SUPPORTING SYSTEMS ENGINEERING ACTIVITIES BY ARTIFACT-ORIENTED DESCRIPTION AND SELECTION OF METHODS

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ABSTRACT

Systems Engineering (SE) is becoming increasingly relevant in industrial application since more stakeholders are involved in engineering activities. To implement SE, companies have to adapt existing engineering processes and methods. This adaption requires knowledge about new methods as well as their integration into the engineering activities. In order to ensure goal-oriented identification of methods for different SE activities in this contribution an action field profile and the Systems Engineering Method Matrix are proposed. The development of both tools is driven by the assumption that most SE activities and methods can be described based on the artefacts the deliver. In order to get feedback about the proposed tools, semi-structured interviews with two industry partners were conducted, focussing on the tool's usability. These interviews underline the basic usability of the tools and their support to identify SE activities to be supported by (new) methods. Moreover, requirements for further development and adaption are derived from the interviews.

Keywords: Systems Engineering (SE), Design methods, Case study, Design process

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1 INTRODUCTION

Cross-system interactions and an increasing number of functions, making Systems Thinking an essential tool for engineers. Systems Thinking supports a holistic view on cause-effect relationships in delineating, structuring, and subdividing a system. The principles of Systems Thinking are incorporated in Systems Engineering (SE) as an approach for interdisciplinary collaboration within engineering. This approach is becoming increasingly relevant in industry (Dumitrescu et al., 2021) as more stakeholders are involved in engineering activities. To implement SE, companies have to adapt existing engineering processes and methods (Hjartarson et al., 2021). Following the concept of SE illustrated in Figure 1 to streamline the problem solving process, on the one hand, consequent Systems Thinking and an adequate procedure have to be established. On the other hand processes, methods, and tools are needed to implement SE within an organisation.

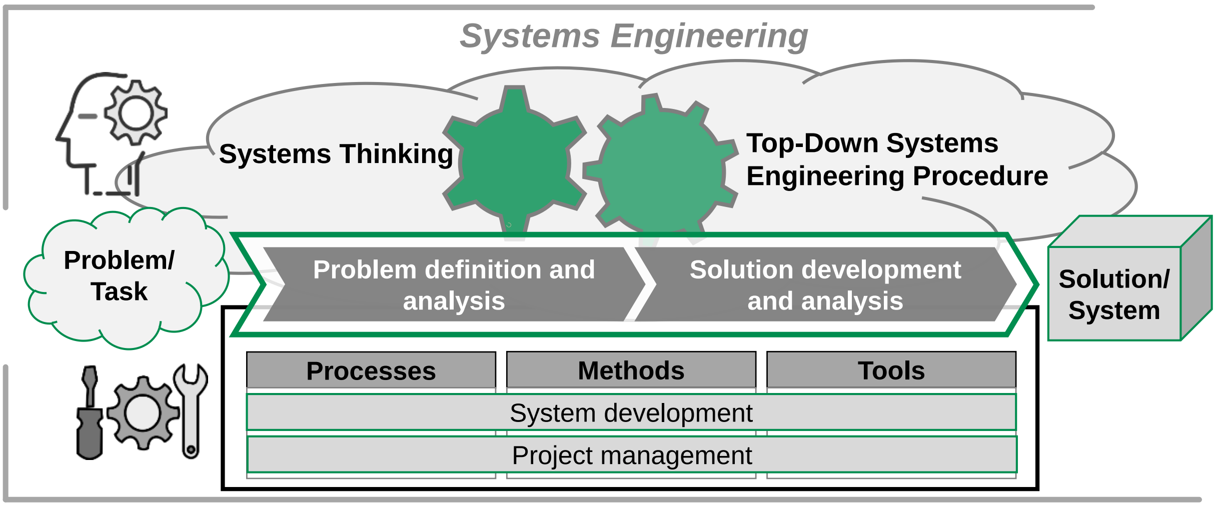

Figure 1. Concept of systems engineering and major fields for implementation within an organization

