Supporting the Synthesis of Validation Environments for Cross-System Generation Validation by Using MBSE Methodologies

Development of an initial approach using the example of the validation of a cyber-physical system "car brake system" based on the design of a component connection in a validation environment

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***Abstract*— The increasing complexity of cyber-physical systems (CPS) and shorter development cycles are leading to growing challenges in the synthesis of consistent and credible validation environments. This article presents a methodical, model-based approach for instantiating such validation environments in the form of concrete validation configurations and validates this approach using the example of an existing, non-model-based validation environment for an electromechanical brake system As an example, one of the component connections in the validation configuration is considered in the form of a shaft-hub connection. This connection should be selected and designed so that it is suitable for several generations of passenger car brake systems as well as for several development generations within a product generation. This example shows the procedure for creating the system of objectives with the validation objectives and requirements that result for the validation configurations and the resulting validation environment. The operation system is then used to create the system of objects for the validation environment, which involves mutual expansion and comparison with the system of objectives for the validation environment and comparison with the system of objectives for the product. The goal is to use this approach to come up with a model-based method for creating consistent validation environments. Initial implementations of the approach in a model-based systems engineering tool have already been done.**

Keywords—Model-based Systems Engineering, Cyber-physical System, Validation, testing, product generation engineering

I. Introduction

The development of many products today requires an interdisciplinary product development process involving mechanical engineering, electrical engineering, and information technology. The resulting products are called cyber-physical systems (CPS). The electromechanical passenger car brake system with anti-lock braking system (ABS) examined in this article, for example, contains elements from all three of these areas. The existing validation configuration with the passenger car brake system is referred to herein as "Brake-System-in-the-Loop" (BSiL). A validation configuration is a concrete instance of a validation environment for a validation objective and a system to be investigated [1, p. 2803].

Due to the central role of validation in product development [2, p. 5], consistent validation is particularly important when considering multiple product generations. Consistency means that there are no known discrepancies in one or more models, as there would be in the case of inconsistency [3, p. 912]. The model of the System Generation Engineering (SGE) model can be used here to transfer reference system elements from an existing validation configuration of a generation G_n to a validation configuration of a future system generation G_{n+1} [4]. Due to the transition from G_n to G_{n+1}, a new system under investigation (SuI) is now in place, which brings changes while at the same time the verification and fulfillment of the validation objectives remain necessary. Support is needed to assess the suitability of an existing validation environment for a new product generation G_n and to ensure the necessary consistency of the models. This support could not be found in sufficient detail in a systematic literature review.

The synthesis of validation environments is currently mainly based on experience and implicit knowledge of experts in the field [5][6]. The procedure can be supported and classified using VDI 2221 for the development of technical products and systems [7] and the integrated Product engineering Model (iPeM), which describes the continuous interaction of systems of objectives and system of objects via the operation system in product development [8]. The extended ZHO triple forms the fundamental basis for this [9].

To close this research gap, the model-based systems engineering approach has been chosen because it enables better handling of inconsistencies and, consequently, improved consistency, greater traceability of design decisions, systematic reusability of existing validation environments, increased robustness, easier reproducibility, and optimized future-oriented design based on current knowledge of the generations. [10]

In particular, persons who have the appropriate engineering education but do not yet have extensive professional experience could receive support in the synthesis of validation environments without having to consult experienced experts. Experienced people would also receive support in the synthesis of appropriate validation environments in the event of changes to the SuI, the validation objectives, or the boundary conditions.

II. Background

An initial systematic literature review identified the need for model-based methodological support in the synthesis of validation environments for CPS and their consistency across multiple generations. No significant number of relevant approaches could be found for the methodological procedure for achieving the appropriate validation configuration for a SuI, its validation objectives, and other boundary conditions, nor for ensuring cross-generational consistency, nor for modeling validation environments. The validation configuration has a significant influence on the SuI and thus also on the validation results [5, p. 2], which has been demonstrated in experiments with the same tests and the same SuI [11]. The synthesis of validation configurations is usually based on experience, and the interaction between the physical and virtual components used cannot be predicted entirely [5, p. 2]. Koppelsystems are necessary, particularly for connecting physical and virtual components [12]. Storing accessible references and knowledge promises great advantages in terms of reusability [5, p. 2].

