Role model of model-based systems engineering application

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Abstract. The transition to model-based systems engineering (MBSE) is essential to meet the demands of increasing system complexity, productivity, quality and shorter design cycles. Necessary perspectives, associated roles and competencies for the application of MBSE are not sufficiently defined. The paper at hand presents a role model for the practical application of MBSE based on three major steps: (1) identification, (2) categorization and (3) association of stakeholders, which implement and apply MBSE within an enterprise. The use of the role model is demonstrated and evaluated in a test case based on personas within a fictional scenario which illustrates the implementation of MBSE. The roles, which are adapted to today's conditions, serve as a practical guide comprising all basic conditions that have to be considered when applying MBSE. Practitioners can easily tailor the illustrated results to their own use case.

1. Introduction
Trends like digitalization and increasing system complexity lead to changes in working environment, engineering approaches and required competencies [1–4]. Systems Engineering (SE) practically represents the most relevant approach to handle these challenges. Combining SE with the transition from a document-centric to a model-based approach leads to Model-based Systems Engineering (MBSE). It is essential for Systems Engineering to meet the demands of increasing system complexity, productivity by the engineering team and within the desired quality of the system model [5]. The extending demand for MBSE implies the requirement of specified roles to define the activities and tasks, which have to be performed to implement and apply MBSE. Without corresponding guidelines, the implementation and application of these theoretical approaches fail due to the lack of necessary environmental conditions. An essential element of guidelines to support the implementation is an applicable Role Model. Roles represent and define activities and tasks to be taken into account for performing Systems Engineering throughout the entire system life cycle [6]. Two crucial Lessons Learned from the application of MBSE are [7]: (a) The best way to start modeling is to hire people who already know how to do it and (b) everyone needs training, but not to the same depth. The research question to be raised is stated as follows: Which participating actors and competencies can be defined to enable a successful MBSE application and adaption? The aim of this research paper is to answer the research question and provide guidance to practitioners in implementing MBSE by defining a Role Model for Model-Based Systems Engineering adapted to the specific circumstances of MBSE. Answering the state problem is important to bridge the gap between the theoretical power of MBSE and the challenges of implementation. For this purpose, results from literature as well as from research projects and industrial applications were analyzed and supplemented to define and adjust a Role Model for Model-Based Systems Engineering Application. The Role Model is an incremental part for defining the theory and supporting the application of MBSE.
2. State of the Art

2.1. Systems Engineering
According to Broy [8], a system is divided in Sub-Systems which interact with one another and can be viewed as a whole that interacts with its external environment to achieve an objective. A practically relevant structured approach to handle the complexity of the development process is Systems Engineering. Systems Engineering is defined as a structured cross-disciplinary approach for the development of complex technical systems to achieve a cross-disciplinary optimum in a specified time frame and budget [9]. The practice of Systems Engineering is supported by SE frameworks (for instance, specified in the INCOSE Handbook [6]) and standards (for instance, IEEE 1220 [10] and ISO/IEC 15288 [11]). The application of SE varies across industries, organizations and system types [12]. In the Systems Engineering Handbook, 30 processes are defined to apply Systems Engineering. These processes are divided into four categories: Technical processes, agreement processes, organizational project-enabling processes and technical management processes. Each process is described by relevant inputs, activities and outputs arising from the application. In order to implement SE successfully, companies need support for the implementation of Systems Engineering to transform their processes, organizational structure, role definition and project responsibilities [13]. The results of the application of SE are document-based artefacts. Several documents include information about the system, which are spread across all related disciplines [14]. This results in the difficulty to assess all relevant information about the relationship between requirements, design, analysis and tests [8].

2.2. Model-Based Systems Engineering
Model-Based Systems Engineering (MBSE) is the formalized application of modelling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases [6]. MBSE is expected to replace the document-centric approach that has been practiced by systems engineers in the past and influence the future practice of Systems Engineering by being fully integrated into the definition of Systems Engineering process [15]. MBSE is characterized by the synergistic integration of model based engineering, systems engineering, and – inherently – digital engineering. Mental models are transferred to digital models to create, manage, review and advance product designs from system to component level across all disciplines.

