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Investigation of advantages of models and the modelling process by introducing a model evaluation concept

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Abstract

Within Model-based Systems Engineering different kinds of model will be created to support the execution of engineering activites. This contribution introduces an evaluation concept which focuses on the model informativity and its usefulness within the modelling process. Thereby, it shall be investigated which advantages the integration of model elements based on different levels of abstraction and a reduction of model formalisation enables. For the model creation the analogue modelling method will be applied, which uses physical (tangible) model elements.

Keywords: *model-based systems engineering (MBSE), design models, model evaluation, analogue modelling method*

1. Introduction

Model-based Systems Engineering (MBSE) aims at the application of digital models instead of documents to conduct systems engineering activities (Friedenthal, 2014). These models typically utilize the Systems Modeling Language (SysML) to increase the level of model formalisation. Additionally, to the established systems engineering activities or rather processes, defined in (ISO/IEC/IEEE, 2015) or (Walden *et al.*, 2015), which can be considered as engineering domain-independent, the engineering of complex systems also requires domain-specific engineering activities, like mechanical, electrical or software engineering. Within these domain-specific engineering activities also models will be developed, like CAD models in mechanical engineering or state-machine diagrams in software engineering. It can be concluded that based on the specific engineering activities different models will be created, which differ in their level of abstraction and formalisation (Schumacher and Inkermann, 2022). This contribution introduces an evaluation concept which analyses models regarding their comprehensiveness and informative value and the modelling process regarding the modelling purpose and proceeding. Thereby, it shall be investigated which advantages the integration of model elements based on different levels of abstraction and a reduction of model formalisation brings. This paper does not focus on the corresponding process chain, which integrates different model elements into one model presentation. For this purpose, previous publications propose the use of heterogeneous models, as an approach to combine elements with different levels of abstraction and formalisation (Schumacher and Inkermann, 2022, 2023; Schumacher *et al.*, 2022).

2. Research objective and questions

This Section presents the research objective and the corresponding research questions. The overall objective of this publication is, to develop a concept to evaluate models regarding their model content (*model comprehensiveness and informative value*) as well as the modelling process (*modelling purpose and proceeding*). Thereby, this publication addresses the following research questions:

1. Which criteria can be applied to evaluate models, to assess their comprehensiveness and informative value?
2. Which criteria can support by evaluating the advantages of the modelling process?

To answer the introduced questions an experiment will be described that uses the analogue modelling method and a concept for evaluating the advantages of models considering the model's informative value and the modelling process will be outlined. The publication is structured as follows: Section 3 introduces the State of the Art regarding, model evaluation and the analogue modelling method. Section 4 describes the experimental application of integrated models by applying the analogue modelling method. In Section 5 an evaluation concept will be presented to assess the advantages of models and in Section 6 the paper will be concluded by a summary and an outlook on further research activities.

3. State of the art

This Section introduces the fundamentals of model evaluation and the analogue modelling method.

3.1. Model evaluation

Models are appropriate illustrations of objects and reproduce their properties. Within systems engineering it is important to determine which properties shall be visualized by a model and what is the purpose of the model (Andreasen, 1994). These questions are strongly linked with the corresponding engineering activity which shall executed. Additionally, the model scope and expressiveness are important to create appropriate models, which can support the engineering activity. (Mordecai and Dori, 2016) refer to this as the value of a model and state that the advantages of models are significantly affected by the amount and quality of information that the model expresses. Additionally, (Mordecai and Dori, 2016) propose the usage of the *model informativity*, as the value of information that the model conveys, as an appropriate criterion for evaluating models. The model informativity can be evaluated by structural and functional measures. Structural measures are based on the model structure and the information or knowledge it represents. Functional measures of knowledge consider the applicability of models concerning task execution and problem-solving (Mordecai and Dori, 2016). Structural and functional measures can be evaluated as qualitative or quantitative, problem- or task-specific (Reich, 1995). Therefore, (Mordecai and Dori, 2016) define evaluation cluster and criteria to assess model informativity, see Table 1.

