Article Identifier
DOI: 10.22032/dbt.58908
URN: urn:nbn:de:gbv:ilm1-2023isc-087:1

60th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 4 – 8 September 2023
URN: urn:nbn:de:gbv:ilm1-2023isc:1

IMPROVING SYSTEM OF OBJECTIVES MATURITY THROUGH SYSTEMATIC REUSE OF KNOWLEDGE USING ONTOLOGY-BASED KNOWLEDGE REPRESENTATIONS

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ABSTRACT

Technical products are developed to meet the needs of different stakeholders. In addition, various constraints from all phases of the product life cycle have to be considered. In existing work, this information and its dependencies are systematically represented in the so-called system of objectives. A major challenge in modeling the system of objectives is that the necessary information in the system of objectives is often incomplete and uncertain. In addition, this uncertainty and the maturity of the system of objectives cannot be directly quantified because the target state of the system of objectives often cannot be unambiguously described. This research investigates a methodical approach to assess and improve the maturity of the system of objectives. Two means to reduce uncertainty and thus increase the maturity of the system of objectives are the systematic reuse of knowledge and the systematic building of knowledge through verification and validation activities.

Index Terms – System of objectives, requirements, maturity, uncertainty, knowledge graph, verification, validation

1. INTRODUCTION

During the development of technical products, the specific needs of different stakeholders must be addressed properly at the right time, taking into account a wide variety of boundary conditions in different application scenarios across the whole product lifecycle [1]. The concrete needs of the stakeholders as well as boundary conditions and the development objectives derived from them must be fulfilled by required properties of technical products to be developed. These needs and constraints can be detailed by analyzing product-specific use cases [2]. Each use case can again be divided into different use case scenarios. The scenarios depend on the intended and unintended interactions with stakeholders and environmental systems [3]. Furthermore, the scenarios can be described at different levels of abstraction, from abstract functional scenarios to concrete scenarios including concrete target parameters [4]. For product development, information about stakeholders, requirements, boundary and environmental conditions, use cases/scenarios, and derived development objectives as well as their interrelationships must be systematically prepared. In the work of Ropohl [5], Albers [6], and Ehrlenspiel [7], the so-called system of objectives is formed for the consolidated description. In this understanding product development can be described as the continuous transformation of a system of objectives into a system of objects by a socio-technical operation system [6] (see Figure 1). An iterative cycle of design and verification/validation always takes place between the system of objectives and the system of objects (see Figure 1). Following this understanding, validation does on the one hand serve as an analysis activity to compare a given state of the system of objects to the formulated system of objectives. On the other hand, validation is the central means to gain knowledge in the product development process to further concretize and enrich the system of objectives.

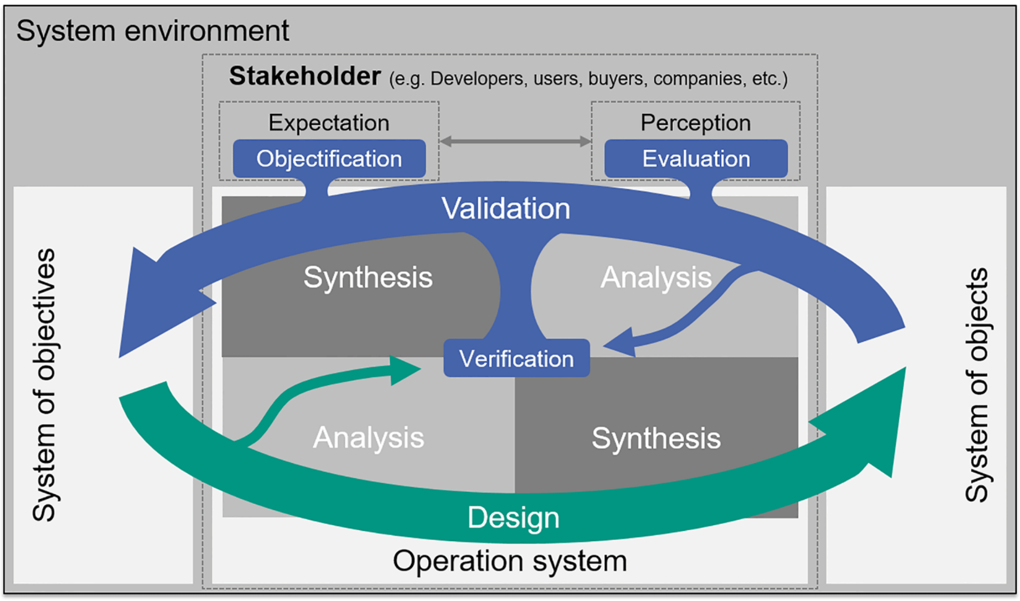

Figure 1: Interrelation between the system of objectives, system of objects, and operation system in product development [8]

