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Model Based Requirements Engineering for the Development of Modular Kits

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Abstract

The introduction of modular design increases complexity within product development and especially within Requirements Engineering. To handle this complexity, the approach of Model Based Systems Engineering is applied in this contribution. First, the origins of complexity in modular product development are introduced. Key challenges within Requirements Engineering are drawn up and then verified. A modeling method for requirements of modular kits is introduced and validated in the series development of hybrid drivetrain systems at a German automotive manufacturer. Increases in quality and a requirements reusability of over 80% were achieved. Thus, the capability of the modeling method is verified.

Keywords: Modular Design; MBSE; Systems Engineering; Requirements Engineering; Product Generation Engineering

1. Introduction

The development of modular systems is a productive and well-established measure in the automotive industry to increase the diversity of vehicles offered and to lower the variety of components in-house at the same time. However, the modular principle increases complexity within product development. In literature, multiple methods for the modularization of technical systems (transferring a conventional into a modular product generation) are introduced [i.a. 1, 2, 3, 4, 5, 6], some of them with a considerable focus on testability [7]. For the early stages, approaches have been developed [8, 9], too. However, for the series development of modular kits, there are only a few methods available. This paper focuses on Requirements Engineering, due to its large impact on a successful development. The paper describes, how the Model Based Systems Engineering (MBSE) approach can be used to support Requirements Engineering activities within modular kit development.

2. State of the Art

2.1. Modular Kit Development

In existing literature, SCHUH et al. – amongst others – claim modular kit development as a sequential process, which is independent of and prior to the actual product development [10, 11]. According to this, it is possible to develop all modules first and consecutively configure customer-ready products out of these modules. However, referring to the central hypothesis of product development of ALBERS, a product development is a continuous and highly iterative process, gradually increasing the maturity of the product [12]. Consequently, a lot of essential information about the products, which the modules shall later be part of, is not available at the time the modules are developed. This is why a modular kit development, which is independent of and prior to the product development, isn't feasible since the development of the modules cannot be finalized before the development of the products. Hence,

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modular kit development must rather be considered a process permanently ongoing during product developments [13], leading to a large time scope (see fig. 1).

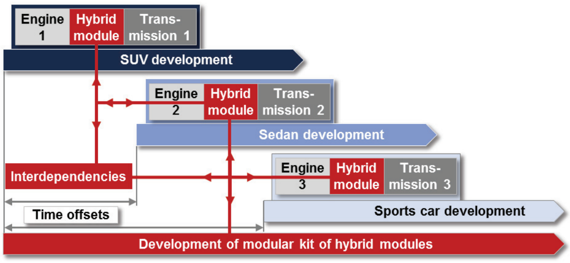

Fig. 1. Challenges of Modular Kit Development in the Automotive Industry

The development of modular kits being an ongoing activity, some specific challenges can be observed, especially as far as Requirements Engineering is concerned [14].

2.2. Requirements Engineering for Modular Kits

In this section, some general facts about Requirements Engineering and its relevance are compiled from existing literature. After that, key challenges within Requirements Engineering in the development of modular kits are drawn up.

Requirements Engineering is an essential element of a successful product development [15]. The quality of Requirements Engineering activities has a large influence on the quality of the result of a product development [16], those activities being: identification, documentation, validation and managing of the system of objectives [17]. Each of these activities brings its own challenges in industrial applications. The most significant factors within the automotive industry are: permanent enhancements and late modifications of the system of objectives as well as a large amount of stakeholders [18]. Furthermore, there is a huge demand for the reusability of the elements within a system of objectives, which must be achieved by appropriate approaches [19].

Now, the initial origins of complexity within the development of modular products are introduced and their immediate impact on Requirements Engineering is drawn up. As explained above, considering modular kit development as a steadily ongoing activity can lead to large time scopes. This leads to two key challenges for the development of modules:

1) Large time offsets: To use a company's resources (e.g. development teams, test benches, tools for computer aided engineering) consistently, vehicles using the same module are usually not developed simultaneously, but with offset program milestones (see fig. 1), thus extending modular kit development even further (10 years or more are common in the automotive industry) [20]. This means, at the beginning of the module's development, when all requirements for the module must be identified, a lot of information, regarding the vehicles which are developed later, isn't available yet. The initial system of objectives cannot be entirely completed. Hence, these time offsets within modular kit development lead to an increased uncertainty regarding the corresponding requirements within the module's system of objectives, and thus leading to higher complexity [1]. As proposed by ALBERS et al. [21], uncertainty of objectives, requirements and constraints can be expressed with the help of

- the degree of maturity (describes the completeness regarding the understanding and realization of an element of the system of objectives) and
- the degree of rigidity (indicator for the trustworthiness or rather the changeability of an objective).