Table 1. Model evaluation cluster and criteria, based on (Mordecai and Dori, 2016)

Evaluation cluster	Evaluation criteria	Explanation
Specification	Pattern	Specification patterns describe the structure and behaviour of the system as well as procedural and precedence relations.
Uncertainty	Reliability Discovery Simplification	Uncertainty of a model can be evaluated by the correctness and truthfulness (reliability) of the model, by the level of unknown information (discovery), and by the perceived complexity of the specified system (simplification).
Meta-Specification	Rationale Initiator Category Priority Maturity	Meta-specification is the specification of information about the model. These provide details about the model, like the maturity level, the rationale for its existence, its originator and modelling tool, the category it pertains to, and its priority.
Specification Management	Traceability Demonstrability	The traceability of the model (elements) to another model (elements) can be evaluated, for instance, to identify their dependencies. Furthermore, the executability of models can be evaluated. The ability to present, demonstrate, simulate, or execute models in virtual or real environments can provide various benefits in the engineering process.

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These evaluation criteria will partly be revived within the evaluation concept (Section 5) to analyse the advantages of the models.

3.2. Analogue modelling method (tangible business process modeling (t.BPM))

The analogue modelling method emphasizes the use of physical (tangible) model elements instead of digital models applying software-based modelling tools. This approach eliminates the need for specific skills for operating with these tools, which enables a broader application of models within an organisation (Edelman *et al.*, 2009; Luebbe, 2011), e.g., the involvement of domain experts. This kind of modelling is especially established in business process management, which focuses on the development of business processes (Luebbe and Weske, 2012). For the application of the analogue modelling method acrylic plates were created as physical model elements. These plates can be transcribed by whiteboard markers to describe process steps. To model the relations between the process steps a rewritable folie placed on a table is used (Luebbe and Weske, 2012). The shape of the model elements reflects the syntax and semantics of the Business Process Modeling Notation (OMG, 2009).
This approach we will revive in Section 4 to model system architectures based on physical SysML and CAD model elements without using software tools.

4. Experimental application of the analogue modelling method

In this Section, the experimental use of the analogue modelling method will be defined, thereby, especially the considered engineering use case and modelling purpose as well the experiment proceeding will be introduced.

4.1. Engineering use case and modelling purpose

Within this experiment, the attendees shall analyse an existing system architecture because of changed customer requirements and disruptive factors. This presumes that a previous product generation already exists, which needs to be adapted to fulfil the new requirements. This domain-spanning use case, describing the engineering of products in generations, represents the majority of engineering projects (Albers *et al.*, 2014). The use case also includes that system knowledge comprised of models from previous product generations is available and shall be considered for the to-be-developed product generation. Summarizing, we focus on the system architecture definition process as a consequence of changed requirements and disruptive factors within a product generation engineering scenario.
As modelling purpose an adapted system architecture shall be visualized considering functional and structural views on the architecture and the realization of functions by subsystems. The model shall support the system architecture analysis due to arising requirement changes and disruptive influencing factors.

4.2. Experiment execution

This Section describes the experiment execution by introducing the engineering scenario, the product example, and the concrete task description. Additionally, an exemplary realization will be presented.

4.2.1. Engineering scenario and product example

As an engineering scenario, we consider product development in generations, which means out of the previous generations knowledge about the system is available in kind of models. As a product example, we utilize a roll stabilizer, which represents a subsystem in the car chassis. Figure 1 presents the previous product generations of the roll stabilizer and the changed customer requirements, which involve the engineering of a new generation. The reference product of the roll stabilizer is a passive mechanical stabilizer followed by the first active hydraulic actuator. The occurrence of changed requirements, like better driving stability, increased working dynamics and better maintainability, lead to the development of a new product generation, the electro-mechanic roll stabilizer.

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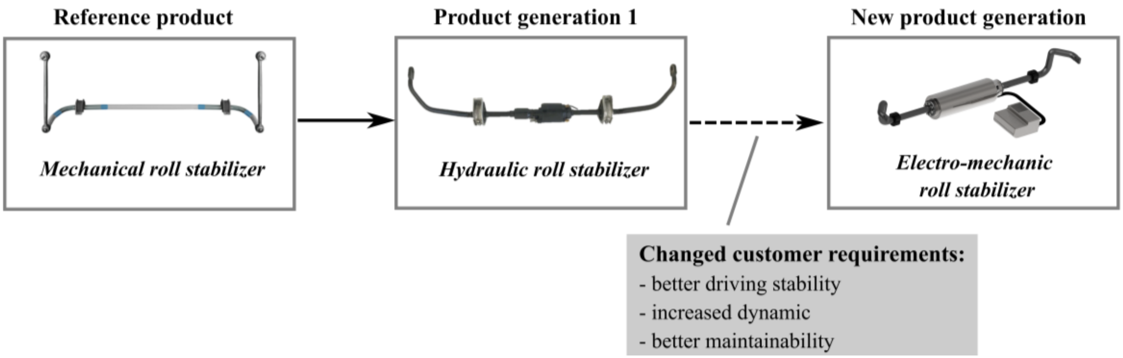

