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Enhancing Consistency in Development Projects by Employing a Digital Model Master

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1 Introduction

Advanced engineering and predevelopment projects are characterized by a high level of novelty considering the so called system in development. Simultaneously, they are impacted by frequent changes of stakeholder needs due to uncertainties regarding the objectives, such as the application of the product. To meet these uncertainties with a high level of flexibility, agile and interdisciplinary engineering teams are utilizing model based development and validation approaches. [1 3]

A key objective for advanced engineering projects is to build up a knowledge base, which can be used as references for following development activities [4]. Especially in early development phases, the understanding of technical interdependencies and operating principles is stored and transferred via models. Multiple system and component representations with partly matching and partly varying aspects and purposes exist at the same time [5, 6].

In the sense of holistic and continuous validation, both subsystems and the entire system in development (SiD) are tested in interaction with the respective super system [3]. All these so called X in the Loop configurations, which are often set up in parallel and represent different integration levels of the SiD, are fed with models and parameter data.

Thus, the characterization and validation of the deployed models is of high significance. Not only to validate the system in development, but also to evaluate the models' fidelity as well as the characteristics of the utilized validation environments, a high level of consistency and traceability at all integration levels is pursued.

In this contribution, an approach for consistent and traceable data exchange is to be presented which was simultaneously developed and evaluated in a research cooperation between the IPEK Institute of Product Engineering at Karlsruhe Institute of Technology (KIT) and the MAHLE International GmbH. The implemented Digital Model Master (DMM) contains the product geometry as well as behavioral models of the SiD. Thus, serving as a unique platform for the data exchange concerning all available representations and physical prototypes of the SiD.

This contribution provides insight to the exemplary implementation of the DMM at advanced engineering projects at MAHLE. In combination with an existing superordinate and consistent test automation methodology as well as a flexible postprocessing toolchain, inconsistencies of model data can be identified. With the support of the DMM, these inconsistencies can be avoided in advance.

2 Background and Related Work

2.1 Model Theory

A model is a representation of a system, phenomena, or process. In general, a model is a simplified abstract of a more complex reality [7].

According to Stachowiak [8] models are characterized by at least three main features:

1. depiction feature: models are representations of natural or artificial originals.
2. reduction feature: models rarely cover all attributes of their originals.
3. pragmatic feature: models perform specific replacement functions under defined constraints.

The purpose of models can either be characterized as descriptive or as predictive. Descriptive models, such as process, organizational or system models, are mostly used to visualize or illustrate the interdependencies of the complex reality. In the context of the development of mechatronic products, descriptive system models are drawn up in a standardized System Modeling Language (SysML) to provide a common and discipline independent understanding. [9]

Predictive models, like mathematical or physical models, are used to explain and simulate the behavior of the models' originals. Regarding their specific purpose, these models can vary from component simulations (e.g. CFD) to system integration tests (e.g. Matlab Simulink).

2.2 Validation in Product Engineering

In a volatile development environment, which for example automotive suppliers face, decisions concerning for example the products design can be based solely on the results of these simulations. Consequently, validation the continuous and systematic investigations of differences between the developed models and the anticipated product is essential for successful product development [3]. The activity of validation ensures that the considered models meet the respective objectives. As a result of the initial validation activities sub objectives can be derived for further development and validation activities. Accordingly, Albers [10] describes validation as a central activity in product engineering.

2.3 Approach for Effective Validation

In interdisciplinary projects, physical prototypes of the complete system in development are only available in later development phases. To ensure early and continuous validation, approaches like Model in the Loop, Software in the Loop and Hardware in the Loop have been developed [11]. Thus, enabling early validation of subsystems integrated in virtual supersystems.

The IPEK X in the Loop (IPEK XiL) approach emphasizes the importance of continuous validation from subsystems to overall systems. Hence, the investigated subsystem must be integrated into the overall system, the environment, and other interacting systems to consider application specific interdependencies. "X" is the representative for the system which is of interest for the specific validation activity. Therefore, the IPEK XiL approach integrates all integration levels (virtual, mixed virtual physical & physical) as well as detail layers (from working surface pair to overall system). [3]