2) Increased interdependencies: When looking at the initial goal of modular design to reduce the in-house variety of components of a company, one could assume modular kits can lower development efforts as well. However, one module now must satisfy the objectives, requirements and constraints of several vehicles. Thus, Requirements Engineering for the module's development becomes more complex due to the larger extent, variety and interdependency of the module's system of objectives [14, 22]. Furthermore, these interdependencies (see fig. 1) require close collaboration between the vehicle's developments and the module's development, leading to significant processual complexity [23].

The complexity of modular kit development can hardly be abolished since the origins of complexity cannot be changed. This is why new methods must be found that address the large times scopes and highly increased interdependencies within the series development of modular kits.

2.3. Model Based Systems Engineering

Even though working with a large number of documents (document-based development) is still widely spread, this approach is not capable of dealing with the high complexity of modular kit development [20]. In contrast, Model Based Systems Engineering (MBSE) offers new opportunities. It is based on a system-theoretical approach [24], in which a technical system and all data occurring in its development is captured and handled in central, computer-based product models [25]. These models replace the unmanageable amount of documents. It is accessible for all development stakeholders; hence, knowledge is made available more reliably. Thereby, MBSE enables large improvements regarding the consistency, perceivability, but also the reusability of the data [26]. Especially the reusability is important since the most products are developed in generations, with a share of subsystems, which are carried over [27].

The capabilities and benefits of the MBSE approach could already be proven in complex environments (e.g. in the development of space and defense systems [28]), yet the need for MBSE is rapidly growing in the automotive industry [29]. To handle the complexity in Requirements Engineering of modular kit development, the MBSE approach is applied in this contribution.

3. Methodology

To manage systems of objectives in conventional developments, some MBSE solutions are already applied in automotive companies. However, the research demand, that is investigated in this paper, focuses on systems of objectives in modular kit development. In particular, the origins of complexity in modular kit development shall be addressed. Therefore, the following research question has to be answered:

How can Requirements Engineering within the series development of modular kits be supported by an MBSE method for the systems of objectives?

As some further implications of this question, the method must pay special attention to the large time offsets as well as to the grown interdependencies of modular kit development. Furthermore, the method shall enable a large degree of reusability for the elements within the systems of objectives.

4. Empirical Studies

In this section, the results of two empirical studies – both carried out in the series development of modular hybrid drivetrains of a German automotive manufacturer – are introduced: The first one is a case study defining four key challenges in modular kit Requirements Engineering. These key challenges were found by observing Requirements Engineering processes in modular kit development. They are verified through a questionnaire in the second study. The key challenges are:

1) *The system of objectives is incomplete*: Due to the larger extent of modular kit requirements, it is more likely that some objectives, requirements and constraints are missing.
2) *Not all stakeholders are aware of the latest version* of the system of objectives: Due to the complex network of today's modular kit developments (e.g. collaborations between several OEMs and suppliers), it can be challenging to keep all stakeholders up to date at all times, despite continuous requirements changes that occur.
3) *Lacking analysis of consequences* of the systems of objectives: Stakeholders must question and fully understand all objectives, requirements, and constraints regarding their impact on the module's design. Due to the larger variety of modular kit requirements, it is more likely that some issues remain unregarded.
4) *Varying degree of maturity and rigidity* of the system of objectives due to the large time offsets in modular kit development, resulting in a lack of information about objectives, requirements, and constraints.

The four key challenges in modular kit Requirements Engineering could be confirmed through a questionnaire among 31 developers for modular kits. Essential results are shown here: On average, 60 % of the developers are affected by the key challenges of modular kit Requirements Engineering (see Question A, fig. 2). Moreover, 75 % (average value of the four key challenges) of the developers wish to be supported by new methods in Requirements Engineering of modular kit development. Summing up the two empirical studies, four key challenges in modular kit Requirements Engineering – derived from the characteristics of modular kit development – could be found and the demand for suitable methods to support the developers could be shown.