However, frequently challenges are reported when implementing SE in industrial practice. These challenges include the *transformation of organizational structures* (Friedenthal, 2014; Huldt and Stenius, 2019), a *lack of methods to introduce SE* (Gausemeier et al., 2015), as well as a *diffuse understanding of SE* itself. These challenges correlate with hurdles in the transfer of methods discussed in the engineering design community for years, e.g. Birkhofer et al. (2002a), Wallace (2011), Gericke et al. (2020). While there is a great body on literature including standards focussing on the description of processes, relevant for SE, e.g. ISO 15288 (2015), INCOSE Handbook, Walden et al. (2015), there is little assistance to identify and evaluate the needs to change existing processes and implement new methods within an organization (Inkermann, 2021). In order to support implementation of SE, in this contribution we propose a guideline that enables to evaluate required adaptions of existing engineering activities as well as an artefact-oriented identification of methods. Moreover, the focus on artefacts enables to build up method chains and thus provide a more holistic view upon the complex processes of SE. The main objective of this paper is to explore potentials and challenges of structured process analysis for the implementation of new methods as well as requirements and further fields of action for systematic transfer of knowledge about methods. The contributions made do not include validated concepts for method description and implementation, but insights on how to structure method knowledge and how to explore the need for new methods based on activities and artifacts within the process focussing on initial exploratory interviews with partners form industry. Therefore, the paper is organized as follows. In Section 2 essential terms and the role of methods in SE are introduced. In particular the interaction between activities and methods are explained to enable structured identification of method adaption and implementation of new methods. In Section 3 the research approach and the guiding research questions are introduced. In Section 4, we present an initial concept to structure and provide knowledge about methods based on the definition of activities to be performed in SE. In Section 5, the results of two initial exploratory interviews are reported that enable to derive first conclusions about the proposed concept and derive needs for adaptions and further research.

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2 BACKGROUND AND STATE OF THE ART

Literature in the fields of SE and engineering design presents a divers understanding of terms, resulting in divergent approaches to describe processes, activities, and methods associated with SE. Based on a survey on the status quo of SE in industry and science, Dumitrescu et al. (2021) indicate, that most companies are aware that SE affects processes, methods and IT tools. This is in line with the established understanding of SE as a methodology, see Figure 2 left. In this Section, we clarify the role of methods in SE and explain existing concepts to describe and select engineering methods.

2.1 Terms and definitions – role of methods in systems engineering

According to Estefan (2008) and Gericke et al. (2017), SE must be understood as a methodology comprising processes, methods as well as guidelines and tools to support engineers, see Figure 2 left hand side. A methodology is a clearly and explicitly articulated approach to produce designs for a class of systems, which specifies in more or less detail the activities to be carried out. It defines the relationship and sequencing of activities, the methods to be used for particular activities, and the information artefacts to be produced. Within the field of SE standards like ISO 15288 (2015) are defining core processes and corresponding activities with regard to the life cycle of systems.

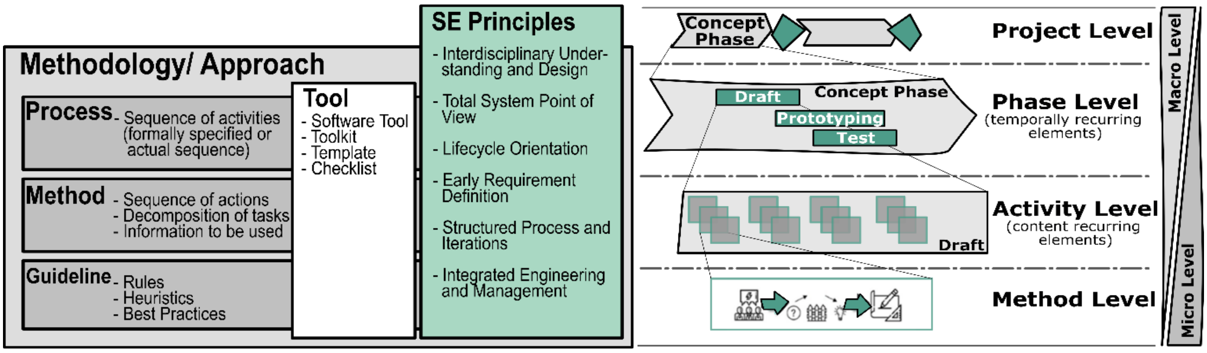

Figure 2: Concept of central terms and their definition based on Gericke et al. (2017) and Inkermann (2021) (left); Different level of planning and implementation within engineering projects based on Lindemann (2009) and Albers et al. (2019b) (right)

