e. company-specific) MBSE approach be derived from the developed MBSE methodology and introduced in a company context?

A central environment for the research described in this paper is the project MoSyS. MoSyS includes 18 partners from industry and research and aims at developing new methods, tools, and guidelines to support the development of todays and future complex systems of systems. Therein, the IPEK MBSE methodology from existing research is applied, concretized, and further developed to a MoSyS MBSE methodology (RQ 1). To tackle RQ 2, seven semi-structured interviews with partners from six different companies are performed. The company-specific implementation of the MoSyS MBSE methodology is performed at HARTING AT (RQ 3). As a user company, HARTING AT is involved in the MoSyS research project with the motivation to introduce and consolidate MBSE in its own company. The company develops, designs, and manufactures special-purpose machines in the field of assembly and automation technology and has a high level of expertise in the development of batch-size 1 solutions.

4. The MoSyS MBSE methodology

Over the first two years of the project duration, concepts from the IPEK MBSE methodology have been introduced in MoSyS and further developed in several workshops. The further development aims at refining the MBSE methodology to fit demands seen in industrial applications of MBSE. The developed MoSyS MBSE methodology consists of the four MBSE pillars: an ontology, a set of viewpoints arranged in an architecture framework, methodical descriptions of individual modeling activities as well as tool customization and templates to support the modeling.

The ontology, as the basis for the modeling language, is developed and refined in regular workshops with ten partners from industry and research within the MoSyS project. In the ontology, classes of elements as well as their relations that should be used for modeling are defined. Not only classes for the description of the product but also for modeling of the problem space (e.g. Stakeholder Needs), production system (e.g. Production Processes), and validation system (e.g. Test Cases) are defined. The ontology is further used to define new classes of modeling elements in the software tool iQUAVIS as well as for the definition of a SysML profile.

Based on the ontology, we define a structuring architecture framework and viewpoints. A viewpoint of the framework is based on concerns that a stakeholder wants to resolve by working with the model. Those concerns have also been identified and detailed with the partners from the MoSyS project. They include, for example, the analysis of environmental- and boundary conditions for the system in its use or the functional architecture of the system. Each viewpoint covers a sub-set of the ontology, i.e. selected classes and their dependencies that should be modeled for the viewpoint. Like this, when implementing the viewpoints in a tool, the useable elements for modeling can be restricted, helping users in focusing on exactly the information, they should present in the viewpoint. Just like the ontology, the viewpoints for the MoSyS MBSE methodology are implemented as templates in iQUAVIS as well as Cameo Systems Modeler. The viewpoints can be structured along different dimensions [19]. In this way, they can be represented in multi-dimensional matrices, similar as it is done for the SPES or MagicGrid framework. The framework for the MoSyS MBSE methodology uses a two-dimensional matrix for each, product, production system, and validation system. The first dimension structures the framework into the description of Problem Space, Requirements, Functional Architecture, Logical Architecture, and Physical Architecture. The second dimension discerns between viewpoints for the description of the system itself and for traceability across different elements.

While matrix-style frameworks support a clear, reusable structure for modeling, especially users that are new to MBSE appear to favor flowchart-like descriptions to guide their modeling [4]. However, flowchart descriptions of a modeling method may guide users to follow a strictly sequential, waterfall-like performing of modeling activities. This does not reflect the practice of product development where, especially for agile approaches, activities are performed iteratively over the whole product development process. To support iterative development while at the same time using easily understandable flowchart descriptions to guide users in modeling, the MoSyS MBSE methodology integrates the concepts of reusable modeling activities from the IPEK MBSE methodology [4]. Therein, a modeling activity describes a consistent micro-procedure for a modeling task (e. g., "model use cases"). Each step of the modeling activity describes analysis (drawing information from the model) or synthesis (adding/altering information to/from the model) activities using the defined viewpoints. An overview of the described concepts of the MoSyS MBSE methodology is given in Fig. 1.

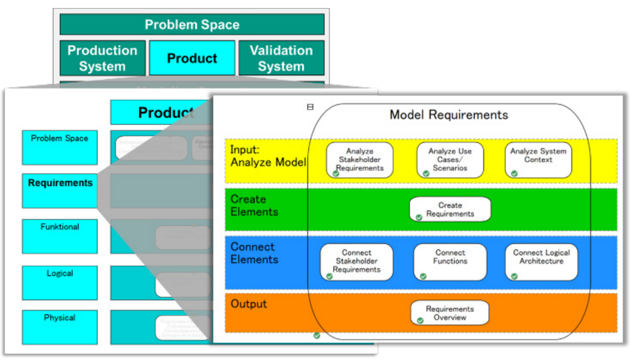

Fig. 1: Structure of the MoSyS MBSE methodology (excerpt)

5. Initial assessment of the MoSyS MBSE methodology

5.1. *Background of the interview study*

In order to analyze, if and how the MoSyS MBSE methodology may impact the acceptance of MBSE in practice, seven semi-structured interviews with MoSyS partners from six companies are performed. The companies originate in machinery (one person), special-purpose engineering (three persons), automotive supplier (one person), product development consultancy (one person), and an MBSE tool provider/consultant (one person). Most of the interviewed persons see their expertise and previous experience with MBSE at a medium to higher medium level. One person each indicates that they are at a beginner or an expert level.