Systems of objectives are always product-specific, as the relevant required properties (see e.g. CPM - Characteristics Properties Model [9]) and their prioritization depend on the use cases as well as application scenarios with their different boundary conditions.
Valid systems of objectives are the decisive guarantor for successful product development. To ensure that a product under development also meets the actual needs of the stakeholders, taking into account the constraints, a maturity level of the system of objectives is required that is appropriate to the progress of the development. This includes the highest possible coverage to validate the system of objectives elements and relationships through appropriate test scenarios and related test cases in suitable test environments for a planned validation concern.
A central challenge in the definition of systems of objectives is, that the necessary information for complex problems can often only incompletely be formulated or is subject to uncertainties. This applies in particular to the identification and description of relevant use cases and application scenarios. Major reasons for this are unavoidable gaps in knowledge. They can be seen, for example, in the fact that stakeholders do not or cannot clearly formulate their requirements and boundary conditions [10]. Furthermore, environmental influences cannot be fully specified or there is too weak knowledge about relevant product properties.
Therefore, the research described in this contribution aims at supporting the assessment and increase of the maturity of the system of objectives in product development. In this way, the validation of a product in development is supported as the most important factor influencing its success.

2. STATE OF RESEARCH

2.1 Maturity description of the systems of objectives and system of objects

Maturity metrics are needed to measure the maturity of the systems of objectives. Current descriptions of the maturity level usually focus on the system of objects or the comparison between the system of objectives and the current state of the system of objects, respectively, as well as the scope and spectrum of the test cases, carried out in specific test environments [11].
There are various definitions of product maturity proposed in literature, which generally define it as the relationship between the actual state and a target state of a product [12–16]. The progression of the product maturity level is characterized by fluctuations due to iterations, changed target values as well as changing indicators and is not consistent with the real progression due to the snapshots and the suggested progression [17, 18].
One of the best-known maturity models is the so-called Technology Readiness Level (TRL), which defines the maturity level on the basis of the verification and validation environment it has been tested in [19].
In further existing approaches, different metrics are usually used to describe the maturity level [20]. For the system of objects as well as for the test coverage, these are used in relation to the system of objectives and the specific requirements. In this understanding, Weber presented an approach for describing the maturity level for the CPM model that also addresses the system of objectives via the target properties [21].
For the system of objectives, the definition of the maturity level is more difficult, since the completeness of the system of objectives is not defined or given. Richter, Tröster et al. [22] and Richter, Felber et al. [23] describe a continuous approach for assessing the maturity level of the system of objectives as a combination of the three dimensions validity, diversity, and level of detail, related to the elements of the system of objectives. The basis for this assessment is, among others, the research of Ebel, who divides the system of objectives into nine sub-models (including objectives, requirements, and functions) [24]. Based on this measurability, the actual state of the system of objectives can be defined, which then allows the next possible steps in development to be derived on the basis of expert assessments, leading to an increase in maturity. This defines the next target state of the system of objectives, whereby an actual-target maturity level determination can be carried out (Figure 2, [25]).

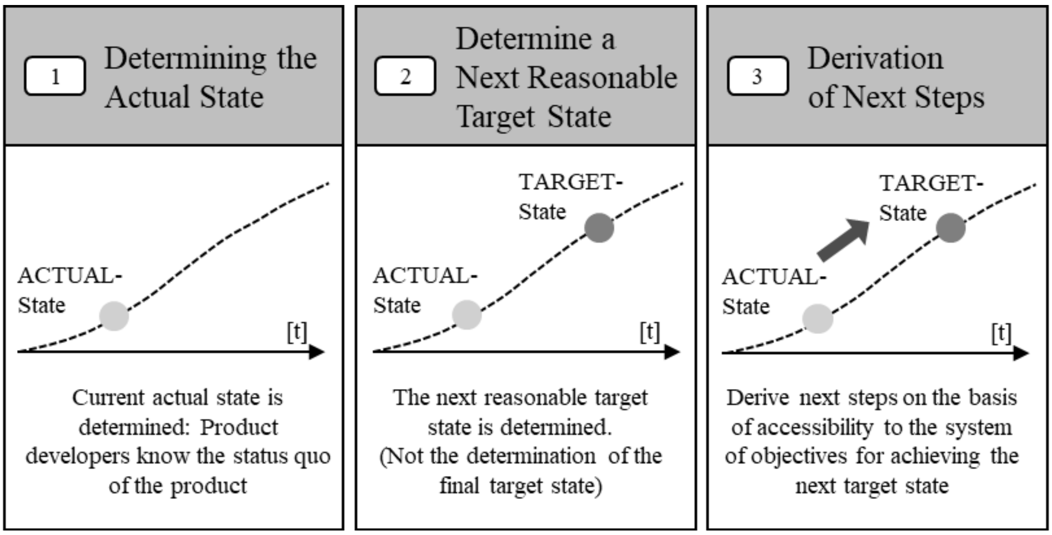

Figure 2: Measuring the maturity level of the system of objectives based on the current and next possible target state according to Richter [25]

