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**Methodology for Consistent and Flexible
Validation of Mechatronic Systems in
Advance Development in the Context of
the IPEK-X-in-the-Loop-Framework**

Methodik zur konsistenten und flexiblen
Validierung mechatronischer Systeme in
der Vorausentwicklung im Rahmen des
IPEK-X-in-the-Loop-Framework

Band 196

Systeme ■ Methoden ■ Prozesse

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(Hrsg.)

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Methodology for Consistent and Flexible Validation of Mechatronic Systems in Advance Development in the Context of the IPEK-X-in-the-Loop-Framework

Zur Erlangung des akademischen Grades eines
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Vorwort der Herausgeber

Wissen ist einer der entscheidenden Faktoren in den Volkswirtschaften unserer Zeit. Der Unternehmenserfolg wird mehr denn je davon abhängen, wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann. Die Aufgabe eines Universitätsinstitutes ist es, hier einen wesentlichen Beitrag zu leisten. In den Forschungsarbeiten wird ständig Wissen generiert. Dieses kann aber nur wirksam und für die Gemeinschaft nutzbar werden, wenn es in geeigneter Form kommuniziert wird. Diese Schriftenreihe dient seit mehr als 20 Jahren als eine Plattform zum Transfer und macht damit das Wissenspotenzial aus aktuellen Forschungsarbeiten am IPEK - Institut für Produktentwicklung Karlsruhe* am Karlsruher Institut für Technologie (KIT) verfügbar. Die Forschung des IPEK ist dabei strukturiert in die Kategorien Systeme, Methoden und Prozesse, um so der Komplexität heutiger Produktentwicklung ganzheitlich gerecht zu werden. Erst die Verknüpfung dieser drei Kategorien ermöglicht die Synthese innovativer Systeme durch Nutzung neuester Methoden und Prozesse. Gleichzeitig werden durch die Systemsynthese die erforschten neuen Methoden und Prozesse validiert und deren Mehrwert für die Praxis abgesichert. Dieses Forschungskonzept prägt nicht nur das IPEK-Leitbild, sondern auch den Charakter dieser Schriftenreihe, da immer alle drei Kategorien und deren Wechselwirkungen berücksichtigt werden. Jeder Band setzt hier individuelle Schwerpunkte und adressiert dabei folgende Forschungsgebiete des IPEK:

- das Entwicklungs- und Innovationsmanagement,
- die Entwicklungs- und Konstruktionsmethodik,
- der Leichtbau von der Ebene des ganzen Systems bis hinunter zur Optimierung des Bauteils,
- die Validierung technischer Systeme auch unter Berücksichtigung der NVH Aspekte (Noise, Vibration, Harshness) mit dem Fokus auf Schwingungen und Akustik an Komponenten und in den Gesamtsystemen sowie deren subjektiver Beurteilung durch den Menschen,
- die Antriebssystemtechnik mit den Schwerpunkten komplette Antriebslösungen für Fahrzeuge und Maschinen,
- das Design, die Tribologie und Erprobung von Kupplungen und Bremsen sowie
- die Gerätetechnik mit dem Schwerpunkt auf Power-Tools.

Die Forschungsberichte stellen Ergebnisse unserer Forschung sowohl anderen Wissenschaftlern als auch den Unternehmen zu Verfügung, um damit die Produktentwicklung in allen ihren Facetten mit innovativen Impulsen zu optimieren.

Albert Albers und Sven Matthiesen

* Eh.: Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau, Universität Karlsruhe (TH)