Some approaches with systematic and methodological support are also available, but these need to be adapted and expanded for a holistic model-based method:

According to Arrieta et al., the high variability makes validating CPS very complex, which makes manual creation of test systems time-consuming and error-prone. A systematic procedure has therefore been developed to select suitable validation configurations and test cases. However, this requires, for example, a modeled form of the CPS and a selection of possible test cases and validation configurations as input. [13]

Approaches such as those proposed by Ullmann et al. take a very close look at the process of modeling CPS without, however, making any reference to the associated validation environments. [14]

The major problem of inconsistencies arising in the development of CPS and thus also in their associated validation environments is based on parallel development of heterogeneous models, poorly understood dependencies, imprecise requirements, or missing information. Appropriate action is therefore necessary to identify and, where necessary, resolve these inconsistencies. [3]

Kürten et al. shows that different validation configurations can lead to different validation results for the same SuI and validation objectives. As a solution, he created a central exchange platform for models and parameter data based on the physical architecture of a SuI in order to reduce these inconsistencies. [11]

In the "Verification Validation Methods" (VVM) project, a methodical, model-based support validation plan was developed in the field of automated driving. [15]

For example, Mandel specifies a model-based systems engineering methodology to support validation in the product development process, but does not focus on the specific selection and development of the validation configuration to be used. [16, pp. 133-134].

This approach by Mandel will be used as a starting point herein, as it already indicates the applicability and benefits of MBSE for validation environments. This and the other approaches identified will now be used to develop a model-based procedure to support the synthesis of suitable validation environments for CPS, from which a general method will later be derived.

After intensive research and analysis, it is difficult to transfer other approaches from the field of information technology with a focus on software to mixed physical-virtual validation environments.

III. Theory, Application and Results

A systematic literature review regarding support for the development and synthesis of validation environments for cyber-physical systems revealed very few comprehensive, systematic, model-based, and methodical approaches. Therefore, the aim is to develop such a model-based method for the development of consistent and credible validation environments. A first draft of a procedure has been developed for this purpose and is presented in A. The first application example and thus also the first validation of the procedure is being done on the validation configuration "Brake-System-in-the-Loop" for an electromechanical passenger car brake system and was developed and set up in real life. This validation configuration contains various linked physical and virtual models and, through the advance planning of interfaces and quickly implementable adjustments is part of a validation environment with further validation configurations that can be adapted for different brake systems or validation objectives using the IPEK-X-in-the-Loop approach [17]. This validation configuration was considered using established process models of the design methodology and machine design in accordance with VDI 2221 [7], as well as (partially implicit) experience, design, assembly, manufacturing and expert knowledge and is described in B.

The different generations of the SuI car brake system considered here have the following basic names, key features, and development sequence:

- Brake system generation G_{n-1} (Electro-mechanical braking)
- Brake system generation G_n (Electro-mechanical braking with ABS and ESP)
- Brake system generation G_{n+1} (Electric braking & electro-mechanical braking with ABS and ESP).

These SuIs were already considered when designing the initial validation configuration as part of the validation environment, with further validation configurations for the specified changes to the SuI to be added in the future, but with the aim of achieving the highest possible robustness regarding possible changes to validation objectives and boundary conditions. These examples with different resulting validation configurations are intended to provide insights based on the procedure, which can then be used to develop a reference process including methodological support and implementation in an appropriate model-based systems engineering tool.

The application of a part of the currently planned model-based approach is demonstrated in Chapter C using an example part of the validation configuration for various changes. Initial implementation is described in Chapter D.

A. Designed model-based approach for the instantiation of consistent and credible validation environments

The following Figure 1 provides a condensed and simplified overview of the current procedure, with the individual steps and their interrelationships explained in detail below.
This generally follows the SPALTEN process, which consists of the following steps: “Situation Analysis”, “Problem Containment”, “Alternative Solutions”, “Selection of Solutions”, “Consequence Analysis”, “Make Decision” and “Recapitulate/ Learn”. In addition to the basic structure of the procedure, this process is also repeated multiple times and fractally, so that in some cases, individual steps of the SPALTEN process involve their own small SPALTEN process. [18]
In the integrated Product engineering Model (iPeM) [8] mentioned above, the model-based approach acts as a link between the “Product G_n” and “Product G_{n+1}” layers and the “Validation System” layer.
The activities involved in the action system include “Validate and Verify”, “Manage Knowledge”, “Manage Changes”, “Model Principle and Embodiment” and others.