In addition, descriptions of the system of objectives are subject to uncertainties, in particular originating in knowledge gaps or definition gaps [26]. Knowledge gaps describe non-existent or imprecise information that is or would be required for system development. Definition gaps, on the other hand, describe a situation in which decisions have not been made or the system is insufficiently specified.
In the current state of the art, various approaches for dealing with those uncertainties can be found [27, 28]. These include a systematic classification of uncertainty types into known and unknown uncertainties as well as uncertainties in data and descriptions/definitions [26, 29]. Hasting and McManus describe a framework for characterizing uncertainties [26]. Chalupnik et al. additionally distinguish between reducible (epistemic) and irreducible (aleatory) uncertainties [30].
In order to assess and enhance the maturity level of systems of objectives in product development, new approaches are needed that take into account those uncertainties.
Two particularly important approaches which can support in identifying and reducing uncertainties, especially in the context of the system of objectives, and thus in increasing the level of maturity in the system of objectives are:

1. the systematic re-use of knowledge from other products through reference systems [31, 32], and
2. the systematic building of knowledge through verification and validation measures [33].

2.2 Systematic reuse of knowledge from other products

According to the model of PGE - Product Generation Engineering [8, 34], the development of products is always based on references. Those references as well as their dependencies and interactions, are modeled in the reference system R_n for a product generation G_n [35]. New (sub-) systems of G_n are developed based on reference system elements (RSE) by a combination of three types of variation [36]:

- Carryover Variation (CV), where RSE are carried over to a new product generation and adjustments are only made regarding their integration and interfaces,
- Attribute Variation (AV), where the solution principle of RSE remains the same for a new product generation but attributes of those elements are varied and
- Principle Variation (PV), where new solution principles for elements of a new product generation are applied.

Modeling and describing information about a product generation and the appropriate reference system is crucial for successful product development. Today, many system descriptions still exist in the form of individual documents (e.g. functional specifications). Against the background of increasing digitalization, model-based system descriptions become more important [37]. For the use of reference systems and the description of systems of objectives as well as systems of objects, a target-oriented system description based on system-theoretical concepts is possible [38, 39].
This description is part of the so-called Model-Based Systems Engineering (MBSE). MBSE aims at replacing the multitude of unconnected elements and documents in product development with a central consistent system model. In the system model, the content-related aspects of the products are described via model elements (use case, requirement, function, logical element, etc.), their parameters, and relationships. The most widely used modeling language in MBSE is the Systems Modeling Language (SysML) [40]. SysML is a semi-formal graphical modeling language to describe products on the mechatronic system level(s) as well as the system context [41]. The SysML model can additionally facilitate analysis, verification,

and validation activities on the design [42, 43]. Model-based solution patterns are being investigated especially for the reuse of system elements [44].

Today's system of objectives descriptions are strongly focused on the product contents and contain a proportion of semantic information, especially for the project organization. As the system of objectives in projects is currently only created for specific requirements as well as specific stakeholders and taking into account specific boundary conditions, the systems of objectives and the knowledge represented in the descriptions can only be transferred to other products to a limited extent [45].

The transfer and evaluation of knowledge across contexts (e.g. products) is enabled by semantic information [46]. In this context, ontologies in particular are increasingly coming into focus as the basis for modeling [47]. In the area of driver assistance systems, for example, standardizations for the description of use cases/scenarios and environmental influences can be found (see e.g. ASAM OpenXOntology [48] or ASAM OpenODD [49]). A central goal of ontologies, besides the description of content aspects, is the representation of semantic information, so that the represented system descriptions can be analyzed and evaluated in a goal-oriented way [50]. For example, Ossig [51] uses ontologies to evaluate scenarios of autonomous driving. The combination of ontologies with systematic scenario analyses enables the identification and evaluation of a broad spectrum of functional system of objectives elements [52].