Various modelling languages, methods and tools can be used to apply MBSE. In particular, a major focus for model-based systems engineering approaches is the ability to understand a system from multiple perspectives and to ensure integration across these perspectives. Thus, activities of both individuals in specific tasks as well as teams in collaborative tasks are supported. Advantages of MBSE are early defect detection, model and data reuse, technical and programmatic risk reduction, improved communication, supply chain efficiency, product line definition, and standards conformance [16]. Beside the implementation into the process and the availability of tools, competent people with the right skills are a fundamental aspect to implement MBSE [15]. Compared to Systems Engineering, additional skills are needed for the successful application of MBSE. Examples are the required understanding of the abstraction of an overall system model, the awareness of the “single source of truth” paradigm and the understanding of the separation between view and model [17]. So far, required perspectives, associated roles and competencies are not sufficiently defined in literature. The resulting challenge for the application of MBSE is the lack of guidelines and support to reconcile different perspectives and enable the multidisciplinary development. Thus, potentials of the approach can rarely be transferred.

2.3. SE and MBSE Role Models
A role is the user-neutral description of a function, a task or an activity to be executed [18]. A role includes a role description that summarizes the objectives, tasks, responsibilities and competences of the role within the specific topic [17]. One person can take on several roles and perform them simultaneously. Interdependent roles that carry out coherent activities can be combined in a role model.
The level of detail in descriptions of roles varies depending on the scope. By defining competencies, tasks and activities, the role descriptions imply additional information which increase the added value of the approach. Competencies are defined by several organizations in context of systems engineering, for example by the INCOSE Systems Engineering Competency Framework [19], the NASA’s Systems Engineering Competencies [20] and the MITRE Systems Engineering Competency Model [21]. Task, on the one hand, are described within other Role Models descriptions and, on the other hand, are derived from the competencies and activities from other literature-based sources. Key activities are described within the processes of the INCOSE Handbook [12]. Sheard [22] defines twelve well established roles of Systems Engineering in 1996. Sheards roles were updated twenty-three years later by Gräßler et al. who define the Role Model for Systems Engineering Application (RM-SEA) [13]. The RM-SEA includes fifteen roles that describe possible and frequent activities and tasks in Systems Engineering projects and is meant to be used as a reference for Systems Engineering application. For MBSE, it needs to be reviewed and extended for dedicated roles regarding model creation and management.

2.4. Narrative methods in product development
The rising complexity in the development of systems and the increasing number of system-elements and disciplines involved lead to a high amount of uncertainties [23]. Researchers in the field of product development explore approaches to handle both complexity and uncertainties. One way to find solutions is to adopt and customize approaches from other domains, for example by adopting narrative methods [24]. As a relevant example, personas are fictional characters built upon available information about a considered group of people. Information is stored in templates structured by different facets, for example name, age, educational achievements, profession and goals [25]. Personas enhance cross-team collaboration, synergy, and communication as well as supporting the decision-making [26]. Another example are user scenarios, which are written in natural language and focus on a user within a considered context [27]. These two approaches can be combined resulting in a Persona-scenario. Here, define elements of persona-scenarios are considered according to Madsen and Nielsen [28] (see Table 1).

| Narrative elements     | Narrative elements in Persona scenario |
|------------------------|----------------------------------------|
| Character(s)           | Protagonists represented by Personas   |
| Time                   | Fixed time horizon                     |
| Problem                | The problem which is investigated (and solved) within the story |
| Setting                | Presentation of the Personas, the problems and the place of action |
| Opening episode        | Definition of Personas goal and start of action |
| Episodic               | Sequences of episodes that concern the problem |
| Resolution             | Reaching the goal / solving the problem |
| Plot                   | Mostly linear manner                   |
| Overall story          | Overall context of the episodes        |

3. Methodology
The methodology to define a Role Model for the practical application of MBSE is divided into three major steps: (1) identification, (2) categorization and (3) association of stakeholders. The term stakeholder indicates people and roles who implement and apply MBSE within an enterprise. The steps are performed sequentially in the logical order which is illustrated in Figure 1.
In the first step (1), Role Models are identified and analyzed using management layers of [29] as search areas: Systems Engineering, enterprise management structures (organizational management) and project management. The literature-based analysis is executed in accordance to Petersen et al. [30]. In the second step (2), the resulting roles are categorized in terms of homonyms and synonyms. Afterwards, an analysis of the semantic similarity is conducted to find taxonomic relationships and clear relation to MBSE. Finally, roles are clustered based on relevance for MBSE key activities. In the third step (3), roles are associated with an implementation process. Personas are used according to Pruitt and Grudin [26], combined with persona-scenarios to create synthetic test cases for validation purposes.