Methodologies are driven by principles, indicating the core ideas like *lifecycle orientation* or *total system point of view* underlying the structure of the process, the methods, or guidelines (Inkermann, 2021). In order to clarify the scope and role of methods, it is expedient to distinguish different level for planning degrees of resolution ranging from the whole problem-solving process (macro level) down to the elementary action processes (micro level) (Lindemann, 2009). A major impact on the tailoring and organization of processes and methods is caused by uncertainties given within the planning and implementation phase of a project (Albers et al., 2019b). To address different level of uncertainties, Albers et al. (2019a) propose to distinguish plan-driven, hybrid, and agile development processes. Moreover, the four level point out different elements to support planning and execution of projects. Thus, activities define recurring elements with regard to the content, like requirement definition or documentation. While activities define *what* to do as well as *which* artefact to be generated or manipulated, methods provide assistance on *how* to perform the activity. Therefore, methods define how to decompose activities into a sequence of tasks, how to represent information as well as what information needed as inputs and which tools to use (Gericke et al., 2017). Methods used in SE are mainly focussing on the overall system definition, decomposition as well as integration, verification, and validation of subsystems and systems. With regard to more formal definition of processes and artifacts like given in ISO 15288 (2015) or established in Model-based Systems Engineering (MBSE) (Berschik et al., 2023) methods to support SE should provide a direct link to specific artifacts as the results of application, see Section 4. In this contribution we pick up the structuring of engineering projects into four level proposed by Albers et al. (2019b) and focus on the activity and method level to support process analysis as well as the selection and implementation of methods to support SE.

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2.2 Approaches and requirements to select and describe methods

To implement new engineering methods, knowledge has to be transferred to engineers (Wallace, 2011). Lavrsen et al. (2022) classify the as the *method operationalization* and *method selection* phase within the lifecycle of engineering methods. This phase is followed by the *method adaption*, *method use* and *method evaluation* phases that are performed by the method users. A main challenge is to provide the information relevant for adaption and use of methods in a comprehensive way. Gericke et al. (2017) define five core elements that comprise an engineering method that are a core idea, the intended use, a procedure, a representation, and a tool. While the purpose and scope of a method defined by the intended use is most relevant for selecting a method, the other elements provide support to apply the method. An extensive analysis of attributes used to describe engineering methods is given in Bavendiek (2018). Available models to describe engineering methods differ in the selection, number and structuring of the raised characteristics (Lindemann, 2009). To address the basics character of methods as a procedure leading to a certain result, most of the method descriptions use a process-oriented presentation. Beckmann et al. (2016) propose a method and process visualisation (MPV) to represent all relevant information for the transfer of methods in visually. Albers et al. (2015) propose at digital method profile, comprising a brief description of the method, input and output, respective work steps, required tools and resources, advantages and disadvantages, area of application, as well as examples of application. Moreover, they provide references to similar methods. Bavendiek et al. (2014) use similar attributes to describe methods and focus of characteristics of the engineering team, like team size, to support selection. The process-oriented method model (PoMM) proposed by Birkhofer et al. (2002b) is organized into two sections - the process modules and the access modules. The process modules refer to the inputs, working steps, outputs as well as working aids and general conditions. Contents of the process modules are relevant when applying the method. The access modules are of superordinate character and are designed for a flexible and detailed access to engineering methods. Access modules are the classification of the engineering method, relationship to other engineering methods, specifications, and links. The selection and number of the description characteristics affect the purposeful use of methods. To support the user, the correct number and details of the criteria/ information are to be selected (Birkhofer et al., 2002b). Existing method collections frequently use description models like PoMM, to characterize different methods and arrange the methods based on different aspects, e.g., phases in the development process or the organizational unit. Major differences do exist with regard to the access criteria. In this research, we pick up the attributes and requirements proposed in the existing models to structure and provide knowledge on methods to support SE activities. The focus here is on the artefact-oriented description and selection of methods to build up methods chains for more consistent implementation of SE in industrial practice. In order to gather essential requirements on methods descriptions and application, we conducted an exploratory survey focussing on engineers (n=17) in small and medium-sized enterprises. Thus, detailed description of the procedure are frequently requested (58.8%). Moreover, it was requested by 82.4% of participants to provide upstream and downstream methods to support SE activities. With regarding to the description, it was stated that visual representation of information is more helpful than textual descriptions. For instance, flowcharts, swim lanes or short video clips were considered helpful. Moreover, examples of applications are considered to ease transfer of the method to the design task. These insights form the exploratory survey are in line with the state of the art and thus do not provide new findings from a research perspective. The requirements captured were used to gather structured feedback, see Section 5, about the first prototypes of tools for method selection and knowledge provision.