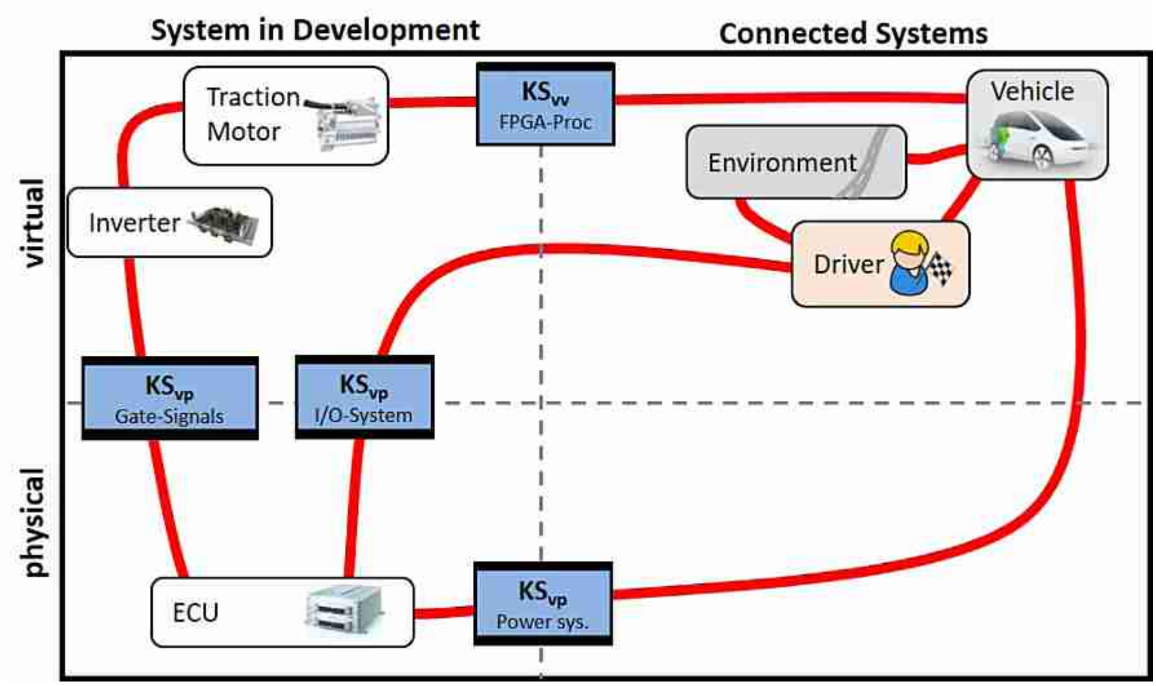


Figure 1: IPEK-XiL Validation Configuration for Electric Traction Drive System

In Figure 1 the model of the architecture of a typical validation configuration of electric traction drive systems (eTDS) during early stages of the development process is displayed. In the presented configuration, the SiD is divided into three subsystems: Electronic Control Unit (ECU), Inverter and Traction Motor. To overcome incompatibilities between virtual and physical models, so called Koppelsystems (KS) are needed. KS are designed to interconnect models but are not meant to add relevant system behavior [12]. To consider the interdependencies of the eTDS in the target application, the vehicle, environment, and driver are modelled and integrated in the setup (Connected System). Based on the validation environment, the respective validation objective determines the configuration and implementation of the used systems and models at the test bench.

2.4 Consistency and Traceability in Model-Based Validation

The shown configuration as well as the utilized models are subject to a specific purpose (cf. Stachowiak [8]), which is expressed in the validation objective. The task of finding suiting validation configurations is manly based on the engineers' empirical knowledge. Alike the product itself, validation configurations are developed in generations [13]. Mandel et al. [14] present an approach to increase the reusability of components of mostly physical test setups. The method described facilitates access to existing knowledge, for example regarding the test equipment and thus, leading to more efficient development of validation configurations.

The development of validation configuration starts with the choice of the investigated system. Before the physical implementation, models are implemented and used for validation. In early development phases, the configurations are predominantly affected by the availability and maturity of the models. In order to enable validation, a description in terms of maturity and uncertainties of the models is necessary. A prerequisite for the separate characterization of sub systems and models of a XiL configuration is a systematic comparison of the result from different configurations.

According to Boog et al. [15], a centralized approach for consolidation of test run definitions and test analysis enables traceability of test run regardless of the validation configuration. Making use of standardized analysis procedures, the consistency of models in different configurations can be continuously analyzed. In addition, the mirroring of results from different configurations is important for quick development iterations. The continuity between high physical integration levels and lower physical integration levels allows reproduction of occurring phenomena and thus, leading to improved maturity levels. For a seamless comparison of results, integration level consistency and traceability are mandatory.

3 Objectives of the Digital Model Master

In the aim of the development of mechatronic products, numerous models for varying application purposes are conceptualized and used for validation. In agile and interdisciplinary project teams, the maturity levels of the deployed models might differ. As the development and validation of all (sub)systems takes place in context with the interacting systems, frequent exchange of modelling and parameter data between the disciplines can be observed. For the setup of a validation configuration, engineers face the challenge of surveying available models and parameter data. Especially before the physical implementation of a prototype, the task of finding suitable configurations in accordance with