4. Elaboration of the Role Model for MBSE
Different Role Models are analyzed in the first step (1) to identify roles that need to be represented with competent employees in order to ensure successful application of MBSE. Based on the management layers of [29], the search areas are compiled to: Systems Engineering, enterprise management structures and project management. The literature based analysis is executed in accordance to Petersen et al. [30]. Strings and keywords are derived for each area to ensure that all relevant literature is identified. The results are illustrated in

Figure 1. Methodology for deriving Role Model of Model-Based Systems Engineering Application
Table 2 and 3. Due to the large number of results a reading scheme is applied to select relevant literature [31]. Within the reading scheme, literature is selected that does not provide definitions of roles, only describes the topic MBSE incidentally or exclusively addresses a certain domain.
Table 2. Results of the string in two different research platforms.

| Platform          | TS (Query)                                                                 | Results | Selected |
|-------------------|----------------------------------------------------------------------------|---------|----------|
| Web of Science    | TS= ("Role-Model" OR "Role Model" OR "Roles") AND "Project Management"    | 518     | 11       |
|                   | TS= ("Role-Model" OR "Role Model" OR "Roles") AND ("Systems Engineering" OR "SE") | 111     | 6        |
|                   | TS= ("Role-Model" OR "Role Model" OR "Roles") AND ("Organizational Management") // TS= ("Role Model" OR "Role-Model") AND "Organization" | 153     | 5        |
| Google Scholar    | allintitle: Role Model “Project Management” // allintitle: Role-Model “Project Management” // allintitle: Roles “Project Management” | 116     | 10       |
|                   | allintitle: Role Model “Systems Engineering” // allintitle: Role-Model “Systems Engineering” | 41      | 4        |
|                   | allintitle: “Role Model” “Organizational Management” // allintitle: “Role-Model” “Organizational” // allintitle: Role Model Organization | 183     | 5        |
|                   | 1.194 // 41                                                                 |         |          |

Table 3: Representation of considered Role models and roles of the three categories.

|                     | Systems Engineering | Project Management | Organizational Management |
|---------------------|---------------------|--------------------|--------------------------|
| Number of literature considered | 8                   | 9                  | 5                        |
| Number of included roles             | 93                  | 90                 | 30                       |

In the second step (2), the resulting 213 roles are categorized. In the beginning, homonymous roles are combined, reducing the number of roles to 166. Afterwards, an analysis of the semantic similarity is conducted. Roles that are semantically close to each other and have a large overlap of the information in their role descriptions are summarized to a superior role, for example the requirements engineer and the request analyst. 91 roles are semantically different. Thereafter, roles are rejected that do not show a clear assignment to MBSE or are described generically, for example “Influencer” [32]. The remaining 66 roles are transferred into a matrix in which they are compared with relevant MBSE key activities. These key activities are derived from the processes of the Systems Engineering Handbook [6]. The processes are categorized into key processes which can be transferred to MBSE. The activities of the key processes are adjusted from an MBSE perspective to cover the specifics of MBSE. The results are 23 key activities which have to be performed for successful MBSE. The roles and the key activities are transferred into a fulfillment matrix ($F_{ra}$). By comparison, it is determined whether a certain role can perform the corresponding MBSE key activities. For evaluation, a five-part rating scale is introduced, ranging from “0” (the role does not fulfill an activity) to “4” (the role fulfills the activity completely). The remaining roles are classified, resulting in the fulfillment matrix $F_{ra}$, where each value represents the fulfillment of an activity $a$ by the role $r$.

The similarity of two roles was calculated by the formula

$$dist(i, j) = \sum_k |F_{ik} - F_{jk}|$$ (1)

The similarity matrix $dist$ is a symmetric matrix where the value $dist(a, b)$ denotes the difference (i.e. distance) in processes between role $a$ and role $b$. To identify similar roles, the distance of all roles was visualized and clustered. The 68-dimensional matrix $dist$ was first reduced to 23 dimensions by classical multidimensional scaling. Therefore a non-classical multidimensional scaling approach is chosen with
presenting the dimension as 2. The resulting reduction was clustered with an average linkage algorithm with a distance-similarity measure, resulting in 14 clusters.

![Identification diagram]

**Figure 2.** Compiling clustering and weighting of the roles for the application of MBSE

For characterization, existing role descriptions from literature are adapted for MBSE, which imply suitable competencies, tasks and activities based on literature-based competency profiles. Due to the strong correspondence of the roles to the RM-SEA, it is adapted as a baseline for overarching SE roles. The remaining roles are classified in three categories, based on the three management layers: Organizational Management, Project Management and technical/Specialty [29]. The adjusted roles as well as the added role are defined in the following:

**(Project) Leader** based on references [13, 17, 32]: The role is responsible for the operational management of the engineering project. Additionally, he is responsible for the achievement of objectives in the project. He provides leadership, coordinates the project tasks and project team members and manages the project-relevant activities. He may be responsible for one or more projects, tasks, other tasks could be delegated to team members. He ensures the optimal distribution of resources. The system architect helps the project leader to break down the MBSE activities in projects into manageable tasks.