Vorwort zu Band 196

Im Bereich des Maschinen- und Fahrzeugbaus haben sich in den letzten zwei Jahrzehnten drastische Veränderungen ergeben. Ausgehend von den ursprünglich im Wesentlichen mechanischen Lösungen für Produkte, wurde durch weitere Anreicherung mit elektrischen und informationstechnischen Elementen in der Architektur des jeweiligen Systems der Weg hin zu mechatronischen Systemen beschritten. Die neueste Entwicklung geht nun weiter über die Einbindung und Vernetzung im Internet hin zu cyberphysischen Systemen oder Produkten. Dieser Trend gilt natürlich ganz besonders auch im Fahrzeugbau. Hier kommt eine weitere große Herausforderung auf die Unternehmen und Entwickelnden zu. Im Kontext der Forderung nach Reduzierung der CO₂-Emissionen auch und besonders im Bereich der Mobilität, um damit den globalen Temperaturanstieg des Klimas zu begrenzen, sind sowohl in Europa als auch in USA und China, ja sogar weltweit, Regelungen und Vorschriften zur Reduzierung der CO₂-Emissionen in Kraft gesetzt worden, die in großen Teilen auch gesetzlichen Charakter haben. Unter diesen Randbedingungen muss die Produktentwicklung natürlich mit neuen Lösungen reagieren. Neben einer weiteren Optimierung der verbrennungsmotorischen Lösungen bis hin zur Nutzung von synthetischen Kraftstoffen sind als Antriebskonzepte batterieelektrische Fahrzeuge oder Fahrzeuge mit Brennstoffzellen und Nutzung von Wasserstoff, der natürlich CO₂-neutral hergestellt werden muss, im Fokus. Die batterieelektrischen Fahrzeuge wurden in den letzten Jahren dabei besonders gefördert und auch vorangetrieben. Trotz der immer noch schlechten Akzeptanz dieser Fahrzeuglösungen bei den Endkunden in Europa und USA, sind sie sicher ein Beitrag, um die CO₂-Problematik anzugehen. Insbesondere für Fahrzeuge, die eher im Nahbereich eingesetzt werden, ist die batterieelektrische Lösung eine sehr gut geeignete Antriebsarchitektur. Grundsätzlich ist allerdings dabei zu berücksichtigen, dass der gesamte Lebenszyklus – also die Herstellung, Nutzung und Entsorgung – unter dem Kriterium CO₂-Fußabdruck beurteilt werden muss, um wirklich nachhaltige Lösungen zu schaffen. Der Trend hin zu elektrifizierten Fahrzeugen hat dazu geführt, dass der Elektromotor mittlerweile eine Renaissance als Antrieb für Fahrzeuge erlebt. Dieser Wandel hat nicht nur bei den OEMs, sondern auch bei den Tier One Zulieferern ganz neue Herausforderungen definiert, die berücksichtigt werden müssen. Grundsätzlich kann aber festgehalten werden, dass die größte Herausforderung – auch bei der Entwicklung von modernen cyberphysischen Lösungen – die Validierung ist. Die Validierung mit dem Ziel, das richtige Produkt von Anfang an zu entwickeln, wie es bereits seit vielen Jahren in einer Grundhypothese der Forschung in der KaSPro – Karlsruher Schule für Produktentwicklung definiert ist, erfordert neue und ganzheitliche Vorgehensweisen. Dabei gilt es, geeignete Validierungsumgebungen zu gestalten, die auch bereits in sehr frühen Phasen der Produktentwicklung eine konsequente Validierung erlauben.

An dieser Stelle setzt die Forschungsarbeit von Herrn Dr.-Ing. Claas Kürten an. Er hat sich zum Ziel gesetzt, Methoden zur Gestaltung von flexiblen Validierungsumgebungen für mechatronische Systeme – insbesondere mit dem Fokus auf die elektrischen Architekturen – zu entwickeln. Dabei geht es insbesondere darum, bereits in der Stufe der Vorentwicklung relevante Validierungsansätze zu definieren. Die Ergebnisse sind grundlagenorientiert und gleichzeitig praxisrelevant. Sie leisten einen wichtigen Beitrag in der grundlegenden Forschung auf dem Gebiet der Entwicklungsmethoden und -prozesse insbesondere im Kontext der Karlsruher Schule für Produktentwicklung - KaSPro. Die Arbeit wird sicherlich Spuren hinterlassen und weitere Grundlagenforschung anregen und gleichzeitig auch die Validierungspraxis in den Unternehmen befruchten.

Dezember, 2025

Albert Albers

Kurzfassung

Um die Effizienz und Flexibilität in der Entwicklung und Validierung komplexer Systeme zu erhöhen, wird die vermehrte Verwendung virtueller oder gemischt virtuell-physischer Testkonfigurationen angestrebt. Gleichzeitig stehen weiterhin physische Prototypen bei Entwicklungsentscheidungen im Fokus. Diese Arbeit liefert einen Beitrag zum Verständnis und der Abbildung von Validierungsaktivitäten in der Vorausentwicklung im Modell der SGE – Systemgenerationsentwicklung nach Albers. Im Zentrum der Arbeit steht die Entwicklung einer Methodik zur konsistenten und flexiblen Validierung mechatronischer Systeme in der Vorausentwicklung im Rahmen des IPEK-X-in-the-Loop-Framework.