A relevant operationalization of ontologies for the transfer of semantic information and thus of knowledge are knowledge graphs [53–55]. An essential question that arises in this context is how the knowledge from other projects can be represented in knowledge graphs and, above all, how the knowledge from the knowledge graphs can be transferred into the system of objectives description of the current projects. The feasibility of transferring knowledge-based information within system models, such as SysML models, into knowledge graphs was demonstrated by Fu [56]. However, the systematic use of information in knowledge graphs for systems of objectives is an open topic.

2.3 Systematic knowledge generation through verification and validation measures

The knowledge identified from reference systems cannot close all knowledge and definition gaps in a product development project. Further knowledge must be built up in a targeted manner during development through verification and validation measures in order to reduce uncertainties and improve the maturity level of the system of objectives. In order to identify and describe test cases for the verification and validation measures, various general methods such as requirements analysis, e.g. system analysis techniques [57] are used. Especially in the software area, concrete methods for test case determination exist, such as "black box testing" e.g. using equivalence class analysis or interface analysis [58]. There are also approaches for risk-based or explorative test case determination [59]. Today, methods from the software area are usually difficult to transfer to mechatronic product development, since the prerequisites for test case determination are not given due to insufficient description of the system of objectives, e.g. definition of equivalence classes or necessary semantic information. A model-based approach to support the planning and evaluation of verification and validation activities in mechatronic product development is described by Mandel et al. and demonstrated for the case of an onboard-charger control unit [33, 60].

Uncertainties also exist in the development of test environments and the interpretation of test cases that are executed in these test environments (cf. credibility e.g. different maturity levels of the sub-systems or the influence of the modeling on the execution of the test cases in the test environment). In order to use findings from verification and validation specifically to reduce the uncertainties in the system of objectives, the question of the targeted definition and description of the system of objectives is essential as a basis for determining the necessary test cases.

3. RESEARCH OBJECTIVES

Transparency of the validity and maturity level of the system of objectives is a crucial factor to support the effective and efficient development of successful products. Analysis of the state of research shows, that especially the handling of uncertainties as well as knowledge and definition gaps within the system of objectives needs further methodical support. Two complementary approaches for this methodical support are identified in the systematic re-use of knowledge in product development and the building of knowledge through verification and validation measures (see Figure 3). However, up to this day, those approaches are not used in conjunction in a structured and target-oriented way to support the assessment and enhancement of the maturity level of systems of objectives. Thus, the aim of the research activities described in this contribution is to develop methodical support to assess and increase the maturity level of systems of objectives through the systematic reuse of knowledge in combination with targeted verification and validation activities.

The reuse of knowledge is mainly to be achieved via semantic information and the relations to specific content. Semantic models based on defined ontologies are already being used successfully today for cross-context knowledge transfer. Knowledge graphs are one of the means used for this purpose. In addition, there are approaches in Model-Based Systems Engineering for content-descriptive modeling of systems of objectives [2, 61]. In order to achieve the research objective, the content-descriptive and product-specific semantic aspects must be combined in the form of MBSE models and the cross-product semantic description by means of knowledge graphs (see Figure 3). The combination should enable the transfer of knowledge between different systems of objectives and a suitable description of the maturity level. Findings from the development of existing systems of objectives as well as their models (product-specific) are to be semantically processed and represented by means of knowledge graphs (cross-product) in order to be able to transfer knowledge to other systems of objectives. Parts or subgraphs of the knowledge graph are transferred to the new system of objectives if relevant content is defined in the new system of objectives. This requires a context-specific instantiation of the elements of the knowledge graph in the system of objectives.

Since the knowledge from the reference system in the sense of the model of PGE cannot be sufficient for the systems of objectives, further knowledge must be gained during development through suitable verification and validation measures. The targeted definition of test cases and associated test environments plays an important role here. In order to determine these, it must be investigated how the semantic information in the system of objectives or across the board in the knowledge graph can be used for this purpose. In addition, information from executed verification and validation activities can be used to enrich the knowledge graph and further enhance the maturity level of the system of objectives. This research investigates methodical approaches to support this enrichment in a target-oriented way.