**Systems Analyst** based on references [6, 13, 33, 34]: A Systems Analyst analyzes, designs, and develops information systems to support the MBSE activities. He is responsible for developing, analyzing and modeling the architecture under the guidance of the Systems Architect. His key MBSE activities include collecting and analyzing objective data, measure the performance of the system model and generating and disposing information. Models are crucial input for all activities. Output is generated which is linked into different partial models. The System Analyst requires explicit and formal connections between system models domain specific models.

**Subject-Matter expert** based on references [6, 13, 35]: The Subject-Matter expert is an expert in his domain. He is responsible for the modeling of the sub-system or system-element architectures in specific areas and disciplines. Furthermore, the role has to establish traceability and implement the required systems elements within his tasks. Compared to the Systems Engineer, the subject-matter expert has the detailed view of a specific subject or discipline. In coordination with the project manager, the knowledge of various subject-matter experts is bundled. Typically, subject-matter experts use domain-specific languages in modeling tasks.
In addition to these roles, the following role is identified but not included in the Role Model, because the responsibilities of the role depend on the firm size and the enterprise organization. It is assumed that this decision-making role exists in every company, which want to implement and apply MBSE.

**Chief Representative based on references [6, 13, 36]:** The Chief Representative is involved in management decisions and has the necessary responsibilities for overall business decisions. The role has to decide, if a project is aligned with the enterprise strategy. The role also receives relevant systems engineering reports (e.g. implementation reports or transition reports), represents the opinion of the company leadership and takes care of MBSE key activities like assessing a feasible project plan. Additionally, the role interacts with the Leader and the Entrepreneur to identify the best possible solutions for the further strategic plan.

_Fehler! Verweisquelle konnte nicht gefunden werden._ depicts which roles are adopted or adjusted from the RM-SEA [13]. Furthermore, two essential roles for MBSE are added, called the Subject-matter Expert and the Systems Analyst. Compared to the Modeling Engineer, the Subject-Matter experts addresses (a) the need of linking models from different disciplines within an overall system model and (b) the detailed decomposition of the overall system into sub-systems and system elements. This requires specific knowledge of a discipline and the understanding of dependencies between partial models. The systems analyst addresses the increasing focus of digital simulations and test cases within an overall system model, for example a change impact analysis in engineering change management [37]. Thus, these essential roles have to be considered additionally when applying MBSE compared to applying the document-based SE.

![Model-Based Systems Engineering Roles](image)

**Figure 3.** Role Model for Model-Based Systems Engineering, based on [13]

Lastly, the roles are associated with an implementation process (3). The association indicates situations in which different roles interact with each other. These interactions are illustrated in a test case, created by a persona-scenario which depicts implementation process. Therefore, the information within the defined role descriptions (2) are extended by additional data for each persona.

The elaboration of personas is done based on a four step approach proposed by Pruitt and Grudin [26]:

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The first step is to choose a manageable amount of personas (3-5 personas).
Afterwards, a common template with relevant facets is developed.
In the following step, this template is filled by internal and external resources.
The final step is the presentation of the personas within the intended context.

By allocating the roles to Personas, it is demonstrated how the role model solves challenges of MBSE described in literature.

5. Validation by narrative test case

The use of the role model is demonstrated and evaluated in a test case based on personas and a scenario within an organizational structure. The narrative elements from Madsen and Nielsen [28] are the foundation of the scenario. By allocating the roles to Personas, it is demonstrated how challenges of MBSE described in literature can be solved using the role model. According to current survey results [38], typical challenges of MBSE are: upfront investment, the purpose and scope definition, the awareness and change resistance as well as the tool dependency.

Four personas are determined as characters of a typical application scenario. Challenges define the setting of the scenario. The time is illustrated by the implementation phase and application phase, which connects the problem with the resolution.

The generic product development process of Figure 1 is deposited in the laboratory environment at the HNI (Chair of Product Creation) of Paderborn University. Within a company entitled HNI Inc. (represented by product portfolio, historic manufacturing data etc. specified for research purposes), a project team is established to implement MBSE, including the project leader, a technical manager and a subject-matter expert. In the beginning, the project team has to convince the Chief Level Managers to implement MBSE.