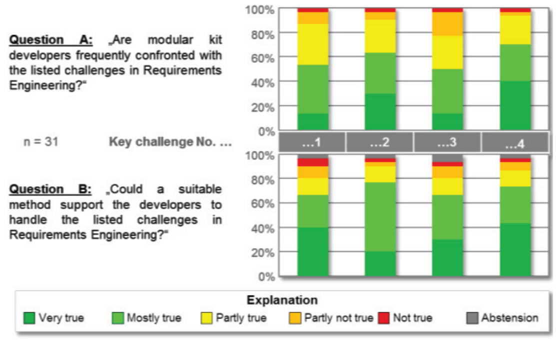

Fig. 2. Questionnaire results on Key Challenges: (1) The system of objectives is incomplete; (2) Not all stakeholders are aware of the latest version; (3) Lacking analysis of consequences; (4) Varying degree of maturity and rigidity (N = 31)

5. Modeling Method for the Systems of Objectives of Modular Kits

As stated in chapter 2.3, the MBSE approach can help developers deal with the complexity in Requirements Engineering for modular kits. Since a computer-based model of the system of objectives can improve availability and accessibility of objectives, requirements and constraints of the modules, it can help stakeholders to be aware of the latest version of the system of objectives, thus addressing Requirements Engineering key challenge No. 2 (cf. chapter 4).

In order to generate models of the system of objectives, a new modeling method is introduced. It combines several approaches to address each of the key challenges of modular kit development (cf. chapter 2.2) and of modular kit Requirements Engineering (cf. chapter 4).

One major aspect of the modeling method is a structure suitable for a modular kit's system of objectives. The structure must be able to incorporate the increased extent and variety of a module's requirements. The principles of the structure are explained using a hybrid module as a schematic example (fig. 3).

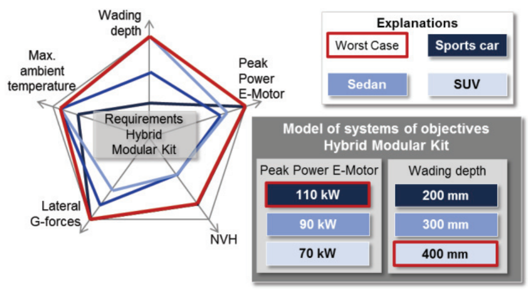

Fig. 3. Structure of the system of objectives for modular kits

As shown, one requirement can have multiple values, depending on the vehicle type the hybrid module is used in (i.e. peak power of the electric motor varies for the vehicle types

SUV and sports car, likewise the values for maximum lateral G-forces).

Hence, each of these multiple values must be modelled in relation to the corresponding requirement on one hand (indicated by gray boxes, fig. 3) and the corresponding vehicle on the other (indicated by shades of blue, fig. 3). This structure allows filtering the module's system objectives for e.g. SUV requirements only. Furthermore, such a structure suitable for modular kits can help discover and complement missing elements, thus addressing Requirements Engineering key challenge No. 1 (cf. chapter 4).

Another feature of the structure is to identify the highest or technically most challenging value of each requirement (often called worst case). Note that the worst case value isn't always corresponding with the same vehicle (e.g. maximum wading depth required for the SUV vs. maximum NVH requirements for the sedan, fig. 3). The aggregation of worst case values can be shown by the red graph. Filtering the module's system of objectives for these worst case values can help planning the validation of the modular kit efficiently: According to the principle "worst case first", the technically most challenging value can be tested first, irrespective of the corresponding vehicle's timeline. Thereby, the least challenging values of a requirement can be validated implicitly at the same time and thus save testing time and cost.

In addition to its structure, the modeling method uses several element types (e.g. objective, requirement, constraint) and relation types (e.g. expressing hierarchical or competing interrelations). The latter plays a significant role in helping the stakeholders analyze and understand the consequences of all requirements in modular kit development (e.g. increasing the value for constant power output of the electric motor requires modification of the requirements regarding cooling), thus addressing Requirements Engineering key challenge No. 3 (cf. chapter 4).

The time offset within modular kit development leads to increased uncertainty within the systems of objectives (key challenge of modular kit development No. 1, cf. chapter 2.1), causing varying degrees of maturity and rigidity (Requirements Engineering key challenge No. 4, cf. chapter 4). To address this challenge, the modeling method uses the following approach: For each element of the systems of objectives, the degree of maturity and rigidity can be defined individually. Tough this is a first step to make uncertainty explicit, it is not sufficient yet to derive an operational solution to deal with uncertainty. This is why in a second step, possible countermeasures must be proposed to overcome the lack of information. Therefore the developers can choose among several activities in both categories – depending on the degree of maturity or rigidity found.