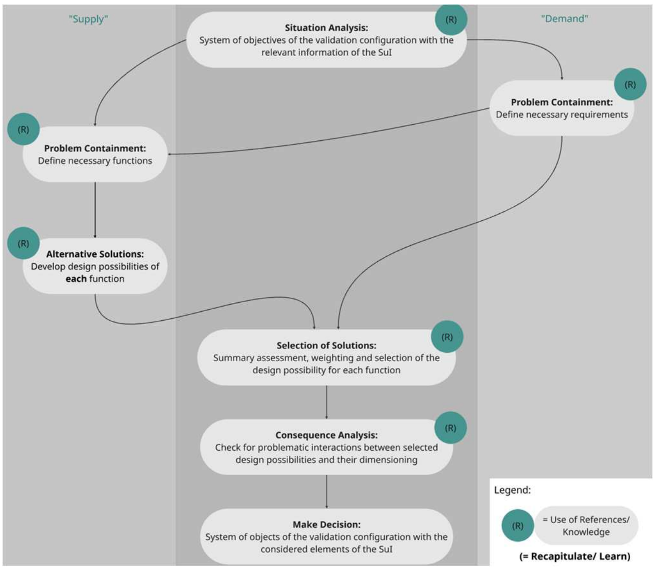

Figure 1: Shortened and simplified Overview about the procedure

Starting from an appropriately structured and modeled form of system of the objectives of the validation configuration with the relevant information of the SuI, the validation objectives, and the boundary conditions, the procedure begins. Existing validation configurations from similar use cases should also be considered and used. In validation configurations from previous generations/ similar SuIs or for the same SuI with changed validation objectives or boundary conditions should be used in accordance with the Model of the SGE – System Generation Engineering [4]. All these elements must be available in a structured, modeled, and machine-readable form or be structured and modeled appropriately (this step is currently still being researched in detail). For the SuI all relevant and available information of all generations considered (including future ones) are taken into account.

References and knowledge that are available and made usable through modeling are used in all steps of the procedure which is marked in Figure 1 with the orange R. All modeled elements are retained for the purposes of “Recapitulate/ Learn” and are available for the future synthesis of new validation configurations.
This input is then used to break down the currently available functions and subfunctions (mainly from the SuI and possibly existing validation configurations) in the left path of the procedure and to define the resulting specific requirements in the right path. This is followed by a comparison to determine whether the currently available functions meet all the necessary requirements.
If this is not the case, further functions must be added in accordance with the fulfillment of the necessary requirements. Once the requirements have been satisfactorily fulfilled by the functions (iterations are also possible at a later stage), an assignment is made to determine which functions are dependent on which requirements/properties, thereby ensuring a more efficient procedure in the following. The steps taken so far can be classified in SPALTEN into the first two steps, “Situation Analysis” and “Problem Containment”.
In the next step, the “Alternative Solutions” are implemented in accordance with SPALTEN by developing open-ended design options that make sense for each of the functions and adopting them from references.
In the course of “Selecting of Solutions”, a weighted evaluation of the design options for each function is then done individually with regard to the fulfillment of the requirements and the characteristics specific to the function, which leads to a preferred design option for each function.
The next step is the “Consequence Analysis”, which involves checking for problematic interactions between the selected design options. In addition to modeled references and knowledge, the previously made assignments of dependencies between functions and properties are also used here to uncover possible common properties and interactions. Also, the chosen design possibilities have to be dimensioned.
After successfully completing this step and if necessary further iterations, the final step of the method follows, which corresponds to “Make Decision” and results in the considered elements of the SuI being embedded in the best possible, credible, and consistent validation configuration as system of objects.
The use and creation of references takes up the already mentioned model of System Generation Engineering (SGE) and facilitates the development of future validation configurations.
The IPEK-X-in-the-Loop approach mentioned above is also being considered and is used when deciding on the physical, virtual or mixed physical-virtual design, while the coupling of the physical and virtual elements is done through the Koppelsystems described above[19].
According to the extended system triple of product engineering (ZHO), constant iteration between the system of objectives and the system of objects happens through the operation system and is very important [20].

B. Development of a validation configuration with a CPS brake system based on approaches from classic design methodology (VDI 2221) – not model-based

In the context of SFB 1608 "Convide" [21], a validation configuration was developed for testing an electromechanical brake system in a current Volkswagen ID.3 as SuI. The associated validation configuration was implemented in accordance with the defined system of objectives with requirements, use cases, personas, boundary conditions, product information, and validation objectives of the SuI using the approaches of classic design methodology (VDI 2221).
The transformation of this system of objectives into the system of objects in the operation system was not model-based, but was based on physical laws, design methodology, and numerous discussions with experienced experts in the fields of production and assembly.