The interviewees participated in the further development of the MoSyS MBSE methodology in the form of multiple workshops over the course of around two years of the MoSyS project. In parallel, continuous exemplary applications of the MoSyS MBSE methodology for the modeling of products and validation systems from the partners have been performed. In this way, a continuous iteration between application, feedback, and further development could be realized.

To structure the interview questions, the described fields of action for acceptance of MBSE (see paragraph 2.2) are used as categories. For each field of action, interviewees are asked to compare the MoSyS MBSE methodology to MBSE approaches previously known to them regarding different aspects (see Table 2). It has to be noted, that the asked questions do not raise the claim to fully evaluate the field of action. The formulation of the questions along the identified fields of action is rather meant to support an extensive analysis of the acceptance of the MoSyS MBSE methodology.

Table 2: Interview questions, organized along the identified fields of action for the acceptance of MBSE approaches

Field of action	Aspects addressed in the questions asked
I1	Perceived performance of MBSE Support for finding the appropriate views/activities that can be helpful for modeling in a specific project
I2	Finding a quick start into modeling Targeted location of modeling activities and views that are relevant to a given modeling purpose/problem statement
I3	Flexible, iterative, agile execution of modeling activities
I4	Usability of the modeling tool
I5	Establishment of a clear target picture for the use of MBSE in a project Continuous use of MBSE throughout all phases of the project
I6	Communication within a team Communication to external stakeholders Support for unambiguousness in modeling and communication
O1	Benefit/effort ratio of MBSE
O2	Teachability/learnability of the methodology
O3	Specific adaptation/extension to own needs Reusability of (parts of) created models
O4	Support for modeling the problem space

To support the analysis of the interviews, interviewees were initially asked to rate their answers on a scale from -2 (the MoSyS MBSE methodology is performing significantly worse with regard to the question) to + 2 (the MoSyS MBSE methodology is performing significantly better with regard to the question). Like this, a numerical analysis of answers can be performed. Discussions of the answers and to further open questions are recorded to further support their interpretation.

5.2. *Results of the interview study*

Analysis of the performed interviews shows, that on average the partners see a positive impact of the developed MBSE methodology across all fields of action. The areas, where interviewees see the biggest improvements in comparison to existing MBSE approaches are shown in Fig. 2.

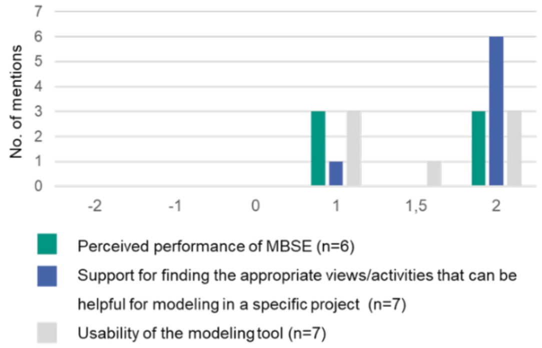

Fig. 2: Identified areas of biggest improvement for MBSE acceptance

The areas, where interviewees see the smallest improvements are shown in Fig. 3.

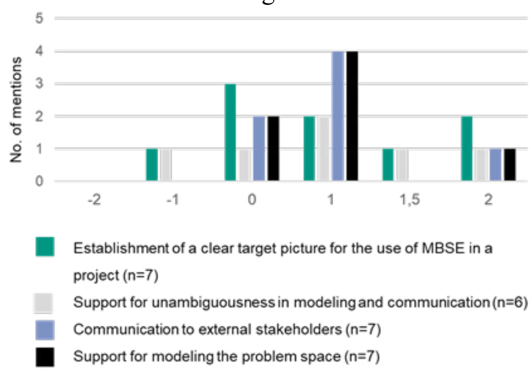

Fig. 3: Identified areas of lowest improvement for MBSE acceptance

Future research needs to further investigate these areas, where interviewees see only minor improvements or some even worsening with regard to existing MBSE approaches. In this context, notable open comments from the interviews include the proposition, to further equip the developed MoSyS MBSE methodology with a stakeholder-specific filtering concept to automatically hide parts of the MBSE methodology that are not relevant for the tasks of a specific stakeholder.

An observation worth noting is, that respondents rate the improvement in communication within a team on a high level (average rating of 1.43). However, improvements regarding communication with external partners (e.g., customers) and unambiguousness in modeling and communication are rated significantly lower (average ratings of 0.86 and 0.75, respectively). The support for communicating contents of created models to external stakeholders was already one of the weakest rated points in the initial analysis of the IPEK MBSE methodology [4]. Thus, further research needs to investigate possibilities for communicating and discussing contents of the created models in a low-threshold form to external partners.