3 RESEARCH APPROACH

Objective of this research is to develop and evaluate an initial concept to describe and assess knowledge about methods to support SE activities in industrial practice. The overall goal is to support the functional selection of (new) methods based on SE activities that have to be established or improved within a company. Therefore, the frequently occurring challenges reported in the Sections before and the demand for more consistent information handling and the combination of different engineering methods should be addressed focussing on the main activities in SE. To guide the research, the following questions have to be answered:

- How can the necessity to adapt existing processes in engineering organizations for more consequent SE be identified and evaluated?

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- How can the information about SE methods be prepared and made accessible to enable selection and use for different SE activities?

The concept of this research is based on the Design Research Methodology (Blessing and Chakrabarti, 2009). The Descriptive Study I includes the analysis of current models to describe methods and an exploratory survey involving 17 participants from six companies that provides essential criteria to evaluate the solutions proposed. Subsequently, two interacting profiles and support for the selection of suitable SE activities were developed based on the collected requirements and the results from the literature (Prescriptive Study). These results were demonstrated in a case study with participants form different companies (Descriptive Study 2) to get feedback for further improvement. The research environment is formed by several collaborative projects funded by the German Federal Ministry of Education and Research. The results presented do not have the character of validated findings but are used for following research iterations. A feature of this research is the integration of partners form different universities as well as companies involved in six collaborative projects.

4 ADAPTING ACTIVITIES AND METHODS IN SYSTEMS ENGINEERING

Successful application of engineering methods requires meeting the needs and supporting engineers in specific activities. In addition, many methods overlap with regard to their use cases that complicate the selection. To assist engineers in identifying relevant SE activities to focus on and select suitable methods, the following sections present two initial tools to support the adaption of SE activities and implementation of new methods. The proposed process of exploration and selection starts with a delimitation of the present field of action supported by an *action field profile*, which narrows down the activities to be considered. The proposed Systems Engineering Method Matrix (SEMM) indicates appropriate method to support the activities to be supported or improved. The knowledge about the specific method is provided by a method profile.

4.1 Action field profile - Identifying SE Activities to be supported

To get a first overview of the activities suitable to meet the current challenge in engineering projects, an action field profile was developed, summarizing the most relevant information about the present field of action. Each field of action combines a fixed set of SE activities which can be implemented in the given field of action. For instance, the activities *requirements modelling*, *functional architecture modelling* and *logical architecture modelling* are combined in the action field *modelling the solution space*. On the left hand side of the profile, input variables are recorded, see Figure 3. The time required for the application of the activities is indicated for the initial introduction and the continuous time required for the implementation of the referenced activities.