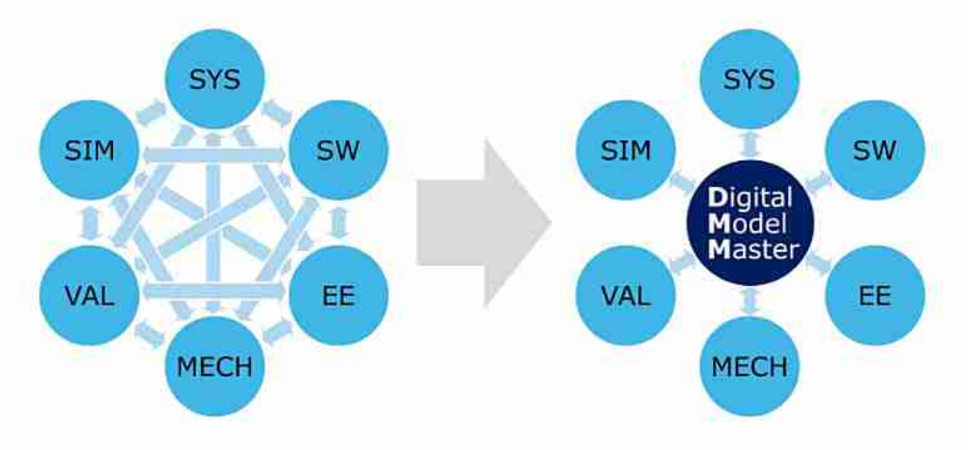


Figure 2: Idea of the Digital Model Master

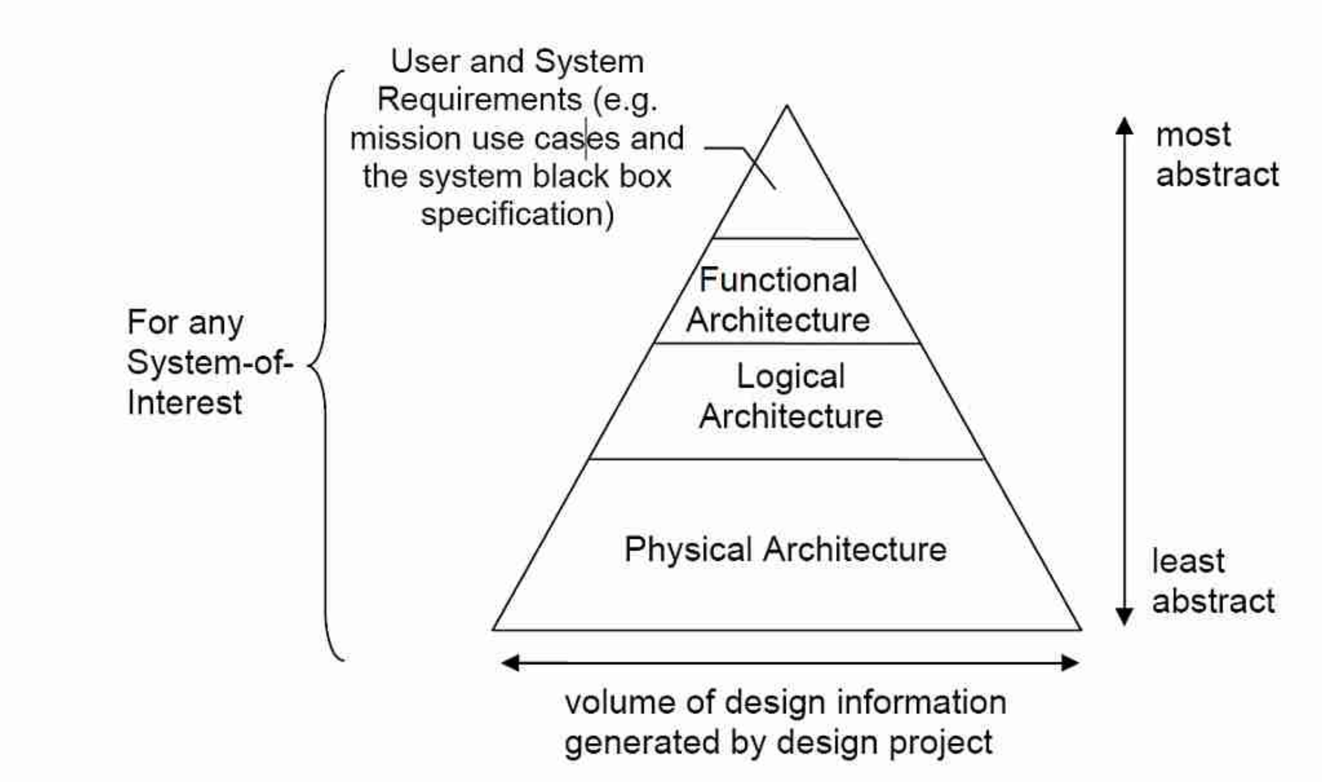


Figure 3: Levels of System Architecture and Abstraction [16]

the validation objective is accompanied by the challenge of maintaining the overview of current model data.

To address this challenge, the idea of the Digital Model Master (DMM) is presented (see Figure 2). Instead of pragmatical and decentral exchange of SiD and Connected System information, the DMM serves as a unique platform for modelling and parameter data exchange. Thus, containing data concerning product geometry as well as all behavioral model data. From the start of the development projects the DMM supplies the engineers with all information for the buildup of (digital) prototypes. The platform is accessible for all project members and simply structured analogue to the physical product. New instances and adaptions of the consisting data are traceable throughout the complete development process due to automated distinctive versioning.

4 The Digital Model Master Concept

4.1 Structure – System Model

As mentioned in a previous chapter a model based approach is used developing new systems in the advanced engineering department. This model based development approach starts with the elicitation of a system architecture based on the stakeholders' objectives and requirements. The