Figure 1. Product generations of the roll stabilizer and changed requirements

4.2.2. Preparation and application of the analogue modelling method

Before developing models, the definition of the considered engineering activity is important to determine the modelling purpose. Based on the modelling purpose the required model elements including their syntax and semantics need to be specified and in the case of analogue modelling the physical model elements prepared (see Section 3.2). The engineering process considered in this experiment is the system architecture definition. A comprehensive description of the system architecture requires domain-independent as well domain domain-specific model elements. For this purpose, the application of heterogeneous models, integrating SysML- and CAD model elements into one visualization, can be a great support. Thus, we defined the required SysML model elements, like functions, subsystems and interface descriptions, and CAD model elements, like drawings and sketches, to enable a comprehensive description of the system architecture. To apply the analogue modelling method the specified model elements, need to be prepared and their syntax and semantics must be known by the attendees. Additionally, to the physical model elements rewriteable underlays shall be used to concatenate the model elements. The target is, to develop models, based on physical SysML and CAD model elements to support the system architecture definition process.

4.2.3. Task description

The first part of this experiment is the development of an architectural model, describing the system architecture of the electro-mechanic roll stabilizer, based on the changed requirements, and considering the available knowledge of previous product generations. Therefore, the analogue modelling method shall be applied by using physical model elements within teams. The following subtasks need to be executed:

1. Analyse the system knowledge from previous product generations, by investigating the available CAD- and SysML model elements.
2. Investigate additional or changed requirements, by comparing them with initial requirements for previous product generations, described on plates.
3. Develop system behaviour, by modelling the functional system architecture. Adjust or add system functions described on physical plates.
4. Develop the system architecture of the roll stabilizer. Define the structural design as a realization of the functional architecture, considering structural descriptions from previous product generations and changed requirements.
5. Ensure comprehensiveness and traceability of the architecture model. Check if all requirements are satisfied by a functional or structural model element and if all functional model elements are realized by a structural model element. Additionally, necessary interfaces within and at the system boundary shall be included.

The second part of the experiment is about analysing the developed architecture model regarding external influencing factors, like temperature influences, to develop a robust system architecture. Therefore, the following subtasks need to be executed:

1. Analyse which functions and components can be affected by external influencing factors.
2. Adjust your architecture model to be robust against external influencing factors.

After the finalization of the experiment, the created models shall be evaluated regarding their informative value and the modelling process evaluated regarding the modelling purpose and proceeding. The underlying evaluation concept is described in Section 5.

4.2.4. Exemplary application

The described tasks were exemplary performed twice. Thereby, the following slightly different analogue, heterogeneous models were developed, see Figure 2. Both models represent the electro-mechanic roll stabilizer reusing model elements from previous product generation (red-coloured model elements). Especially the stabilizer arms, as connection elements to the car chassis, can be reused in this example which means the geometry and stiffness among other properties are the same. Other elements (blue coloured) like the ECU or e-motor are new subsystems, which are required to satisfy the customer requirements (green font) and need to be developed without knowledge from previous product generations. This can be considered as the emphasis of the engineering process. Furthermore, the models were applied to identify external influencing factors, which are highlighted by yellow cards.