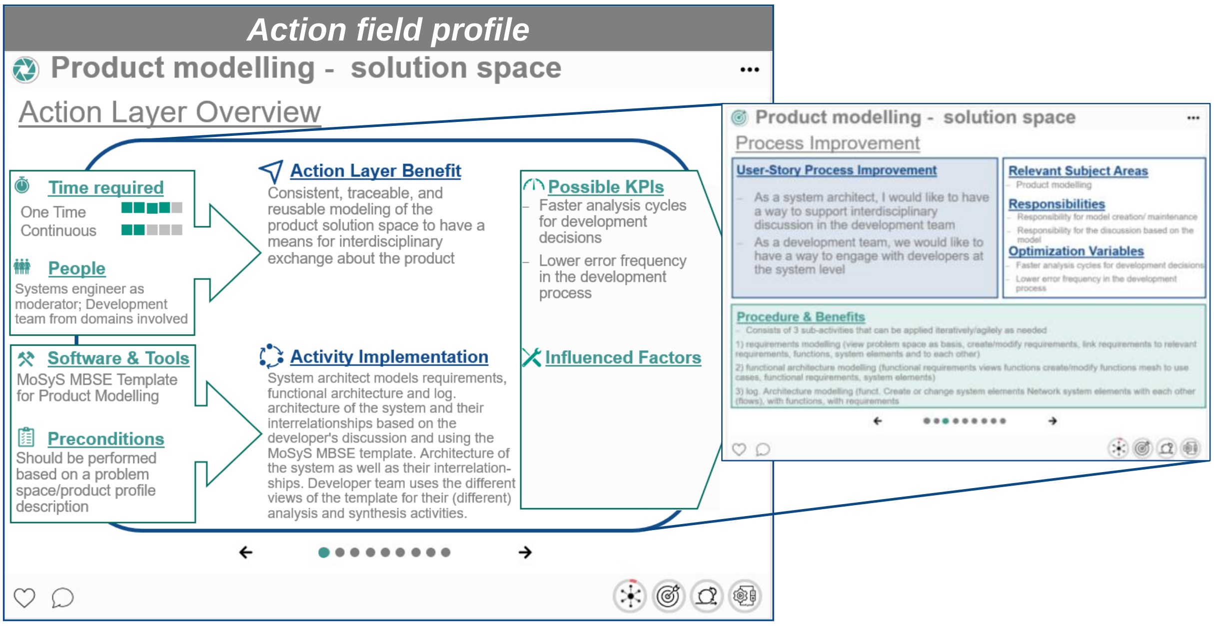

Figure 3: Action field profile "product modelling - soultion space" to identify relevant activities and estimate required efforts for adaption

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This allows a user to assess whether the time required is compatible with available resources. In addition, an overview of the persons involved in activity implementation is provided. The implementation of each set of activities requires certain prerequisites and tools. These are presented in the overview to be able to estimate which efforts are necessary. The main part of the profile describes the benefits and the implementation of the activities. By comparing different profiles, the field of action that best addresses the given challenge can be chosen. In addition, insights can be drawn about the steps to be carried out in order to implement the corresponding activities. On the right hand side of the profile outputs are described, see Figure 3. Here an overview of possible KPIs that can be improved by the set of activities is indicated. This way, the success of the implementation can be continuously measured early in the transformation process. The aim of the first page of the profile is to provide a rough overview of the inputs, benefits, implementation, and outputs of the field of action. Moreover, the profile provides additional content in a slideshow. These are divided into initial situation and prerequisites, process improvement, introduction of the field of action, implementation of the activities, measurement of the process improvement and a summary with additional literature, advantages, and disadvantages. The field of action identified using the action profiles narrows down the SE activities to be considered within the Systems Engineering Method Matrix, see following Subsection.

4.2 Systems engineering method matrix and method profile

To support systematic selection of methods to support the different SE activities that are prioritized using the action field profile, a tool as well as a method profile are proposed in this section. Both, the Systems Engineering Method Matrix (SEMM), see excerpt in Figure 4, and the activity profile follow the hypothesis, that methods in the context of SE are primarily used to produce different results and thus deliver concrete artefacts.