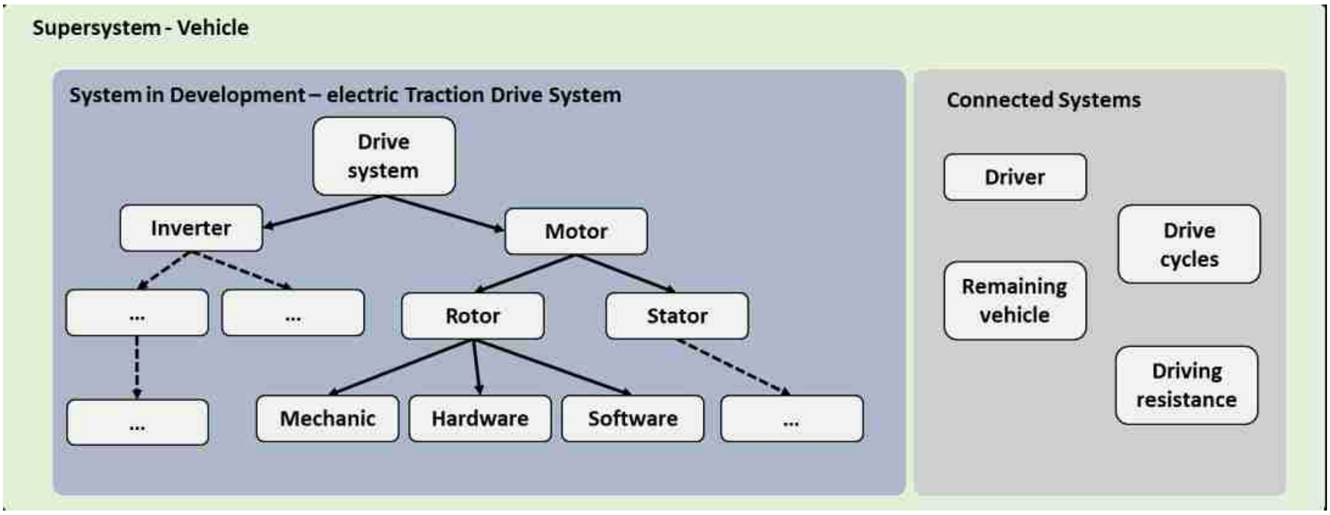


Figure 4: Extract of the Physical Architecture of a MAHLE eTDS

resulting system architecture contains every relevant component and the interfaces (internal and external) of these components.

While creating the process for the DMM, it was important to create structure that provides the user with an intuitive and logical way to organize the data stored in the DMM. Therefore, the system architecture is used based on the reason that the system architecture is the common understanding of the project team on how the system is build up, it is well maintained and graphically visible.

According to Pearce and Hause [16] the architectural levels are defined as following (see also Figure 3):

“The least representation of a system is the physical architecture detailed in real world components. Logical and functional architectures are respectively more abstract representations of physical architecture. Functional architecture is comprised of solution independent descriptions; whilst logical architecture describes solutions in terms of logical components that represent technology and implementation independent abstractions of physical components. Physical architecture then defines a specific design implementation corresponding to a particular logical architecture.”

A key objective of advanced development projects is the buildup of working prototypes. Accordingly, the physical architecture is used to define the structure of the DMM. Consequently, the accessibility of the data and parameters is identical from the setup of first simulations up to the parametrization of the working prototype.

In Figure 4 an extract of the physical architecture for an eTDS at MAHLE is presented.

In the context of the case study at MAHLE, this structure is best suited to link the architecture level to the simulations and models stored in the DMM, as the simulations are alike the physical architecture based on real life components. Simulations can be done for single components (e.g., stator, rotor) or on a system level (e.g., e machine). The physical architecture with the possibility to include different levels of technical details (e.g., level 1: e machine, level 2: rotor, stator) makes it intuitively possible to make the connection between models and architecture. Thereby a traceable connection between the descriptive system model and the predictive models of the subsystems is created. Furthermore, different representations of the same subsystems can be included in the structure and evaluated independently (e.g., different types of stators for one project).

Additionally, the usage of single components opens the possibility for the reuse of single components in different projects. As for example, several projects are focusing on the development of different kind of rotors in e machines, the component stator can be reused in all these projects. Similarly, for branching an existing project for a new project with a new development objective, the components that are not changed in the new project can be reused. Since the architectural items of these components are linked to requirements and therefore testcases, the user can also identify which requirements are considered and which testcases can be reused for the testing of the component.

After components are defined, each component has the possibility for storing data for each discipline (e.g.: hardware, software, simulation, design, validation).

4.2 Method, Rules & Guidelines

In the course of the case study at MAHLE, a server based versioning tool is used for the DMM to ensure traceability of the shared data. Every project has its own implemented DMM server structure, which is also separated per product sample. This depends on different physical architectures of different products and their sample architecture. Every participating project team member has the possibility to synchronize the whole Digital Model Master folder of the project or component and discipline specific subfolders from individual paths. The unique versioning numbers for the server located data keeps a lean data structure and the sustainability of model and data processing activities: On the one hand, version counter states can be documented for reproducibility. On the other hand, every user can check the provided and shared data by the unique version numbers to ensure consistency. Thus, the same models and parameter sets can be used simultaneously by multiple users.

For updating the provided Model Master data solely for crucial content updates, the synchronization process of server and local data is not running automatically in the background but must be started manually. If there are committed new or modified files to the server, a comment for the new version is mandatory. The manual synchronization leads to the recommendation to update the local data before starting work to avoid synchronization errors caused by changes from other participants. In the change log (user, date, time, comment) the history documentation can be displayed, and previous versions of the data files are also available on the server.

In general, data must be shared via the Digital Model Master, which is used by multiple participants, disciplines or other possibly external teams in the engineering project.

For a traceable use of unique basis of data in every XiL configuration the Model Master shall be used for documentation of data revision.

4.3 To share or not to share

The folder structure is derived from the physical architecture and every component gets is own data container. For inter component data on system level and model data of the external systems, additional data containers for the entire system and external systems like remaining vehicle or driver models according to Figure 5.

Every component data container entails a structure of possibly participating disciplines and each subfolder is reserved for the naming discipline to share their data with the remaining team:

- SYS System (exists only in the data container for the entire system)
- SW Product Software
- EE Hardware
- MECH Mechanical Design
- SIM (office desk) simulation
- VAL Testing & product validation

The system (SYS) content covers hardware software interface, geometrical data on system level, lists of components, functional safety concept and sample planning information. Descriptions of system architecture are linked to the requirements management tool where they are initially shared. In the software (SW) folder, the software developers provide product software releases and controller flash data also for rapid prototyping and software interface descriptions for debugging & diagnostics. Electrical circuit diagrams/models and expected powered losses are to share in the hardware (EE) folder, as well as layout files or table of components (e.g., for ordering or cost calculation). The team members for technical design allocate their 3D engineering data, technical drawings and mechanical parameter sets in the design (MECH) space. Provided data from simulation (SIM) consist of electrical simulation models, lookup tables for system (real time) simulation, operation point and operation strategy limit elicitation for testing plus shape and topology optimized sectional drawings and material specifications. The testing & validation team (VAL) shares models and parameter sets for the external systems, templates for test bench