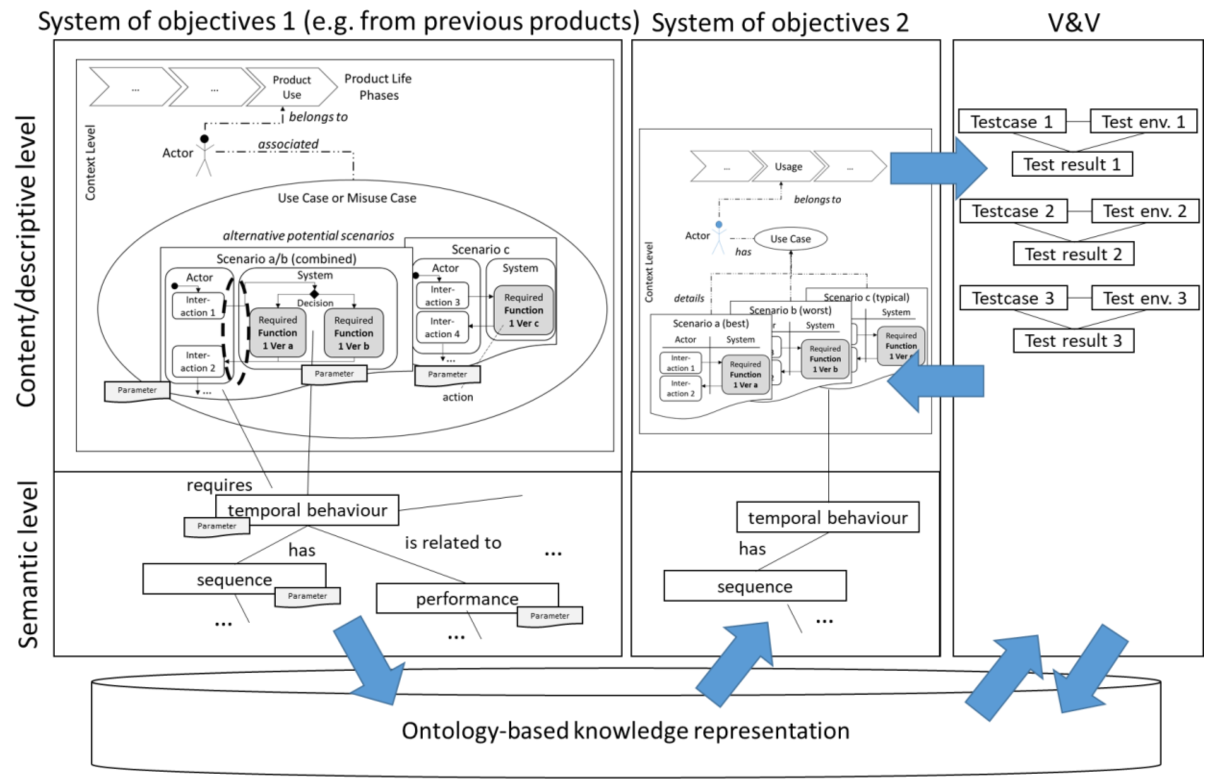

Figure 3: Model-based description of the system of objectives with content and semantic level

Several research questions arise in conclusion:

- How can the semantic information in the knowledge graph be transferred to the systems of objectives in order to increase their level of maturity?
- How can semantically prepared model-based elements of the system of objectives be used to identify and plan test cases and test environments?
- How can the results of verification and validation be used specifically to improve the systems of objectives and thus increase the level of maturity?

In this contribution, the authors describe their research approach to answering these research questions.

4. OVERALL APPROACH

4.1 Transferring knowledge between model-based systems of objectives using knowledge graphs

For the realization of the transfer of knowledge between model-based systems of objectives, three essential aspects are needed:

1. Metamodel of the system of objectives with content-descriptive and semantic levels as well as associated methods for matching between the levels.
2. Methods for retrieving relevant knowledge from existing systems of objectives in the knowledge graph on the basis of existing specifications in the relevant system of objectives.
3. Methods for enriching the knowledge graphs on the basis of existing systems of objectives (this aspect is not discussed in the paper).

The content-descriptive level for the first aspect is already present in today's systems of objectives. A metamodel is already used for this in SysML as an extension of the metamodel of the UML language (at least in versions 1.x) [62]. The SysML metamodel includes all elements relevant for content-descriptive modeling. The metamodel can be extended by stereotypes, which are combined in so-called profiles. For the semantic level, only a few elements currently exist in the SysML metamodel. These are mainly attributes on the elements and relationships for the organization of the models (e.g. the representation of the creator).

The semantic information as a basis for knowledge transfer between the systems of objectives must describe the meaning of the elements, their origin, boundary conditions, limits, etc. This information is not described in the current SysML metamodel. Therefore, an extended metamodel is required. There are essentially two approaches for the extension:

1. Extension of the existing SysML elements by supplementary attributes to represent the semantic information. The semantic information is thus directly assigned to the individual elements.
2. Creation of new elements based on existing SysML elements, which are used to represent the semantic information and are then assigned to the content-descriptive elements in SysML by means of specific relations.