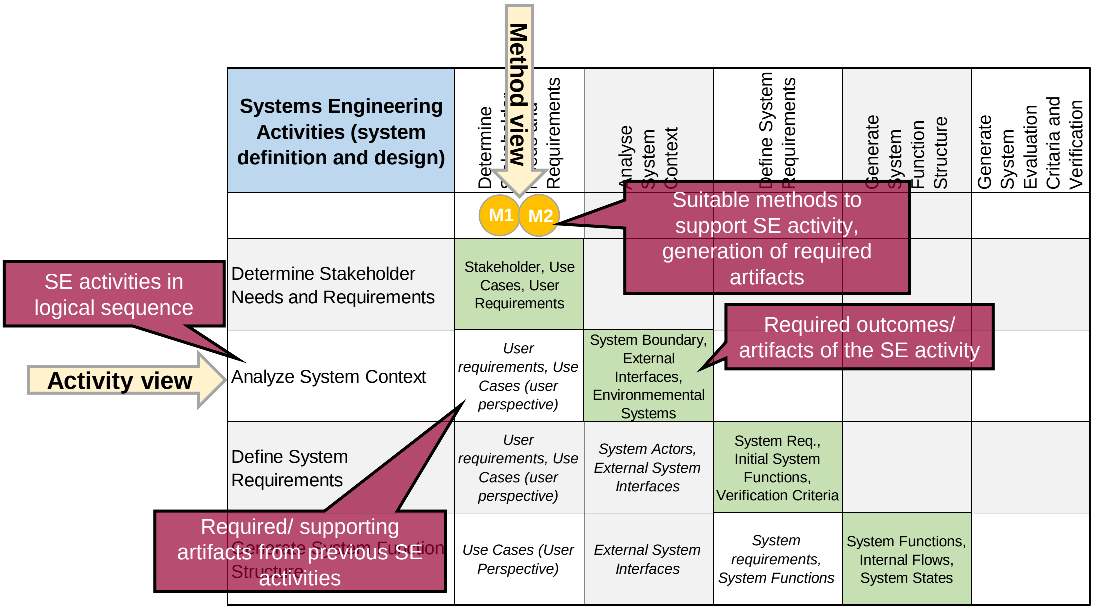

Figure 4: Structure of the systems engineering method matrix (excerpt). SE methods are used to generate specific artefacts for SE activities. Detailed information about the methods are provided by a method profile, see Figure 5

This limits the methods considered here to those supporting SE activities directly, while those fostering creativity or communication in engineering are not in focus. The SEMM was developed to provide a knowledge repository for methods and support the selection of methods for different SE activities. The concept of the SEEM is based on the matrix to classify engineering methods proposed in Jones (1970). The matrix, therefore, represents the relationships between SE activities, required and produced artefacts and specific methods, see excerpt in Figure 4. The methods can be selected based on artefacts and as well as concrete SE activities to be performed. The current prototype of the SEMM comprises ten SE activities of the phase *system definition and design*. These activities form the columns and rows of the matrix, see Figure 4. In the main diagonal, highlighted in green, the required results of the activities are indicated. Here is to be read line by line, e.g. SE activity *analyse system context* provides as results (artefacts) a *system boundary*, *external interfaces* and *environment systems*

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for the system under development. In each case, required/reasonable results from previous activities are indicated in the cells below the main diagonal. The current matrix is realized using a spreadsheet software and comprises 42 methods focussing on the activities of system definition and design on the overall system level. The SEMM supports two scenarios of application.

4.2.1 Analysis of systems engineering activities and artefacts

In order to be able to provide knowledge about methods in a targeted manner, an analysis of the company-specific SE activities and existing artefacts is first required. In a first step, this is supported by the action field profile on company level. Within the SEMM, typical activities and artefacts are specified, e.g., according to ISO 15288 (2015). The process analysis examines on a company-specific basis which SE activities are established or missing, and which results (artefacts) are produced in current engineering projects. This allows to identify weak points and areas for action to implement (new) methods. To guide the analysis of SE activities and artefacts, the following questions should be in focus:

1. Which of the proposed SE activities are established in engineering projects and which artefacts are usually generated?
2. Which focal points result from the analysis, which SE activities should be established in the future and where are (new) methods needed?

These guiding questions help to identify the SE activities and artefacts most relevant within the engineering organization. At the same time, artefacts that are needed to close the information flow and traceability are identified.

4.2.2 Selection of methods to support systems engineering activities

To support the various SE activities, (different) methods are provided in the SEMM. The methods are described using a method profile and are intended to enable independent application in practice. The proposed method profile, see Figure 5, picks up the requirements for structured representation of knowledge about methods and is based on a process-oriented model. Therefore, the inputs and outputs of each method represent one or more artefacts of a SE activity listed in the SEEM. The methods provided in the repository are assessed by the choosing a SE activity in a column and the required artefacts. In the cells above the main diagonal, an ID that is linked with the specific method profile indicates different methods. Since in most cases more than one method is available for one SE activity, engineers can choose the method with regard to the engineering context at hand considering for instance the degree of formalization of the artefacts or the time needed for application of the method. To apply the method the core idea and procedure as well as an example are described within the method profile. Moreover, simple tools and templates as well as tools for MBSE are listed, see Figure 5