The development also included the requirement that the validation configuration should be as reusable and adaptable as possible for testing other brake systems: both brake systems from other vehicles with electromechanical brake systems and brake systems from other vehicles that, in addition to electromechanical braking, also include regenerative braking with an electric machine (in the second case, significantly major changes to the validation configuration are to be expected).

The following requirements to be fulfilled by the validation configuration have been derived (as examples, without claiming to be a complete list):

- From the operating states/ behavior of the SuI brake system:
  - Be able to perform repeated braking cycles with variable braking force at continuous wheel torque/wheel speeds without the wheel/brake disc coming to a complete standstill.
  - Be able to perform an emergency stop from 50 km/h to 0 km/h using all available braking force
  - Be able to perform braking operations during forward and reverse movement of the brake disc with reversal of the direction of rotation of the brake disc
- From planned test cases derived from the operating states of the SuI during operation:
  - It must be possible to specifically change the coefficient of friction in the friction contact through: (a) replacement of the friction pad, (b) defined application of liquids (e.g., oil, water) without costly modification of the test system.
  - The test bench must allow intervention on the ABS control unit, e.g. through connection of alternative control units or superimposition of sensor signals to test manipulated intervention strategies.
- From the requirement for variability for future brake systems as SuI:
  - The mechanical design of the test bench must be such that the brake system under test can be easily replaced using standard tools.
- For economic, safety, manufacturing, and assembly reasons:
  - All test bench components must be manufacturable using conventional manufacturing methods (turning, milling, laser cutting, welding).
  - All test bench components under load must be designed for the maximum expected stress without failure or critical crack formation.
  - The test bench must be free of critical natural frequencies throughout the entire operating range. Vibrations induced by brake applications or an electric machine must not cause resonance effects.
  - Sensors (e.g., force, temperature, speed) must be placed at a short distance from the SuI and protected against brake dust, heat, and liquids.

Following the classic application of the design methodology (VDI 2221) and discussions with many experienced experts regarding the bearing concept, arrangement of the elements, and selection of the necessary component connections, the test bench was constructed as shown in the simplified schematic diagram in Figure 2:

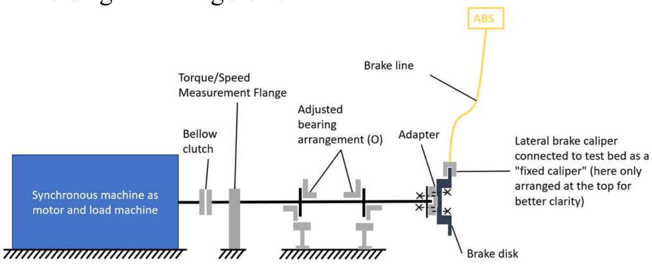

Figure 2: Principle sketch of the validation configuration

With further iterations, the following model of the validation architecture was then established in Figure 3 according to the IPEK-XiL approach, in which the physical and virtual components of the SuI and the connected systems are identifiable:

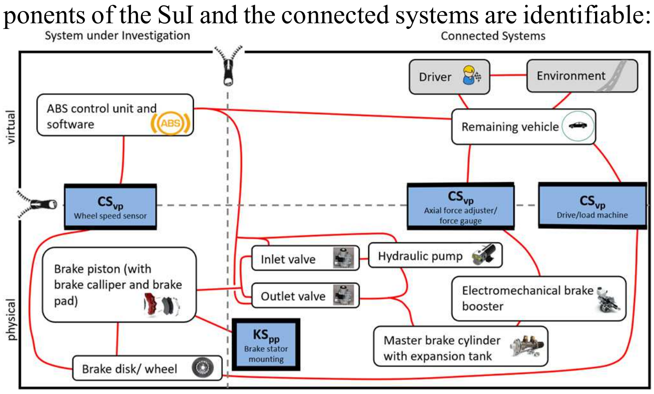

Figure 3: Model of the architecture of the validation configuration "Brake-System-in-the-Loop"

The physical systems of the validation configuration developed in the model creation and implementation process:

- Electric machine,
- Measurement technology,
- Bearings,
- Shafts,
- Screws
- Connections between the respective elements, such as the Brake caliper connection, the bellows coupling and an adapter as the connection between the brake disc and the mounted main shaft

have been dimensioned for sufficient load-bearing capacity in accordance with the physical influences M(t), n(t), f(t), F(t), T(t), etc. to which they are expected to be subjected, and designed in compliance with the other requirements already mentioned herein.