- The representative of the Chief Level Managers is called Paul. He is 56 years old and was promoted to CEO after many years as CFO. His high integrity, his ethical principles, his proactive approach, but most of all his respectful manner, has helped him to work his way to the top of the company. As CEO, he is characterized by his critical and constructive thinking, but also by his creative, visionary and holistic approach. Paul interacts on the one hand with the board members of the organization, but also directly with the CTO / CIO and CFO. His connection to the other employees is mostly indirect.
- The Project Leader is called Susanne. Prior to her position as Project Leader, she distinguished herself through her very good results as Project Team Member. Additionally, she holds a Master of Business Administration. Through the coordination of the MBSE project there is a direct contact to C-level roles like Paul. Their tasks include the definition of roles and responsibilities, the communication of management expectations, and the management and review of results. Personally, she is committed to the development of her employees, positive project results and continuous improvement.
- The Technical Manager is called Natasha. She has a Master of Science in Mechanical Engineering. Technically, she distinguishes herself above all by her logical thinking, her problem-solving skills and her general knowledge in the field of engineering sciences. She is in close contact with your team, but also forms the bridge to the C-Level she reports to.
- Kyle is enterprise-internal Subject-Matter engineer of the discipline Software. His statement about MBSE was: "We (i.e. the developers) have wanted an MBSE solution for a long time. The other departments just don't understand how important the implementation is." His IT skills mainly include UML and SysML. He cooperated directly with the project team and sees himself as a representative of the users.

The objective of HNI Inc. is change from a document-centric to a model-based development environment and therefore to implement and apply MBSE. When he was CFO Paul has supervised the ERP implementation five years ago and remembers how many unforeseeable difficulties arose during
the implementation, which delayed the project by 6 months. He also regards the upfront investment critically, as the benefit of MBSE is not sufficiently high. Paul’s decisions are influenced by the role of the Project Leader. Susanne assigns her MBSE implementation team to identify the potential of MBSE. The team prepares a set of slides which Susanne uses to convince Paul to implement MBSE in a meeting. The advantage becomes especially clear to him when Susanne presents how a comprehensive analysis of the required modeling depth is performed before each modeling. The issue of modeling depth was identified by Kyle, who was able to identify an MBSE method that considers setting the modeling depth as the first step of the method. The purpose and scope of MBSE becomes more transparent for all involved. Natasha remains skeptical. From a technical perspective, she thinks that the switch to model-based development will lead to resistance from her employees. She also fears that the investment will make the company become too dependent on an IT vendor. Due to the increasing relevance of Kyle's role and his involvement in the MBSE team, there is a conversation between the Technical Manager and the System Architect. With an insight into a system model that he developed in a freeware software environment, Kyle explains the benefits and highlights the increasing system quality, the reduction of errors and defects and the improved traceability. Additionally, Kyle's previous experience with SysML means that he knows the different vendors of the tools and can discuss with Natasha which vendor would be most suitable for a pilot project. With the new insights, Natasha improves in arguing the case to her staff, making the added value of MBSE clearer and reducing resistance within her own ranks.

Figure 4. Persona-scenario of the MBSE implementation process within the HNI Inc.

The narrative test case represents an example for the application of the role model. Roles can be adapted and transferred to individual needs of a company. Based on the Role Model, the MBSE Project Leader can infer job profiles from role descriptions to receive decision support for the selection of suitable employees. In addition, actions required can be derived in order to fill the roles that are necessary for the application of MBSE. One example is the additional qualification of employees.

6. Conclusion

The paper at hand contributes a role model for the implementation and application of Model-Based Systems Engineering. Due to the specific circumstances of the MBSE application, actors and competencies have to be defined to enable successful MBSE application and adaption. Therefore, a comprehensive literature analysis is conducted to identify roles from the areas systems engineering, enterprise management structures and project management. 213 roles are identified and then condensed to 66 semantically different roles. Additionally, key activities of MBSE are derived from the processes of the INCOSE Handbook to benefit from MBSE advantages. The identified roles and key activities are transferred to a similarity matrix. The matrix enables the clustering and weighting the identified roles due to their field of activity. Based on the results, the existing Role Model for Systems Engineering Application (RM-SEA) is adjusted and expanded to satisfy the specialities of model-based development.
An adaptable role model for MBSE is presented. The application of the role model is demonstrated in a synthetic test case. Narrative methods are combined to create the test case and apply a scenario, where personas are defined, which have MSBE roles within the fictional enterprise. Industrial application demands are considered, which increases the acceptance and the necessity to implement the model-based approach. The test case illustrates that the definition of roles is crucial for the successful implementation of MBSE. The role model helps the development team to define relevant responsibilities and key activities to implement and apply an appropriate MBSE approach. The approach supports the multidimensional development and reconciles different perspectives on the system model.

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