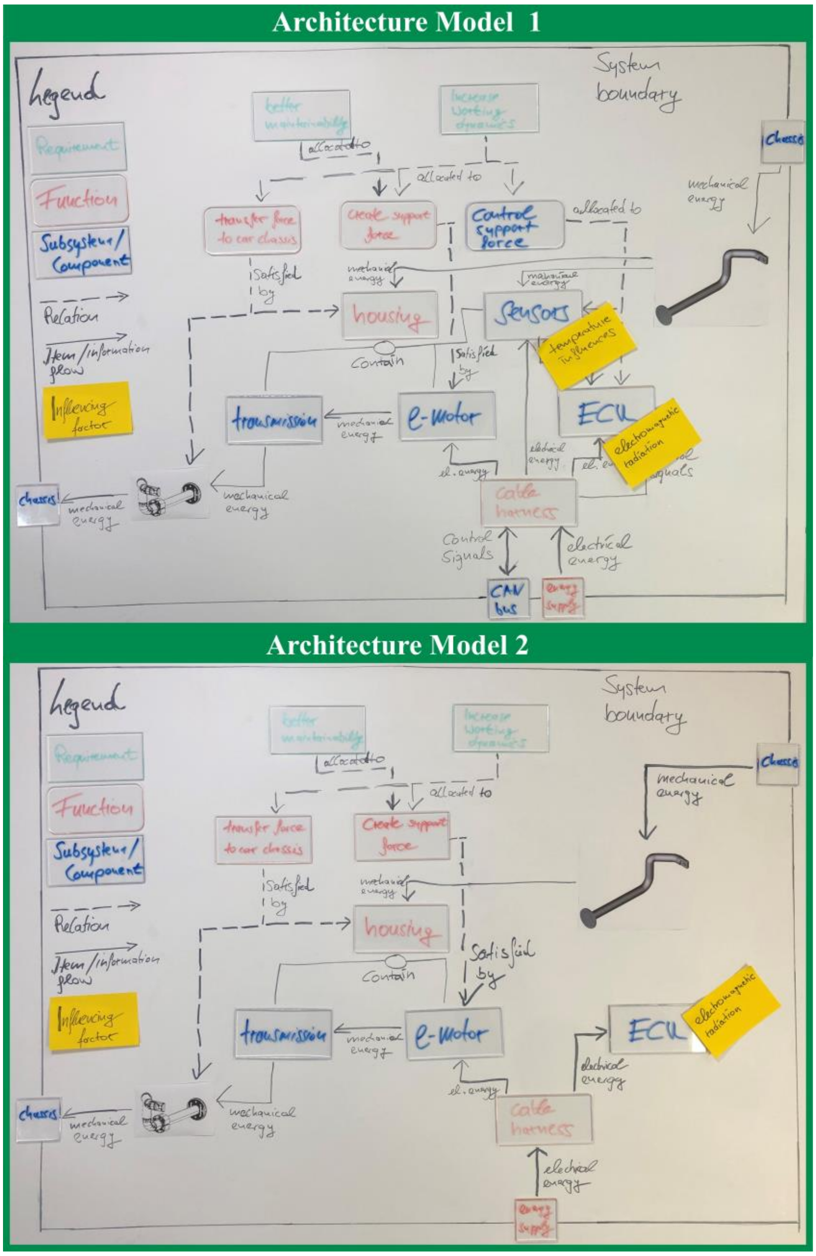

Figure 2. Exemplary architectural models based on the provided experiment description

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5. Concept to evaluate model informativity and modelling process

This Section presents a concept for evaluating the models and corresponding modelling process by assessing the developed models based on evaluation criteria and interviews with the experiment attendees. Figure 3 presents the developed concept to evaluate the model itself and the modelling process, both will be explained in more detail within the following subsections.