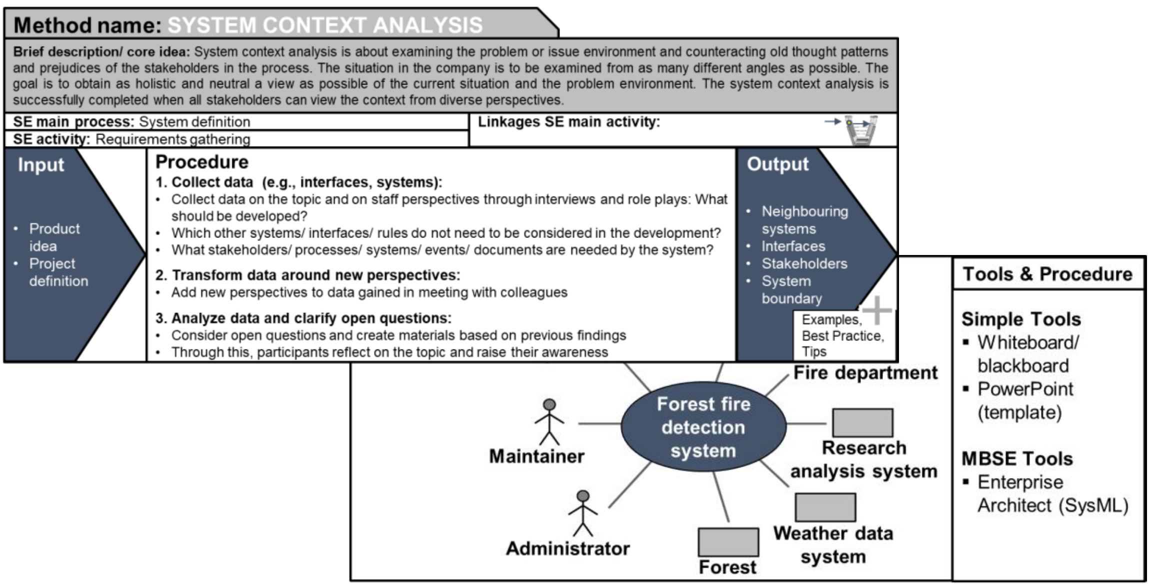

Figure 5: Illustration of the method profile used to provide knowledge about methods for specific SE activities, showing the example of the method system context analysis

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The described SEMM as well as the activity and method profiles are first demonstrators. In order to gather feedback about the basic concept and determine requirements for further improvement and adaptions these prototypes were provided for semi-structured interviews with industry partners.

5 FEEDBACK INTERVIEWS AND FURTHER REQUIREMENTS

Early evaluation and feedback of solution concepts and results becomes relevant not only for the engineering of systems but also within method research (Duehr et al., 2022). Two semi-structured interviews with engineers from different companies were conducted to gather feedback on the applicability of the SEMM and the proposed method profile. SE experts, who did not participate in the development the tools, carried out the interviews. A protocol has been filled to document the insights on the applicability and required adaptions found in each interview. This protocol includes the evaluation of the implementation and needs to support the ten SE activities given in the prototype of the SEMM prototype. In addition, it includes five methods to illustrate the structure and content of the proposed method profile. These first interviews focus on the developed tool's usability and not on the impacts of the tools on the performance within the engineering.

5.1 Results from semi-structured interviews

The semi-structured interviews were conducted in two different companies from the aerospace industry and the medical technology sector. In each interview, one engineer was involved. The interviews were carried out by different persons knowing the companies and the persons interviewed. The interview protocol consisted of open and closed questions regarding the problems, needs, and requirements in the understanding and use of the SEMM and the method profile. In the *first step*, the prototype of the matrix was presented to the interviewees. They were called to evaluate the relevance of SE activities for *system definition and design* within the company and give feedback on the structure and usability of the SEMM. The need to support the given SE activities was rated on a scale covering high, medium, and low. Overall, the interviewees perceived the SEMM as a useful tool for identifying and implementing new SE activities and improving the companies' engineering process. In the first interview, a high demand for new methods was identified for five of ten SE activities (two medium, three low). While most SE activities and resulting artefacts were classified as well established, there were strong inconsistencies between the terminology and activity aggregation used in the company and in the matrix. In the second interview, all activities mentioned in the SEMM were considered to be established, except the elaboration of functional structures. The current documentation within the company focusses on identifying stakeholder needs and performing trade studies. In order to improve the problem analysis and solution identification the focus of method implementation should be on the elaboration of functional structures. In the *second step*, the proposed method profiles were presented to the interviewees, and they were called to evaluate the structure and content considering the application of the methods in industrial practice. In the first interview, on average, on a five-point Likert scale, the structure and ease of finding information was classified as good (4/5). The understandability of method application and results was equally classified as given (4/5). The definition of output artefacts was perceived as a useful means for knowing a method's goal and when it is accomplished for engineers. Additionally, it increases the measurability of a development project's progress for managers. In the second interview, the proposed profiles were rated very good (5/5) in their structure. The content still needs to be worked on so that further requirements are met (4/5).