For the present research activities, approach 2 is chosen, which allows an n-m mapping between semantic information and content descriptive elements. This makes it possible to assign the same semantic information to several content-descriptive elements. This is an important basis for transferring the knowledge from the knowledge graph to the system model and finally enriching the knowledge graph.

In order to query knowledge in the knowledge graph, specific search queries must be made. For existing knowledge graph frameworks, various query methods exist that generate specific search queries. A well-known query method is e.g. SPARQL query [55, 63]. To compose expressive queries, SPARQL offers various predefined advanced operators such as SELECT, WHERE, OPTIONAL, FILTER, etc. [64]. SELECT{} stores query results in specified variables, WHERE{} is used for query pattern matching, and so on. To query knowledge about systems of objectives, the query needs already defined content or semantic information from the system of objectives to be newly developed. If this system of objectives is built with the elements of the SysML language, the elements and their relationships can be traversed on the basis of the SysML metamodel, and query contents can be generated from them [55].

Figure 4 shows a part of a system of objectives for a precision engineering product. The elements of the use case description, the associated scenario, and the system context are connected to each other via the relations. Each of the elements of the system of objectives has a definition in the SysML metamodel. Thus, it is possible to create search queries starting from certain elements or relations (as in Figure 4 at the starting point of the interaction between system and measurement object) and linked elements. For the example in the figure, this would be e.g.:

1. Which known system of objectives elements or knowledge are available for the transmission of movements?
2. Which known system of objectives elements or findings are available at interfaces for the transmission of movement?