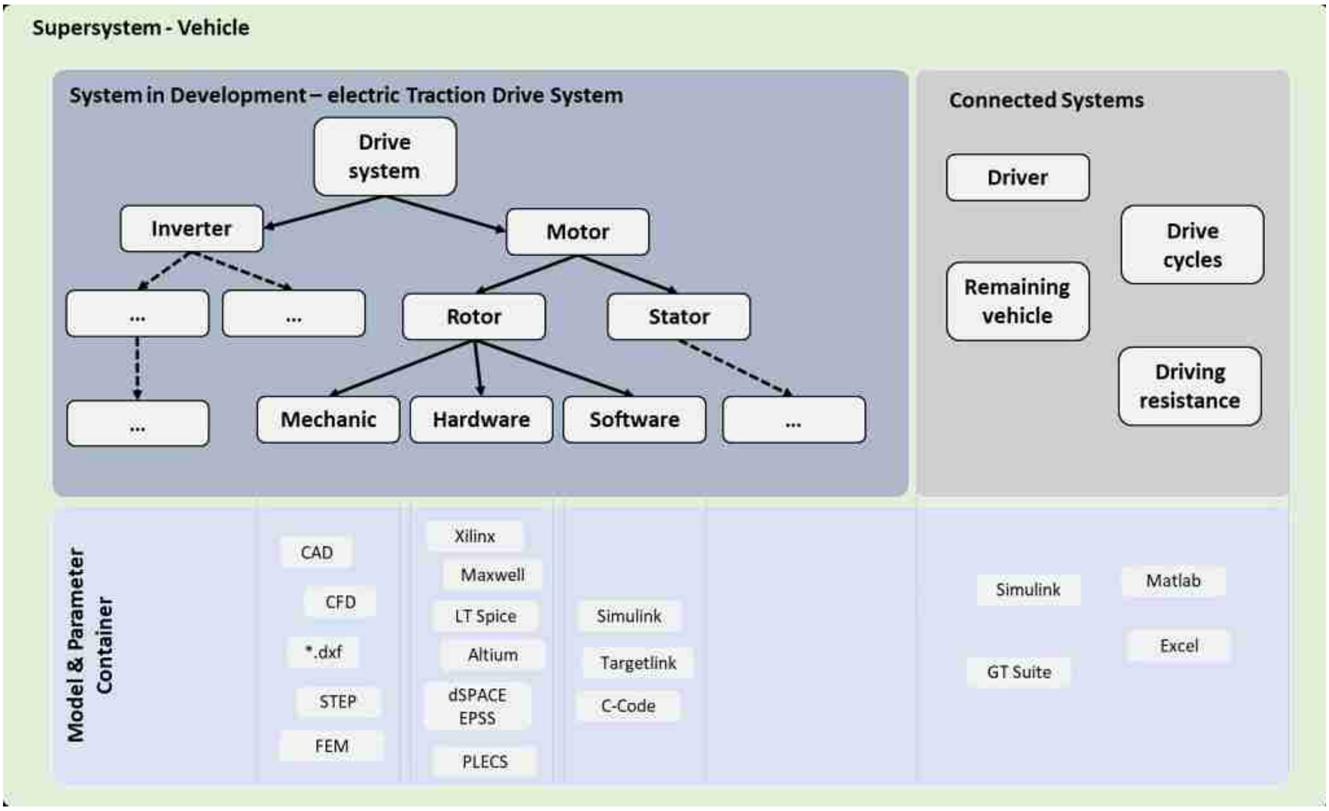


Figure 5: Suiting Model Container for the Extract of the Physical Architecture of a MAHLE eTDS

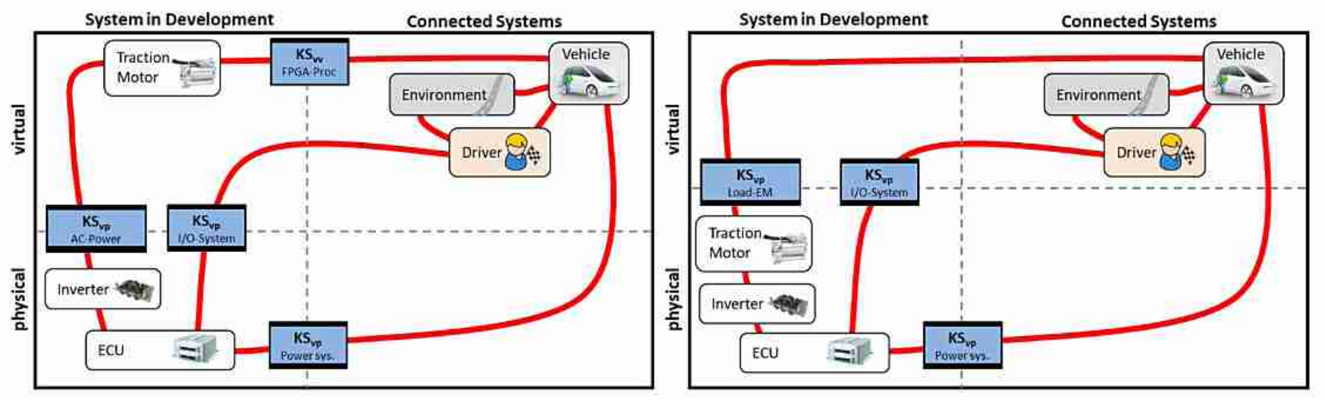


Figure 6: Validation Configurations, Left: Inverter-Power-Level Setup,
Right: System Setup at Electric Motor Test-bench (EMT)

data import and test bench limits, test run sequences or calibration data.