The shaft-hub connection considered in the following section C was selected, as all other elements, in accordance with the already mentioned VDI 2221. Starting from the requirements, basic solution concepts were developed and, after several iterations in consultation with experienced experts about the advantages and disadvantages of each solution concept, the preferred solution concept was finally determined. This was followed by dimensioning and detailed design so that it could be integrated into the entire remaining validation configuration.

C. Example application of a part of the new model-based approach for instantiating consistent and credible validation configurations for the Brake-System-in-the-Loop

In the following, a part of the new model-based procedure from A will be demonstrated using the selection and design of a shaft-hub connection between the mounted main shaft and an adapter (see red marking in Figure 4) to which the brake disc is attached, with various changes. The connection between the brake disc and the adapter is already specified by the brake disc and is not considered.

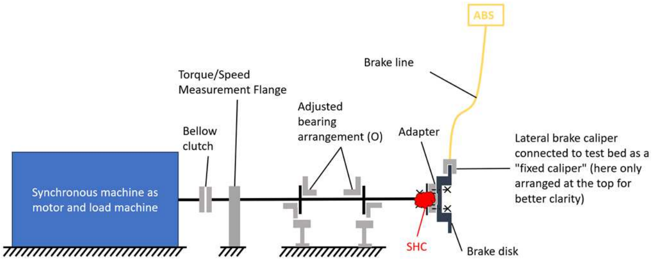

Figure 4: Principle sketch of the validation configuration with red marked shaft hub connection (SHC)

In the first steps, the functions currently fulfilled were iteratively expanded in accordance with the requirements using the relevant information from the SuI brake system, the validation objectives of the SuI, and the boundary conditions for the validation configuration, in accordance with the procedure described above. Subsequently, the best possible design option must be selected for each of the functions and their connections that are not already specified by the SuI or boundary conditions.

Here, the function "Connecting a shaft and hub to transmit power by form or friction" is discussed as an example. There are various design options for fulfilling this function, but for the sake of clarity, only the four design options "key with shaft nut," "tapered press fit (in-house design)," "ring clamping element with tapered press fit (purchased part)" and "screw connection with centered flange," which are shown in this order in the following Figure 5, will be discussed in the following.

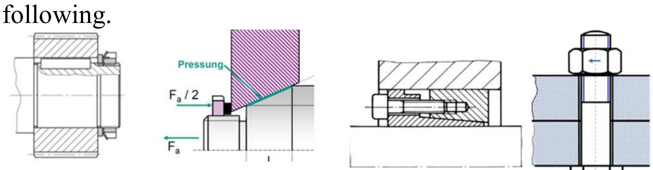

Figure 5: Exemplary design possibilities of a shaft hub connection

Once the properties required for this function have been assigned, these four design options can be weighted and evaluated in relation to them. Depending on changes to the SuI, the validation objectives or the boundary conditions, a different design option for the shaft-hub connection may emerge. In Figure 6 below, for example, the boundary condition for the validation configuration "Quick and easy interchangeability possible repeatedly" was included in the overall evaluation in the second-to-last row, while it was excluded in the last row, resulting in a different suitable design for the shaft-hub connection:

	Weighting	Feather key with shaft nut	Cone press fit (own design)	Ring clamping element with cone press fit	Screw connection with centered flange
Alternating load transmission possible in both directions	X2	-	+	+	+
Disassembly easily and repeatedly possible	X3	+	-	0	+
Freedom of movement	X2	-	+	+	+
Sufficient torque transmission possible	X3	0	+	+	+
Limited installation space	x2	0	+	-	0
Robustness against thermal influences	x1	-	+	+	0
Sum of weighted valuation for $V_{n-1,c}$ (Electromechanical braking with even full braking on chessboard with RB interchangeability)		-2	7	6	10
Sum of weighted valuation for $V_{n-1,b}$ (Electromechanical braking with even full braking on chessboard without RB interchangeability)	(here lower weighting x1 for disassembly)	-4	9	6	8

Figure 6: Weighted assessment of the shaft hub connection with different design possibilities as result of changes in the constraints

An example overview of how the shaft-hub connection of the validation configuration changes with different validation objectives or boundary conditions while keeping the SuI constant with the brake system generation G_{n-1} is shown in Figure 7:

Changes to the next configuration

Validation configuration and situation	$V_{n-1,a}$: Start configuration	$V_{n-1,b}$: Other validation goal	$V_{n-1,c}$: Other constraint
Braking system generation G_X as SuI	System under Investigation (SuI): Bremssystemgeneration G_{n-1} Electro-mechanical braking	System under Investigation (SuI): Bremssystemgeneration G_{n-1} Electro-mechanical braking	System under Investigation (SuI): Bremssystemgeneration G_{n-1} Electro-mechanical braking
Validation goal	Observation of uniform full braking with small μ	μ-split test (checkerboard test) with uniform full braking → induces load change	μ-split test (checkerboard test) with uniform full braking → induces load change
Constraint	/	/	Quick and easy interchangeability of the braking system
Exemplary resulting shaft-hub connection in the validation configuration	Feather key with shaft nut	Cone press fit (own design)	Screw connection with centered flange

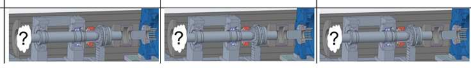

Figure 7: Validation configurations with different shaft hub connections for same SuI

Considering further brake system generations with additional ABS (G_n) or even recuperative braking (G_{n+1}) leads to different shaft-hub connections in the validation configurations, as there would be with the same validation objectives and boundary conditions, as can be seen in the overview in Figure 8:

Changes to the next configuration

Validation configuration and situation	$V_{n-1,d}$: Start configuration	V_n: Other SuI (new generation)	V_{n+1}: Other SuI (new generation)
Braking system generation G_X as SuI	System under Investigation (SuI): Bremssystemgeneration G_{n-1} Electro-mechanical braking	SuI: Bremssystemgeneration G_n Electro-mechanical braking with ABS and ESP	SuI: Bremssystemgeneration G_{n+1} Electric braking & electro-mechanical braking with ABS and ESP *Hybrid drivetrain*
Validation goal	Observation of uniform full braking with small μ	Observation of uniform full braking with small μ	Observation of uniform full braking with small μ
Constraint	Quick and easy interchangeability of the braking system	Quick and easy interchangeability of the braking system	Quick and easy interchangeability of the braking system
Exemplary resulting shaft-hub connection in the validation configuration	Feather key with shaft nut	Screw connection with centered flange	Screw connection with centered flange

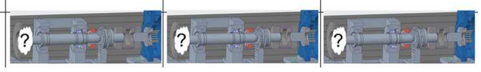

Figure 8: Validation configurations with different shaft hub connections for different SuI (other generations)

In the first version of the validation configuration, the screw connection with a centered flange was chosen as the design option for the shaft-hub connection under consideration. This promises to best fulfill the requirements, especially for the brake systems already planned for the future and also for the currently planned validation objectives and given boundary conditions. A CAD sectional view of the entire validation configuration is shown in Figure 9. Figure 10 shows a real photo of the validation configuration.

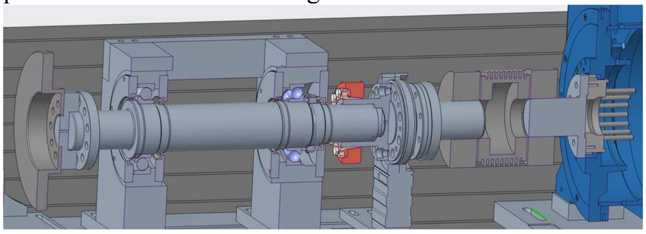

Figure 9: CAD sectional view of the entire validation configuration

Figure 10: Photo of the realized validation configuration (without the brake caliper)

D. *Modeling of the initial validation configuration and initial implementation of the model-based approach for instantiating consistent and credible validation environments*

The modeling of the first realized validation configuration of the “Brake-System-in-the-Loop” is currently being implemented in Cameo Systems Modeler (previously known as MagicDraw), which is part of the CATIA Magic Suite by Dassault Systèmes. In addition to the complete modeling of the elements with their relevant properties (Figure 11), the rule-based linking of the elements with each other and the satisfy links with the necessary requirements are being carried out.