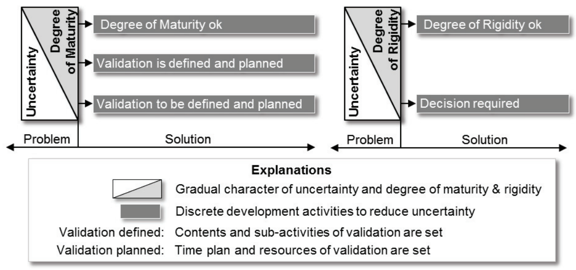

Fig. 4. Degree of maturity and rigidity

As shown in figure 4, the available options to raise the degree of maturity (left) for the developer to choose from are the planning and executing of a validation (e.g. virtual test bench runs with the hybrid unit to clarify requirements regarding its cooling). On the other hand, one most likely reason for a requirement's low degree of rigidity (right) is due to project decisions still pending. In these cases, the developers can indicate the need for a decision (e.g. regarding conflicting objectives) to increase the degree of rigidity. Hence, despite the gradual and rather conceptional characteristics of the degree of maturity and rigidity, a pragmatic solution could be found for the application in industrial companies.

Besides the fundamental components of the modeling method introduced so far, several guidelines out of established Requirements Engineering literature concerning the linguistic format of objectives, requirements, and constraints have been integrated [cp. 17]. They include rules for the authors of the model of the system of objectives, e.g. use only one requirement per element, all requirements must be verifiable etc.

In order to achieve maximum reusability of the elements within a system of objectives for modular kits (cf. chapter 3), the new modeling method cannot only be used to generate project-specific models, but also some more generic reference models. A reference model can be created by merging and aggregating the systems of objectives of several product generations of the past. During its build, a reference model must be exceedingly tested for its completeness, consistency, and linguistic quality. Generating the reference model out of the scope of a contemporary development process offers the chance to take more time and effort to achieve those quality standards. The relatively high effort caused by its initial creation promises to be highly overcompensated during its utilization, as the following section shall explain.

6. Method Application and Validation

After developing the new modeling method, it is applied and thereby validated in the series development at a German automotive manufacturer. It is used to create a reference model for systems of objectives of modular hybrid drivetrain systems. Later, this reference model is utilized to derive several project-specific systems of objectives which are needed for the ongoing modular hybrid vehicle development projects. In order to create the initial reference model, more than seven systems of objectives and specification sheets from older product generations were analyzed and merged into one single model. This step is essential since there hasn't been a reference model for systems of objectives in modular hybrid development before. Furthermore, numerous expert interviews were conducted to capture requirements about e.g. corrosion, cast iron design, recycling and material grades. That way, over 3700 objectives, requirements and constraints were integrated into the reference model. Overall, 13 element types were used, in addition to corresponding relation types; the latter are required on one hand to indicate essential interdependencies within the hybrid module reference model. On the other hand, relations were modeled to express interrelations between hybrid module requirements and requirements of neighboring modules within the vehicle's driveline, e.g. combustion engine, transmission or drive shafts. Additionally, over 110 further applicable documents, like norms, engineer standards and design guidelines were either linked with or embedded into the reference model. As a tool, IBM DOORS was applied, since it was already in use in the company (unlike other designated MBSE tools like SysML). All approaches of the modeling method were therefore adapted into DOORS to build the reference model.

In order to apply the reference model of the system of objectives for modular systems as gainful as possible, it must be possible to deduce project-specific systems of objectives from the reference model, thus the latter serving as a template. In the course of this deduction, it is essential to achieve the highest possible share of reusable elements, in order to save time and to carry on the high-quality standard from the reference model to the project-specific model regarding completeness, consistency and linguistic quality. To serve this purpose of most advanced reusability, the architecture of the reference model allows for the generation of project-specific models of the system of objectives for different types of modular hybrid systems, e.g. a mild hybrid system, a plug-in hybrid system or an electric axle drive for purely electric vehicles (see fig. 5).