Full simulation and test run results must not be shared via the model master depending on wide ranging data consumption. Therefore, a raw data drive is available.

5 Consistency Investigations – Impact of Different Model Representations

In combination with a superordinate test automation from office simulation all the way to system test benches, the DMM provides guidance for using the same models and parameter data. Thus, the approach of a modular validation environment, where test run, models and parameter data are seamlessly exchanged is supported. Only by guaranteeing traceability and consistency throughout all integration levels, the basis for flexible model based validation is set. To support the engineers at the choice for suiting validation configurations in accordance with the respective objectives, detailed comparisons of the available models and test bench equipment are necessary. As a first step, investigations regarding consistent or deviating model behavior were conducted.

The following comparisons of model based testing results are based on the corporate test run and postprocessing approach presented in Boog et al. [15]. For the development of the ECU of traction drive systems the early integration of the SiD into possible target application systems is aspired to. In a closed loop test setup (cf. Figure 1), the input data depend on the behavior of the system in development while being tested. Hence, interdependencies between the SiD and the Connected Systems are taken into account in real time.

The following examples are based on tests conducted in the two different validation configurations displayed in Figure 6

Analogue to the configuration introduced in chapter 2.3 Approach for Effective Validation, the SiD contains the subsystems: ECU, Inverter and Traction Motor. Compared to the configuration shown in Figure 1, further steps towards a fully integrated system are made. At first, the power electronics are shifted from virtual to physical integration while the complementary parts are kept constant (see left part of Figure 6). As a result of the shift in the form of the SiD, the implemented Koppelsystems have to be adjusted as well. At second, the whole SiD is tested on a physical integration level (see right part of Figure 6).

To clarify the effects of even small model deviations on the system behavior, two exemplary deviations in parameterization and modelling are presented. Differences in model behavior of the "Connected Systems" between the configurations displayed in Figure 6 are investigated. The first example shows effects from differences in vehicle mass parametrization. This separated effect is shown at the example of the initial 100 seconds of the drive cycle out of the WLTP.

The diagrams in Figure 7 show the model signals on the Inverter Power Level Setup of motor torque (top), motor torque deviations between the different vehicle masses (1200 kg vs. 1085 kg; middle), and the occurring vehicle speed and acceleration (bottom). The linear correlation between the acceleration and the deviations in motor torque are an obvious result of deviating masses used. When analyzing results of the two validation configurations, parameter deviations never occur isolated and are therefore difficult to assign. Therefore, different model parameterizations should be avoided in advance using the DMM.

The second example illustrates the impact of different modelling approaches to the closed loop operation in model based validation. Depending on different validation configurations across the step by step integration, at the system setup (see Figure 6, right) a remaining vehicle model with the motor torque (T) input and motor speed (n) output (n/T model) is used. In contrast, at previous integration level at the Inverter Power Level setup, the model uses speed input and returns the load torque (T/n model). To separate the impact of the modelling approach, the different model approaches were implemented at the Inverter Power Level setup simulator under the use of the same parameter set.

The impact of the model approach variation is shown in Figure 8, where the same illustration scheme is used as for the vehicle mass variation example. The impact of the inverted flow of signals is not as obvious as shown in the previous example, depending on the complex model interactions in