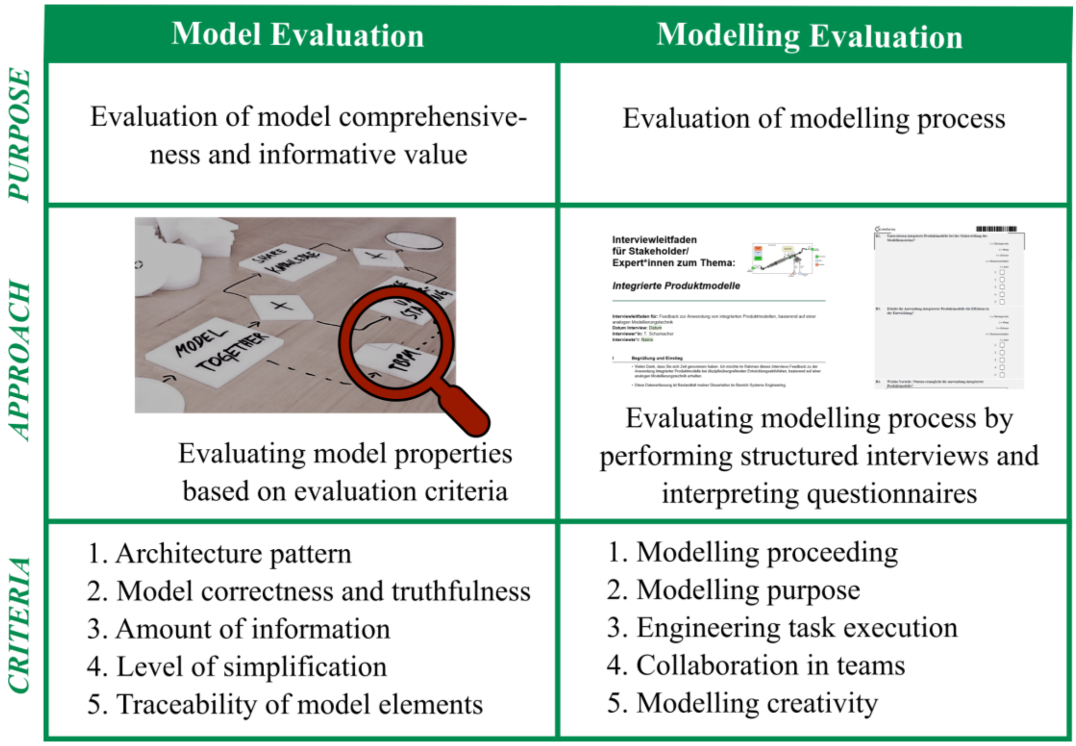

Figure 3. Evaluation concept

5.1. Model evaluation

The purpose of model evaluation is to evaluate the model's comprehensiveness and informative value. Therefore, the developed models within the experiment will be investigated by analysing the model properties based on evaluation criteria. These criteria, based on the model informativity index (Mordecai and Dori, 2016), will in following be described. By evaluating models must be considered that the perception of models differs between different users, like designers or managers, and is based on the modelling purpose (Buur and Andreasen, 1989). This is also true for the evaluation of models because the evaluation result is strongly linked to the modelling intent and knowledge of the assessing person.

5.1.1. Architecture pattern

For the criterion *architecture pattern*, four different pattern groups with twelve architecture patterns were defined, especially focusing on structural and procedural model elements, see Table 2. Thereby, structural elements describe the assembly of the system and the procedural elements the system behaviour.

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Table 2. Model evaluation based on architecture pattern

Pattern group	Pattern
Structural element definition	The structure of model elements is defined
	The behaviour of model elements is defined
	The parameter of model elements is defined
	Element types are defined, e.g., to distinguish different domains
Structural relation definition	Affiliation and relations between structural elements are defined
	Material, energy, and information flows between structural elements are defined
	Relations to the environment, e.g., interface description, and environmental influences, are defined
Procedural element definition	Procedural model elements, like activities, actions, and states, are defined
	Procedural elements are allocated to structural elements
Procedural relation definition	The sequence and precedence of procedural elements are defined
	Relations between procedural elements, e.g., derive, allocate, satisfy, are defined
	Material, energy, and information flows between procedural elements are defined

5.1.2. Model correctness and truthfulness

The evaluation of models also requires an investigation of the model's credibility. Therefore, the criterion *model correctness and truthfulness* was tailed into four subordinated criteria, which are explained in Table 3.

Table 3. Detailed criteria for model evaluation based on model correctness and truthfulness

Criterion	Explanation
Correctness	The model properly represents the system of interest, including system structure, system behaviour, and system parameters. The model can be used instead of the real system to answer questions of interest.
Completeness	The model's maturity is appropriate for the current system lifecycle stage. The model content will accomplish the intended use of the model and the intended use of the system being modelled.
Accuracy	The model can answer the questions that are put to it, given that these questions were defined upfront. The model is built to answer the questions and contains sufficient information to produce the answers.
Compliance	The model properly conforms to good practices and established guidelines. There are no errors and/or omissions relative to guidelines. The model properly employs the ontology for the domain of interest.