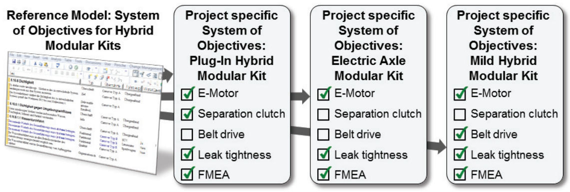

Fig. 5. Configuration of project-specific models out of the reference model

By selecting or dropping relevant sections within the reference model, the content of the project-specific models can be configured. For instance, the modular mild hybrid system needs a section containing requirements for a belt drive, whereas the modular plug-in hybrid system needs requirements regarding a separation clutch enabling pure electric drive. Other sections are mandatory for all the types of modular hybrid systems, e.g. requirements for the electric motor or leak tightness. This functionality is implemented into DOORS with the help of an attribute, which defines whether a section or an element of the reference model is relevant for one or several types of hybrid systems.

The degree of synergy and reusability has been investigated in the course of the deduction of project-specific models out of the reference model for all three types of modular hybrid systems (see fig. 5).

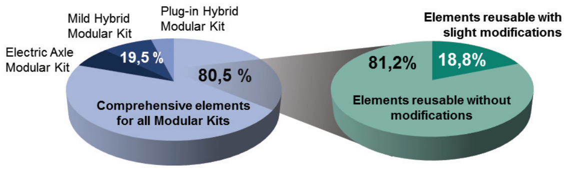

Fig. 6. Reusability of elements of the reference model

The result is shown in figure 6: Over 80 % of the reference model's elements are relevant for all three types of modular hybrid systems, the remaining 20 % being specifically required for one of the types (left). The share of 80 % represents the synergies achievable between the types of modular hybrid systems, thus only one collaborative reference model is needed. These comprehensively used objectives, requirements and constraints can be split up into elements with no modifications required (81,2 %) and elements with slight modifications required (18,8 %; right). The high share of elements without the need of additional modifications also reveal, that the high quality standards of the reference model could be carried over for the large majority of elements. The elements in need of a slight modification, however, can be carried over as well (thus reducing the risk of an incomplete system of objectives). The only modification needed is the replacing of some generic placeholders of the reference model with project-specific data, e.g. performance figures, the timeline or a CAD screenshot revealing packaging constraints.

Overall, the application of the new modeling method to generate a reference model of systems of objectives of modular hybrid systems verified its useability. Furthermore, the deduction of multiple project spefic models in an industrial company revealed the potential for significant improvements, as far as reusability and quality of systems of objectives are concerned.

7. Conclusion and Outlook

In this contribution, a new MBSE modeling method is introduced suitable for systems of objectives for modular systems. Key advantages of the method are its ability to represent the large extent, variety and interdependency of the module's system of objectives, as well as a high share of reusability of requirements. Out of the generated reference model, project-specific models of the system of objectives can be derived for various hybrid drivetrain layouts. The large share of reusable elements enable large time savings possible whenever a new project-specific System Model of Objectives is needed. Furthermore, the quality of the system of objectives could be improved, since its contents are pre-checked regarding consistency, perceivability and completeness. Through the utilization of the method in several modular hybrid development projects of a German automotive company, the capabilities of the modeling method could be verified. Further research should be done by applying the modeling method for e.g. software-dominated products, different industries and company sizes to find out more about its advantages and limitations.

Facing the strategic challenges in modular kit development, companies might face conflicting goals: On the one hand, sticking to the architecture of existing modular kits over a long period of time, products cannot cope with the demand for innovations. On the other hand, steadily extending modular kits with new modules would miss the whole point of modular kits, which is to reduce the internal variety of parts within a company. Hence, managing the generations of products, its modules and the corresponding modular kits demands a systematic approach. If new requirements for modular products arise, one should examine whether these products can be configured with existing parts out of the current modular kit. If this seems not feasible, the options are:

- check, whether the unrealizable requirements can be replaced by different requirements, that are already covered by the existing modular kit
- development of a new module as an element of (and thus extending) an existing modular kit
- development of a new generation of a whole modular kit.

As a conclusion, besides the products, the modular kits and its elements must be developed in generations as well. Therefore, further research is needed in order to find the ideal life cycles for products, modules, and modular kits as a function of the characteristics of different industry sectors. This is to create a strategic life cycle concept, which both satisfies the demand for innovative products and for the cost savings that the modular approach offers.

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