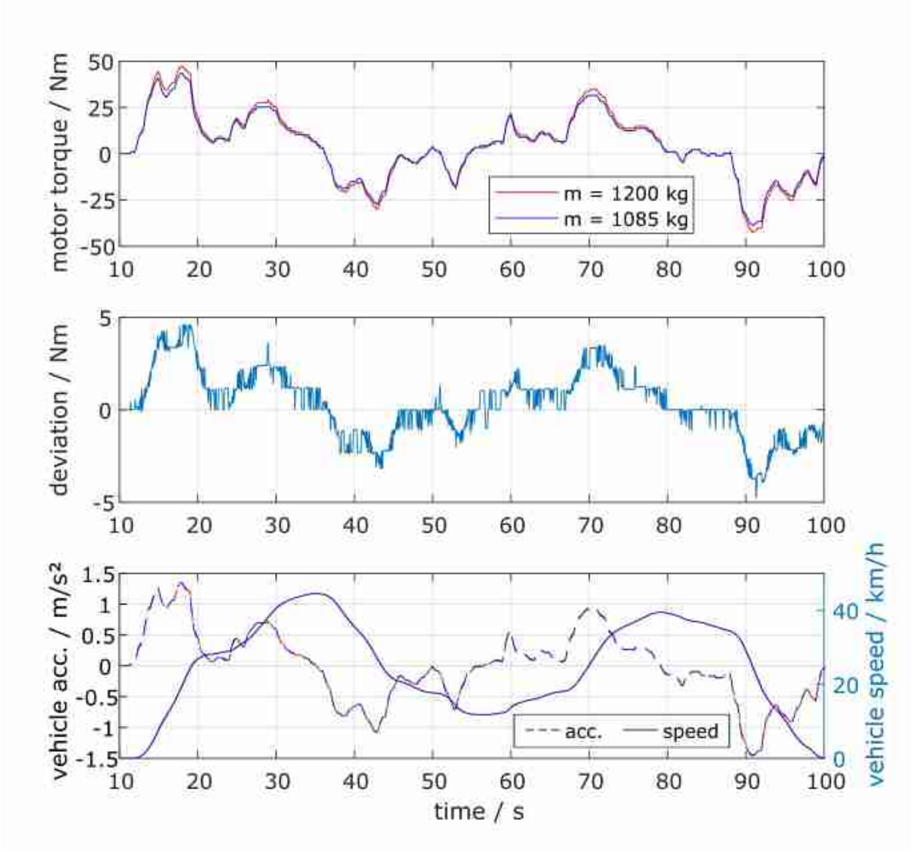


Figure 7: Effects from Different Model Parameterization of Vehicle Mass

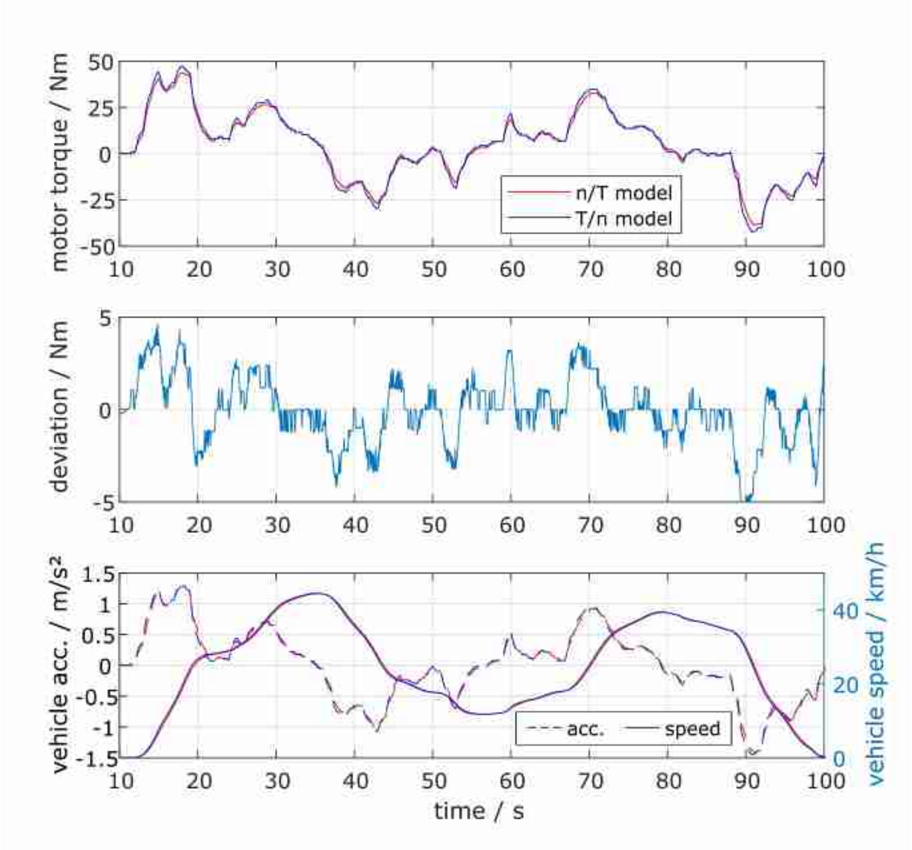
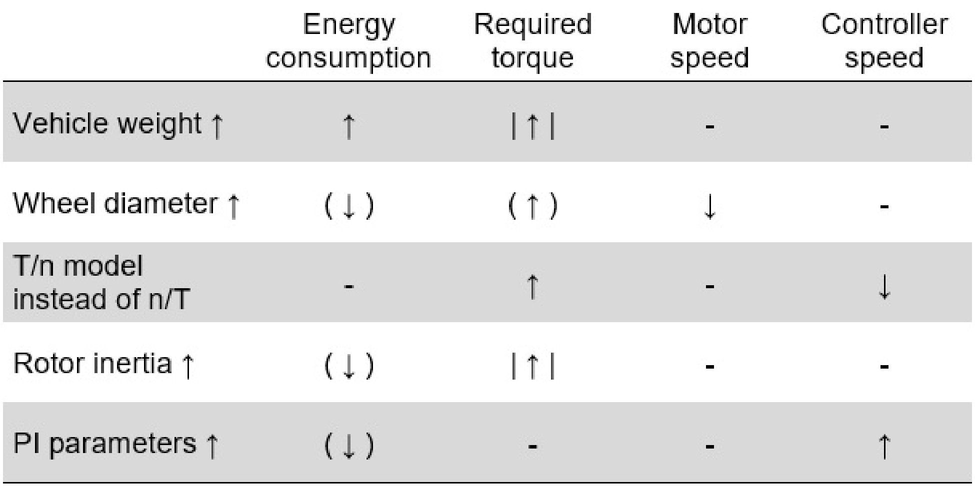


Figure 8: Effects from Different Modelling Approaches



	Energy consumption	Required torque	Motor speed	Controller speed
Vehicle weight ↑	↑	| ↑ |	-	-
Wheel diameter ↑	(↓)	(↑)	↓	-
T/n model instead of n/T	-	↑	-	↓
Rotor inertia ↑	(↓)	| ↑ |	-	-
PI parameters ↑	(↓)	-	-	↑

Figure 9: Impact of Various Parameter and Model Configurations

closed loop operation. In difference to the mass variation, the torque deviations are not linear correlating to the

(de)acceleration. Also, a small latency in vehicle speed at the T/n operation is visible in the bottom diagram, which is due to the response time of an additional speed controller. The shown example underlines the complex interdependencies in system validation, which raises the need for detailed understanding of the utilized systems.