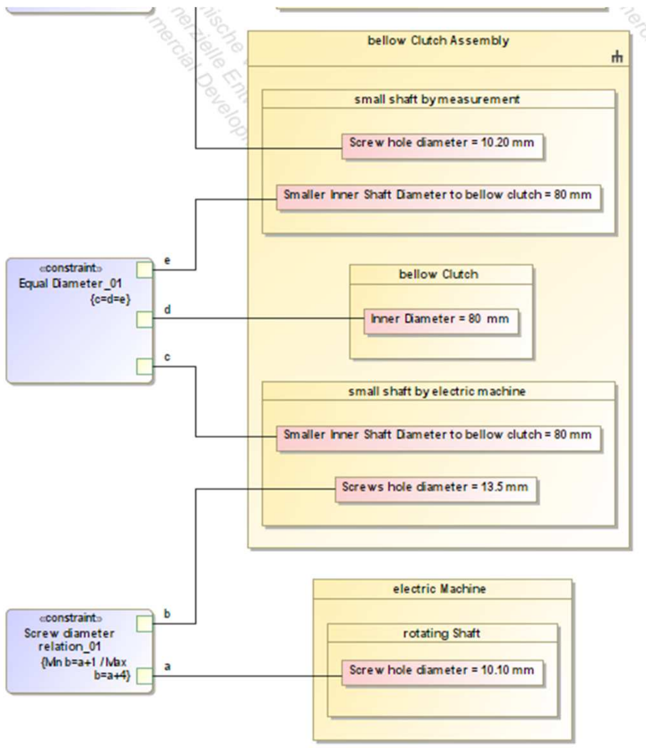

Figure 11: Excerpt from the modeling of the BSiL

The first steps currently enable the detection of inconsistencies, for example, when shaft and hollow shaft diameters do not match, hole patterns do not match, the shape of the shaft-hub connection between components is not suitable, etc. (Figure 11Figure 12)

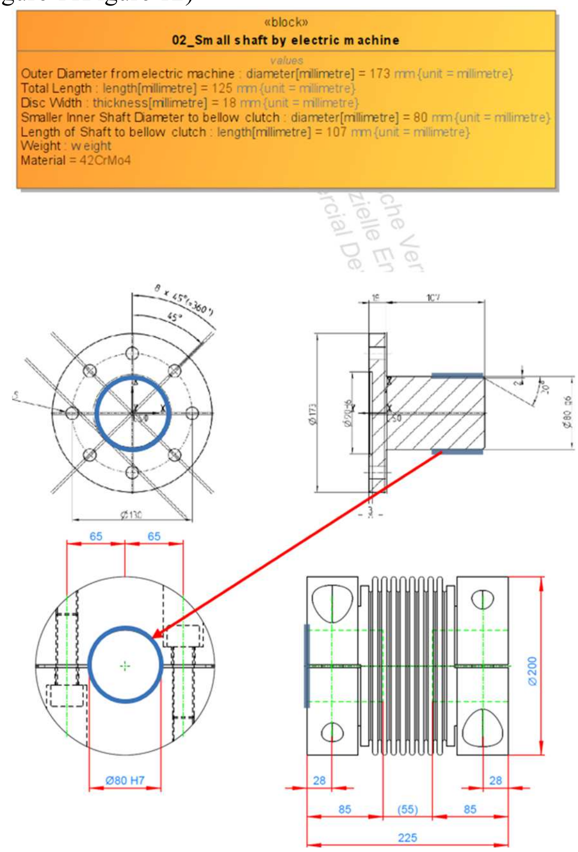

Figure 12: Rule-based connection between physical systems of the validation configuration: At the top a small shaft with an inner diameter that has to fit in the outer diameter of a hollow shaft of the lower bellows coupling)

The fulfillment of a few exemplary requirements through the design possibilities of the shaft hub connections described in the previous chapter C is shown in Figure 13: For the specific requirements derived here from the SuI, the validation objectives, and the constraints, the shaft hub connection actually selected in the current validation configuration, a screw connection with centered flange (marked in green), is the most suitable solution due to its ability to satisfy most of the relevant requirements. In the case of future changes and resulting changes to the requirements derived, it will thus always be possible to select the most suitable shaft hub connection and also other elements in an efficient and traceable manner.