Requirements elicited by discussing the SEMM and method profiles with the interviewees from the two companies are listed below:

- Establishment of a consistent terminology between the method description and the company
- Information box about differences between similar methods
- Information about roles and experts having the knowledge necessary to conduct a method
- Reference to method templates and tools which significantly simplify conducting the method
- Reference to examples of output artefacts for having a clearly defined picture of the goal and when it is accomplished
- Information about how mandatory artefacts are considering the company's standards
- The description of each method is very theoretical and needs to be adapted to practical application.
- In addition, descriptions for the MedTech area should be adapted so that regulations and QM guidelines are also observed

The initial evaluation reveals first insights into the applicability and required adaptions of the SEMM as well as the method profiles. These findings serve as the basis for further development of the tools within the next development cycle.

5.2 Conclusions from the initial evaluation

The initial evaluation of the proposed tools to identify relevant SE activities and provide knowledge about methods point out their basic applicability and usefulness for engineers in industrial practice. Relevant improvements and adaptions are concerning the extension of the activities and methods provided as well as the terms used in particular for the artefacts. However, the focus on artefacts were considered helpful since these provides a clear reference to the existing engineering process. Since the tools used for the initial evaluation represent very first demonstrators the usability should be improved for instance by an interactive graphical user interface, which is known form current method toolboxes like proposed by Bavendiek (2018). With regard to the methods provided, there is a demand for more formal methods used within Model-based Systems Engineering (MBSE). This demand is in particular given for industry partners that have already implemented processes and associated activities like defined in ISO 15288 (2015). The resulting requirements were discussed with an industry partner from the medical focus is on the roll-out of a core SE-Framework and MBSE for purpose- and function-centric system specification. In this case in becomes clear, that more methods are needed to establish the link of the different artefacts e.g. for verification and validation planning and implementation activities. Here, the proposed SEMM is also seen as a suitable tool to document the different method suitable to support the SE activities. In order to support MBSE, here methods have to focus on the modelling in general, application of modelling language, e.g. SysML, and the use of different diagrams to provide views. Furthermore, modelling templates should be part of the method profiles.

6 DISCUSSION AND OUTLOOK

Methods are essential to support engineers in their different activities. In order to support the goal-oriented identification of methods for different SE activities in this contribution an action field profile and the SEMM are proposed. The development of both tools was driven by the assumption that most SE activities and methods can be described based on the artefacts they deliver. In order to address the requirements of engineers in industrial practice, an exploratory survey with 17 participants from different companies was conducted. In line with the state of the art this survey reveals basic requirements for the design of a method profile as well as the information needed to implement (new) methods. In order to gather feedback about the proposed tools, semi-structured interviews with two industry partners were conducted, focussing on the tool's usability. These interviews underline the usability of the tools and their usefulness to identify SE activities that have to be supported by (new) methods. Moreover, requirements for further development and adaption could be derived from the interviews. The research reported has to be understood as an early stage of the Prescriptive Study and provides insights into a basic solution concept to support selection and implementation of new methods for SE activities focussing on artefacts. The proposed tools have to be evaluated in more detail in order to assess their applicability and usability in industrial practice. Moreover, it is required to work out more information about different methods for MBSE, as well as further SE activities and artefacts. Future work therefore will focus on integrating methods of different degrees of formalization as well as further SE activities for instance for verification and validation as well as risk management into the SEMM. This collection of methods will also address demands of different branches. Based on a digital prototype of the matrix as well as the method profiles it is planned to provide company specific SEMM and method profiles. Both, the process for developing the tailored matrices and profiles as well as their application by different engineers and engineering teams will be evaluated.

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