6. Company-specific implementation of the MoSyS MBSE methodology

Initial efforts for a target-oriented implementation of the MoSyS MBSE methodology are performed at HARTING AT. Early insights from this implementation will be discussed here to support the assessment of the MoSyS MBSE methodology. Due to a high degree of individuality, the new development effort and thus also efforts for system modeling at HARTING AT are high for each project. It is therefore necessary to keep the modeling effort as simple and low as possible. Along the development process, it was first analyzed which artifacts in future development projects should be described in a model-based manner. For this purpose, a company-specific ontology was developed analogous to the MoSyS MBSE methodology. Within the analysis phase, various methods, such as an environmental analysis as well as the consideration of requirements and risks, were located to understand the task and to document it in a model-based manner. For each of these methods, the sequence of concrete analysis and synthesis activities was defined in the form of modeling activities. In addition, it was defined in which form of representation (e. g., tables, hierarchical structure models, flowcharts) these activities could be documented. These viewpoints were then transferred as templates to the modeling tool iQUAVIS. In addition to detailed method documentation, the various methods in form of step-by-step guides were implemented into the modeling tool. Interactive navigation within the modeling activities, so that the views can be opened directly for editing, is realized by the use of hyperlinks in the modeling tool. The method instructions are in turn integrated into a project template where they are arranged in the graphically represented development process to support the user, see Fig. 4.

The individual methods were assigned to the different project phases to support the modeler with the sequence for developing a system model. High quality of the system model can be guaranteed by the predefined modeling templates and the method guidelines. Due to the various modelers in the same project and a large number of interconnections between different data elements, such specifications are necessary to make the structure of the system model manageable.

The company-specific adjusted MBSE methodology, including the modeling guidelines and view templates, enables the execution of MBSE efficiently and equally across projects. Furthermore, the adjustment to stakeholder concerns e.g., by adding data attributes in views, has increased acceptance.

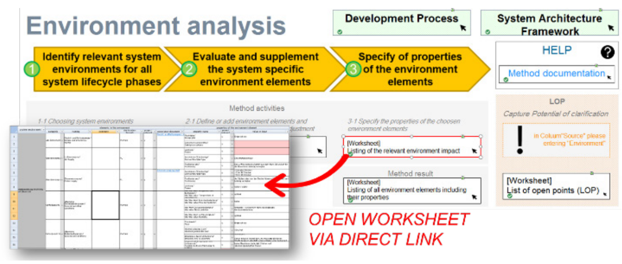

Fig. 4: Example view of the modeling activities in iQUAVIS

7. Statement of contribution and discussion

In this paper, the comprehensive MoSyS MBSE methodology consisting of a modeling language, architecture framework, tool customization, and a modeling method of reoccurring modeling activities is presented. The analysis of seven semi-structured interviews indicates, that the MoSyS MBSE methodology may have a positive impact on user acceptance across all described fields of action. It is thus expected to make a contribution to overcoming the described challenges of acceptance of MBSE in practice. Aspects for further development have been identified especially in supporting the establishment of a clear target picture for users as well as communicating contents of the created models to external stakeholders like customers.

However, the fact that the interviewees participated in the further development of the MoSyS MBSE methodology has to be noted. On the one hand, like this it could be ensured, that experiences and best practices from various industries could be implemented in the methodology. On the other hand, the answers to the interviews have to be analyzed carefully in front of this background. A presumably existing bias, as inputs from the partners have already been taken into account when developing the methodology, has to be further analyzed. In addition, future research needs to detail the identified fields of action in order to expand the coverage of the fields by questions asked in the interviews.

As demonstrated in the example of HARTING AT, the MoSyS MBSE methodology can be straightforwardly customized to fit a company-specific context. Further investigation of this customization and introduction process is already ongoing. Their analysis, as well as the analysis of the acceptance of the introduced MBSE approach, will be part of future research. In addition, the assessment and company-specific implementation were performed together with companies with prior experience in MBSE or participating in MoSyS, an ASE research project. Further research needs to cover a comprehensive evaluation with further companies having less prior involvement in ASE and that may be less affected by a bias, in order to fortify the results.

8. Outlook

The MoSyS MBSE methodology is further evaluated and refined in the context of the project MoSyS. In particular, solutions for the identified areas of improvement for the MoSyS MBSE methodology (see paragraph 5.2) will be investigated. In addition, further modeling activities will be defined and introduced in the methodology. Especially for modeling activities regarding the validation system, research is already ongoing and shows positive feedback regarding user acceptance [20]. Furthermore, research regarding the introduction of model-based engineering change management into the MoSyS MBSE methodology is ongoing [21].

In addition, the development of further company-specific implementations of the MBSE methodology with additional companies can give additional insights into its applicability and acceptance. HARTING AT will validate the MoSyS MBSE methodology adapted so far in selected pilot projects and thereby introduce more and more employees to working with it. The feedback will then be fed back into the MBSE methodology regularly, resulting in improvements through further need-based adjustments. The changes can then be evaluated in new projects and the methodology can thus be integrated more and more into everyday project work.

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