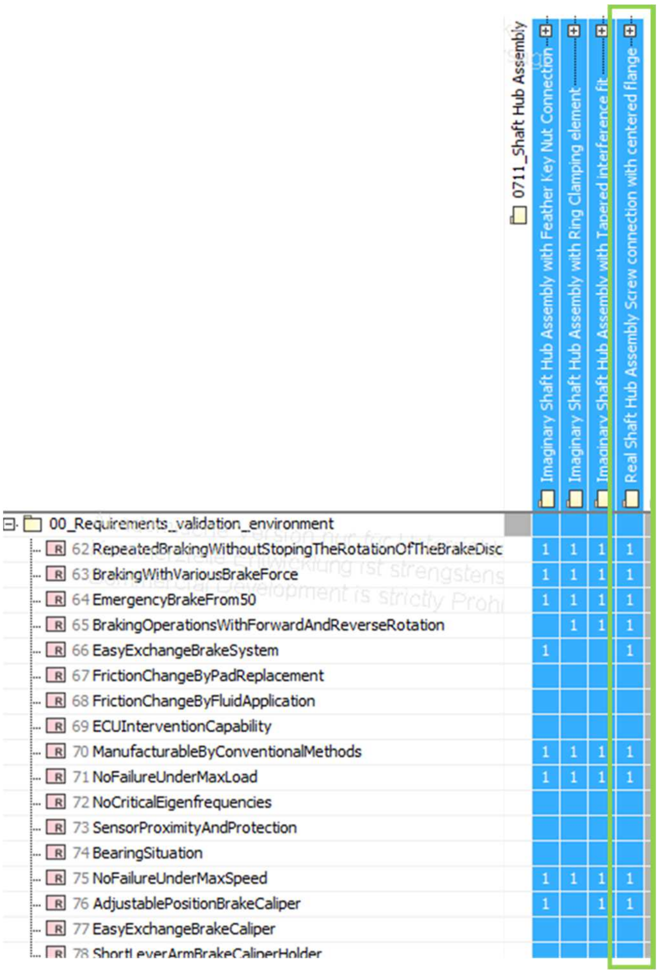

Figure 13: Excerpt of requirements satisfied by the different design possibilities of the shaft hub connection

The ultimate aim is to use the method derived from the procedure to detect and resolve existing/ emerging inconsistencies in the validation configuration when changes are made. Modeling the views created during the intermediate steps of the procedure in Cameo Systems Modeler is planned. In addition to providing a good visual overview and traceability of decisions, this will also enable targeted changes to be made at each intermediate step.

IV. Discussion

The model-based approach enables a more effective and targeted design and adaptation of validation environments. Although it initially requires more effort than conventional synthesis, the effort decreases as more references and knowledge are modeled for reuse, while inconsistencies are reduced. This is illustrated by the design options for the shaft-hub connection: the consensus reached in multiple separate expert discussions matches the results obtained using the current model-based knowledge.

Building on this retrospective validation, further concrete application examples are planned in the near future. These include different braking systems as SuI, the choice of a suitable bearing concept, the positioning and selection of measurement technology, the placement of the brake caliper, and residual vehicle simulation. These cases will help to further develop the method and demonstrate its practical applicability.

Beyond the ongoing retrospective validation of physically realized configurations, future validation setups for more advanced braking systems – such as those with additional recuperative brakes – will also be considered and physically implemented. These designs will be evaluated both prospectively, using the model-based approach before physical realization, and retrospectively, after final design completion. The approach is also targeted for external applications to industrial cyber-physical systems (CPS).

Despite its advantages, the model-based approach has limitations. Modeled references and knowledge must be correctly created by experts and stored appropriately to ensure reliable results. Additionally, common obstacles to implementing MBSE in industry – such as cultural resistance, lack of qualified personnel, and tool-related issues [22] – must be addressed.

V. Summary and Outlook

By a model-based approach, consistent validation environments can be systematically instantiated across system generations. Implicit knowledge and experience should be made usable. This allows domain-specific knowledge to be used and inconsistencies to be avoided, which is particularly important for the validation of CPS.

In the development and validation of CPS a growing need for systematic, model-based support for the synthesis of consistent validation environments across multiple system generations is becoming apparent. An initial literature review revealed significant gaps in existing methods and processes. The selection of suitable validation configurations is usually done based on experience, in addition to basic consideration of the design methodology, which means that consistent validation configurations for multiple generations and the reusability of knowledge are often not available.

Based on approaches such as MBSE (Model-Based Systems Engineering) and classic process models such as VDI 2221, an initial real-world validation configuration for a Volkswagen ID.3's electromechanical brake system was designed and physically implemented in the context of SFB 1608 "Convide" (Brake-System-in-the-Loop).Thereby, taking into account future changes to SuIs, validation objectives, and boundary conditions.

While the original development was not yet model-based, a first model-based approach for instantiating consistent and credible validation configurations was developed based on this.

This approach was applied as an example to the selection of a suitable shaft-hub connection in the first physically realized validation configuration. Different SuI generations, validation objectives, and boundary conditions lead to different

suitable design options in a model-based and traceable manner. The initial implementation of the procedure and modeling of the first physically realized validation configuration has already been done in Cameo Systems Modeler.
The results show that a model-based approach contributes to more effective, transparent, and consistent synthesis. In the long term, the initial additional effort can be significantly reduced through the reuse of modeled knowledge. Limitations currently exist primarily in the expertise required for initial modeling and in the barriers to entry into MBSE.

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VI. REFERENCES

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