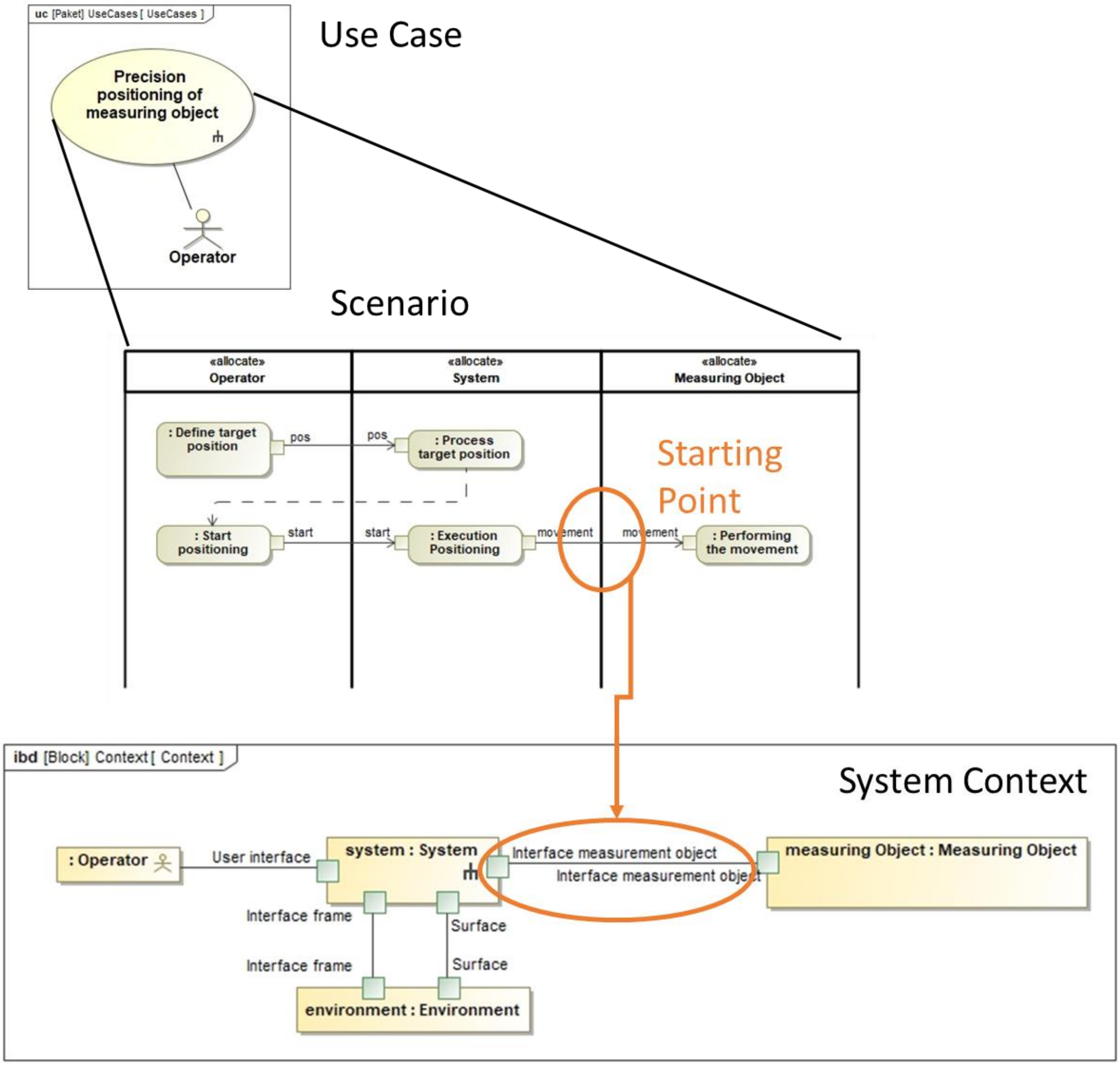

Figure 4: Simple example System of Objectives as a starting point for the query

If knowledge from other systems of objectives is available in the knowledge graph, it can be displayed on the basis of the results of the query method. This would be, for example, the resulting reaction forces for query 1 or the compliance with necessary tolerances, permissible deformations, etc. for query 2.

In order to be able to use these queries efficiently, several research questions are necessary on the design of the necessary metamodels in the knowledge graph or in the extended SysML model as well as on methods for generating the queries from the model contents. These research questions are the subject of further investigation by the authors.

4.2 Identifying test cases and test environments

In general, not all information necessary to build comprehensive systems of objectives for a product generation can directly be gained from a reference system. Verification and validation activities are the central means to create knowledge in product development and thus enrich the system of objectives [8]. Missing information in the model of the system of objectives as well as (modeled) uncertainties are the starting point to identify relevant verification and validation activities. Those uncertainties may on the one hand be knowledge gaps, e.g. use cases described

under assumptions. On the other hand, uncertainties may stem from definition gaps, e.g. logical dependencies between system functions that still have to be detailed.
Having identified those uncertainties, model-based approaches can support the target-oriented identification and analysis of test cases. Mandel et al. and Wiecher al. describe such a model-based approach that serves as a basis and is further developed for the described research [33, 60]. The approach encompasses an ontology to describe information regarding verification and validation activities in a model-based manner. The ontology serves as the source to define extensions of existing modeling languages, e.g. in the form of a SysML profile. In addition, modeling activities to methodically support the planning and analysis of verification and validation activities are defined and arranged in a reusable agile framework (Figure 5).

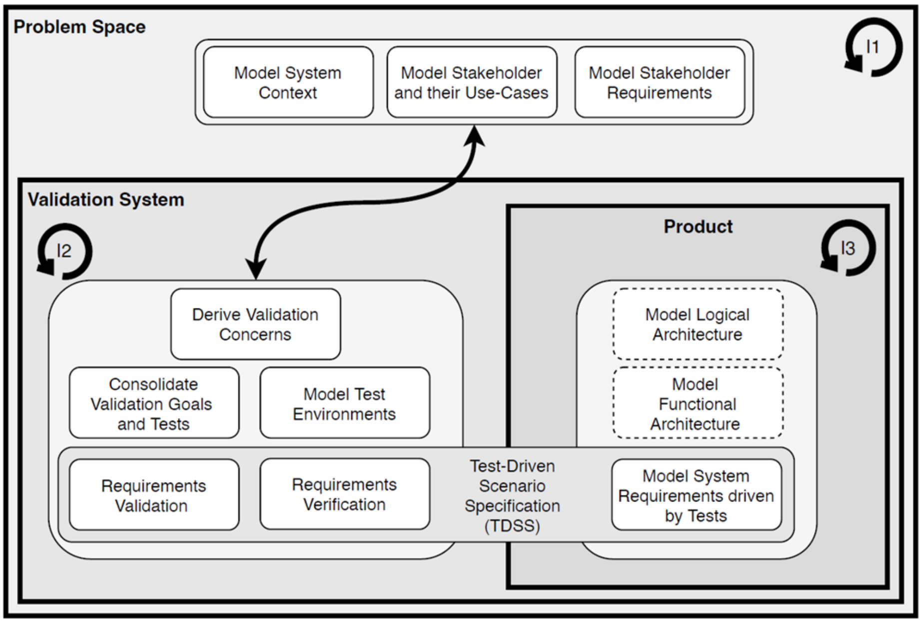

Figure 5: Modeling activities to support verification and validation using MBSE [60]