5.1.3. Amount of information

A model can be understood as an information carrier and knowledge base about the system of interest. Typically, models will be developed with the purpose to support executing engineering tasks. Therefore, the model must be able to carry new or existing information, out of previous system generations, to support the engineering task. Within the model evaluation, the *amount of information* carried by the model and its advantages for the engineering task shall be investigated. To assess the model's informativity structural and functional subordinated criteria can be applied (Mordecai and Dori, 2016). Structural criteria consider the model structure and the information or knowledge it presents. Functional criteria refer to the model's usefulness for the execution of engineering tasks (Reich, 1995). The following criteria will be applied by evaluating the amount of information within models.

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Table 4. Detailed criteria for model evaluation based on the amount of information conveyed by the model, based on (Reich, 2002)

Criterion	Explanation
Structure	The represented number of parts, relations and properties described in the model and relevant for the engineering task.
Function	The represented number of functions described in the model and relevant for the engineering task. This also contains the functions that can be derived from the represented structure in the model.
Additional engineering information	The number of additional information that are part of the model and useful for the execution of the engineering tasks, like specifications and meta-information.

5.1.4. Level of simplification

A main purpose of models is also to decrease the system's complexity. Next to the amount of information a model conveys (Section 5.1.3) also the *level of simplification* increases the informativity of a model. Therefore, all information included in the model will be assessed concerning their contribution to a better model understanding to generate higher clarification or simplification.

5.1.5. Traceability of model elements

The use of models always goes in line with the risk of model inconsistencies. Therefore, especially the linkage between model elements is important to avoid inconsistencies. Consequently, the created models will also be investigated regarding their comprehensive traceability. Thereby, in particular, the relations between requirements, functions and realizing system elements will be assessed.

5.2. Modelling evaluation

This evaluation concept contains next to the developed architecture models, which integrate different kinds of model elements in one model presentation, as well as the investigation of the modelling process. Therefore, structured interviews will be performed with the experiment attendees and questionnaires will be used. The gathered information will be analysed concerning the following criteria, see Table 5.

Table 5. Criteria for evaluation of the modelling process

Criterion	Explanation
Modelling proceeding	Do integrated models, as created in the experiment, support or simplify the modelling proceeding?
Modelling purpose	Do integrated models simplify the definition of the modelling purpose?
Engineering task execution	Do integrated models support by performing the specific engineering task?
Collaboration in teams	Do integrated models increase collaboration within teams?
Modelling creativity	Do integrated models increase creativity while modelling?

5.3. Exemplary application of the model evaluation

The developed evaluation concept, particularly the model evaluation, will be demonstrated within this Section. Figure 4 presents the developed evaluation sheet, which was filled by analysing the presented architectural models in Figure 2. This exemplary application does not consider an evaluation of the modelling process. This will be performed in collaboration with students and practitioners in future.

Based on the performed model evaluation it can be concluded that *Architecture Model 1* is more informative than *Architecture Model 2* regarding the definition of the *system architecture* and will be more beneficial for executing the engineering task. Initial analysis shows that the amount of heterogeneity in the models increases the model informativity and the modelling activity itself improves the system understanding of the modellers.

The presented evaluation concept and the corresponding modelling experiment shall be applied by students and practitioners in future to get a more empirical understanding of the advantages of models concerning the model informativity and the modelling process.

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Model Informativity - Evaluation Sheet

Evaluation scale:

1 inadequate considered *3 partially considered*

5 adequate considered *- not required based on modelling purpose*

Architecture pattern		Architecture Model 1		Architecture Model 2	
Pattern group	**Pattern**	**Evaluation rating**	**Evaluation reason**	**Evaluation rating**	**Evaluation reason**
Structural element definition	Structure of model elements is defined	5	required stucture elements are included	3	stucture elements are partially included (*sensors* are missing)
	Behaviour of model elements is defined	5	required behaviour elements are included	3	required behaviour elements are partially included (*control support force* is missing)
	Parameter of model elements are defined	0	not considered, but required based on requirement changes	0	not considered, but required based on requirement changes
	Element type is defined, e.g., to distinguish different domains	3	Element types are distinguished; domain specific differentiation is missing	0	Function and structure types are not distinguished; domain specific differentiation is missing
Structural relation definition	Affiliation and relations between structural elements are defined	5	all required relations are considered	5	all required relations are considered
	Material, energy, information flows between structural elements are defined	5	all required flows are considered	3	flows are are partially considered (exchange of *control signals* are missing)
	Relations to environment, e.g., interface description, environmental influences, are defined	5	all required interfaces are considered	3	interfaces are partially considered (*CAN BUS* is missing)
Procedural element definition	Procedural model elements, like activities, actions, stats, are defined	-	not required based on modelling purpose	-	not required based on modelling purpose
	Procedural elements are allocated to structural elements	-	not required based on modelling purpose	-	not required based on modelling purpose
Procedural relation definition	Sequence and precedence of procedural elements is defined	-	not required based on modelling purpose	-	not required based on modelling purpose
	Relations between procedural elements are defined	-	not required based on modelling purpose	-	not required based on modelling purpose
	Material, energy, info flows between procedural elements are defined	-	not required based on modelling purpose	-	not required based on modelling purpose
		28		**17**	