Further identified and influencing parameters and model deviations and their impacts on energy consumption, motor torque, speed and control speed are shown in Figure 9.

One of the important and characteristic values of eTDS is the energy consumption of the drive under driving operation. Alike the shown examples, small deviations of single parameter values and modelling characteristics can lead to undesirable influences of the environment on the SiD validation. The comparison between results from previous decentral modelling and parameterization as opposed to centralized model as well as parameter management regarding the DMM are shown in Figure 10.

On the left side, the diagram shows the accumulation of mechanical energy consumption during the initial 450 seconds of WLTP drive cycle for the system setup (EMT) and inverter power level setup (PHiL) under baseline conditions of deviating modelling and parameters. The relative deviation reaches 18%. Detailed consistency investigations allow the allocation to differences in parametrization (mass, inertia, dyn. wheel radius, gear ratio), system response and modelling approaches. Multiple small or presumably obvious sources of errors can accumulate to high deviations. After optimizing the modelling and parameterization consistency according to the DMM, the deviation of mechanical energy consumption between the two setups can be reduced to 0.15%, which is shown on the right hand side of Figure 10. As the case under consideration shows, the importance of

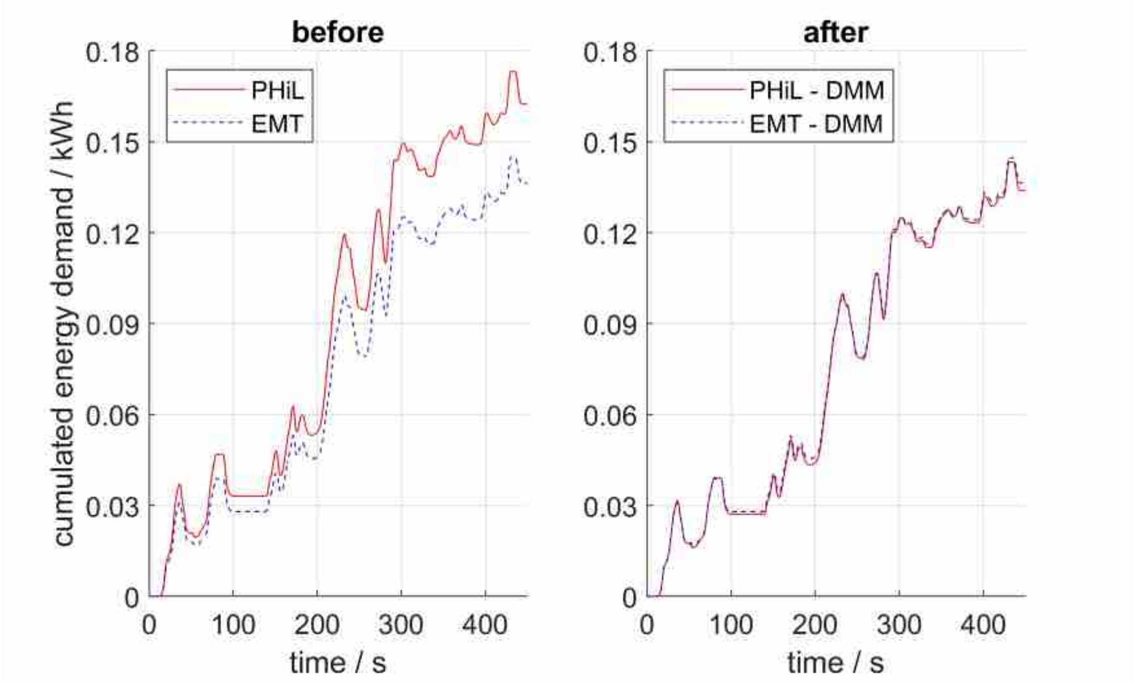


Figure 10: Consolidation of Model Behavior by Digital Model Master Approach

avoiding small inaccuracies cannot be underestimated. The desire to prevent such inaccuracies is methodological supported by the DMM.

6 Conclusion & Outlook

Following model based development and validation approaches, consistency throughout the validation environment is necessary. Consistency between the integration and maturity levels enable quick design and validation loops with a high level of significance. Beside a consolidated test run framework and a centralized postprocessing approach (cf. Boog et al. [15]), the introduced Digital Model Master represents the third pillar to reach an efficient and sustainable traceability of test case results on different levels of product maturity & progressive integration.

The DMM provides a central platform for models and parameter data exchange from the beginning of the product development process. Based on the physical architecture of the SiD the DMM is structured and thus, easily accessible, usable and expendable for all engineers. Thereby, supporting the common understanding of all prototypes of the SiD, regardless of virtual or physical form.

The presented approach is carried out in a case study at three projects at the advanced engineering department at MAHLE. The first results of the case study at three projects in the advanced engineering department of the MAHLE group, show promising accomplishments. Nevertheless, a detailed evaluation of the presented DMM must be carried out.

Examples of inconsistent modelling parametrizations and different model implementations as well as the effects on the test results have been presented. With the consistent usage of the DMM, implementations of differentiating model representations as well as inconsistent parametrization can be reduced. Consequently, the consistency throughout all integration levels is enhanced. Thus, enabling detailed analysis of the maturity and appropriateness of the used models regarding the validation objective.

With the implementation of the Digital Model Master, MAHLE takes a big step towards consistent and traceable validation from the beginning of the product development process. Based on the extended knowledge concerning the deployed models, the flexibility and moreover the validity of validation configurations with a high share of virtual subsystems is enhanced. In a nutshell, the Digital Model Master increases the efficiency of the model based development and validation approach, by ensuring consistency and traceability of the models used.

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