In this understanding, so-called “Validation Concerns” are modeled to address the identified uncertainties in the system of objectives. Validation concerns have to be further detailed into more concrete validation goals, depending on the actual state and maturity of the development. The description of this maturity level of the system of objectives and the interrelation to the defined validation goal is a central research question for the described research. Validation goals again are the source to define test cases and appropriate test environments. By applying model-based approaches, the traceability in the created system models can be used to automatically display relevant information for the selection or definition, respectively, of appropriate test cases and test environments for the defined validation goal. In this way, e.g. potentially relevant requirements, stakeholders, and use cases for a defined test case, addressing a concrete validation goal, are traceable (via the identified validation concern) and can be automatically displayed (Figure 6). Considering the simplified example for the validation of an Autonomous Emergency Braking system (AEB), the displayed table is automatically generated from a SysML model to show the validation goals (second column) addressed by the test case as well as the source of the validation concern (third column) for a modeled test case. In addition, relevant use cases, system elements, requirements, and stakeholders/environment systems traced to the test case are displayed (columns four to seven).
Further research questions to be addressed in the author’s investigations consist in characterizing and supporting the interplay between the identification and description of

validation concerns, validation goals, appropriate test cases, and the use of the knowledge graph as described in section 4.1.

Name	Adresses validation objective	Source of validation need	Relevant Use Cases	Relevant system elements	Relevant requirements	Relevant stakeholders/environment systems
AEB Test_out of town	24 Braking Vehicle out of town	4 Req: AEB_res_dis_min	5 Automatically brake in case of an emergency	AEB Braking Controller	4 Req: AEB_res_dis_min	Driver Traffic Objects

Figure 6: Automatically displayed relevant information for a test case (first column) - example of the validation of advanced driver assistance systems [65]

4.3 Using results from verification and validation activities to increase the maturity level of systems of objectives

As described in the previous section, results from verification and validation activities generate knowledge in product engineering. In the understanding of this research, this knowledge needs to be appropriately processed to serve two purposes:

- Concretizing the system of objectives and thus increasing its level of maturity
- Reuse of this knowledge as part of the reference system in future product generations

In order to support the first aspect, the model-based description of test cases and appropriate test environments (cf. section 4.2) need to be extended by a model-based description of the test result. For this purpose, surrogate elements for specific test results to a defined test case in a defined test environment can be included in the model for the system of objectives. Those surrogate elements link to the more detailed test results, e.g. on a separate server for test data. Like this, the coherent triple of test case, test environment, and test result is included in the model of the system of objectives and traceable to further elements like stakeholders or use cases (see Figure 3). This traceability supports in interpreting the test results and the advancement of the level of maturity of the system of objectives, as the elements impacted by a test result can directly be identified (see Figure 7, simplified example of the AEB system).

Figure 7: Traceability from a modeled test result to further elements of the system of objectives to support test interpretation [65]

As a consequence, further measures, e.g. the addition of additional requirements, the concretization of use case descriptions, or the identification of new knowledge- and definition gaps is supported. Detailed methodical approaches to support those measures are subject of the author’s investigation. However, the interpretation of test results is also subject to further influencing factors, especially concerning the credibility of the chosen test environment. While interpreting test results, it has to be taken into account if and to which degree the chosen test environments are appropriate to close the identified knowledge- and definition gaps. Thus, defining appropriate metrics for the assessment of test results regarding those influence factors and rating the increase in the level of maturity of the system of objectives is another part of the author’s research.

Furthermore, executed test cases and the gained results can not only support in advancing the level of maturity for the current product generation but can also be fed back into the knowledge graph to serve as part of the reference system for future product generations. Therefore, the coherent triple test case - test environment - test result as well as connected information from the system of objectives (e.g. relevant stakeholders or requirements for the test case, addressed validation goal, etc.) can be fed back into the knowledge graph (see the lower right side in

Figure 3). In this way, verification and validation activities enhance and expand the knowledge graph. However, methodical support is needed to transfer results from one product generation in an abstracted form, useable for further product generations and further products. Researching this methodical support is a further part of the author's investigation.

5. CONCLUSION AND OUTLOOK

This paper highlights envisioned research to advance the modeling of the system of objectives with appropriate descriptions of its level of maturity. The research is expected to support working with the system of objectives as a significant success factor for successful product development. The combination of models of the system of objectives following MBSE approaches with semantic descriptions in the form of a knowledge graph should not only support the development of a single product generation but also help to continuously generate and process knowledge in a reusable form for the reference system of future product generations. In this way, even more benefits are expected from the described approach in future product generations.

The authors formulate three research questions to address identified gaps in the state of research. General approaches to address those research questions are presented and will be further investigated. The research is applied exemplarily to two use cases from precision engineering and Advanced Driver Assistance Systems (ADAS). This ensures a high level of practical relevance. At the same time, the aim is to generalize the approaches, already in the exchange between the two selected product groups, but also for other products in the future.

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