Model correctness and truthfulness	Heterogeneous model 1		Heterogeneous model 2	
Criterion	**Evaluation rating**	**Evaluation reason**	**Evaluation rating**	**Evaluation reason**
Correctness	5	The model represents the system enough to develop the system architecture based on changed requirements	3	The model represents the system not enough to develop a comprehensive system architecture based on changed requirements
Completeness	3	The model content accomplish the use of the model partially, because of missing system parameter	0	The model content accomplish the use of the model not sufficient (missing: parameter, structure and functional elements, flows and interfaces)
Accuracy	5	The model is able to answer the questions concerning realisation of changed requirements and analysing subsystems regarding external influencing factors	3	The model is able to answer the questions concerning realisation of changed requirements and analysing subsystems regarding external influencing factors partially
Compliance	5	Modellierung guidelines and syntax (SysML, CAD) followed	3	Modellierung guidelines and syntax are partially followed (function syntax is not considered)
	18		**9**	

Amount of information	Heterogeneous model 1		Heterogeneous model 2	
Criterion	**Evaluation rating**	**Evaluation reason**	**Evaluation rating**	**Evaluation reason**
Structure	5	The amount of structural information is sufficient to execute engineering task	3	The amount of structural information is partially sufficient to execute engineering task
Function	5	The amount of functional information is sufficient to execute engineering task	3	The amount of functional information is partially sufficient to execute engineering task
Additional information	5	The amount of additional information (requirements) is sufficient to execute engineering task	5	The amount of additional information (requirements) is sufficient to execute engineering task
	15		**11**	

	Heterogeneous model 1		Heterogeneous model 2	
	Evaluation rating	**Evaluation reason**	**Evaluation rating**	**Evaluation reason**
Level of simplification	5	Due to the applied abstraction the level of simplification is high and the system understanding can be increased	5	Due to the applied abstraction the level of simplification is high and the system understanding can be increased
Traceability of model elements	5	Traceability between system elements is well established	5	Traceability between system elements is well established
	10		**10**	

MODEL INFORMATIVITY **71** **47**

Figure 4. Filled evaluation sheet concerning model informativity

6. Summary and outlook

This paper presents a concept for the evaluation of models and the corresponding modelling process. Thereby, especially the comprehensiveness and informative value of models and their usefulness within the modelling processes will be investigated. To evaluate model informativity, model properties will be analysed based on defined evaluation criteria. These criteria are based on model patterns, the correctness and truthfulness of models, the amount of information a model conveys, the level of simplification a model provides, and the traceability of model elements. The evaluation of the modelling process is based on feedback from the modellers. Therefore, structured interviews and questionnaires are used to gather information about the modelling process. This information will be analysed by considering the following criteria: modelling proceeding, modelling purpose, engineering task execution, collaboration in teams,

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and modelling creativity. To enable a broad application of the evaluation concept within an organization, the models will be developed by using the analogue modelling method. This method emphasises the use of physical model elements instead of software-based model elements to eliminate the need for specific skills for operating with these software tools. An exemplary application of the analogue modelling method and the assessment of the developed models based on the presented evaluation concept are also included in this publication. The superordinate goal is, to apply the analogue modelling method and the evaluation concept to get a more empirical understanding of the advantages and limitations of integrated models. Future research will investigate if the heterogeneity of models increases the model informativity and supports the modelling process in case of simplifying the definition of the modelling purpose and improving the executability of engineering tasks.

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