Teilnehmende Beobachtungen und Experteninterviews in der Vorausentwicklung des Automobilzulieferers MAHLE bilden die Basis für die erfolgreiche Anwendung des Modells der SGE – Systemgenerationsentwicklung zur Beschreibung der Zusammenhänge zwischen der Vorausentwicklung und der Produktentwicklung. Darüber hinaus werden Anforderungen an eine methodische Unterstützung der Validierung in der Vorausentwicklung abgeleitet. Das gemeinsame Verständnis der verschiedenen Entwicklungspfade ermöglicht die Entwicklung und Übertragbarkeit von Methoden und Prozessen für die Produktentstehung.

Die im Rahmen dieser Arbeit entwickelte Methodik zielt darauf ab, das Vertrauen in virtuelle und gemischt virtuell-physische Testkonfigurationen zu stärken. Sie umfasst eine Methode zur Verbesserung der Konsistenz und Nachverfolgbarkeit von Testaktivitäten, eine Methode zur Verbesserung der Durchgängigkeit von Modell- und Parameterdaten in virtuell oder gemischt virtuell-physischen Testkonfigurationen, sowie eine Methode zur konsistenten Analyse und Klassifizierung von Testkonfigurationen in der Vorausentwicklung. Die Anwendung der Methoden wird durch die Entwicklung und Anpassung von Tools systematisch unterstützt.

Anhand verschiedener Entwicklungsbeispiele elektrischer Traktionsantriebssysteme wird die entwickelte Methodik angewendet und evaluiert. In der ersten Fallstudie wird eine gemischt virtuell-physische Testkonfiguration zur Steuergeräteentwicklung weiterentwickelt und evaluiert. Somit kann eine teilweise Verlagerung des Entwicklungs- und Validierungsaufwands für den Regelungsalgorithmus erzielt werden. Im zweiten Entwicklungsbeispiel werden mit Hilfe der Methodik die Stärken und Limitationen einer überwiegend virtuellen Testkonfiguration hinsichtlich der Validierung der Regelungsstrategie des Systems identifiziert. Diese Evaluierung der Testkonfigurationen in der Vorausentwicklung dient als Basis für die Planung und Durchführung der Validierungsaktivitäten für die nachfolgende Vor- und Serienentwicklung des Produkts.

Abstract

In order to increase efficiency and flexibility in the development and validation of complex systems, the increased utilization of virtual or mixed virtual-physical Test Configurations is aspired. At the same time, physical prototypes continue to be the focus point of development decisions. The aim of this thesis is to deepen the understanding and to offer a description of validation activities in Advance Development in the model of SGE – System Generation Engineering according to Albers. The central objective is the development of a methodology for consistent and flexible validation of mechatronic systems in Advance Development within the IPEK-X-in-the-Loop-Framework.

Participating observations and an expert interview study carried out in the Advance Development department of the automotive supplier MAHLE serve as the basis for the successful application of the Model of SGE – System Generation Engineering to describe the link between Advance Development and product development. In addition, requirements on methodical support for validation in Advance Development are derived. The common understanding of the different development paths enables the development and transferability of methods and processes for product engineering.

The developed methodology aims to increase the credibility of virtual and mixed virtual-physical Test Configurations. The methodology includes methodical support for consistent testing, a method to improve consistency of modeling and parameter data in virtual or mixed virtual-physical Test Configurations, and a method for consistent analysis and classification of Test Configurations in Advance Development. The application of the methods is systematically supported by the development and adaptation of tools.

The developed methodology is applied and evaluated in several case studies of the development of electric traction drive systems. In the first case study, a mixed virtual-physical Test Configuration for the development of electric control units is further developed and analyzed in accordance with the proposed methodology. As a result, significant frontloading of development and validation efforts for the control algorithm can be achieved. In the second case study, the methodology is used to identify the strengths and limitations of a highly virtual Test Configuration with regard to the validation of the control strategy of the electric traction drive system. The evaluation of the available Test Configurations in Advance Development serves as the basis for planning and implementation of validation activities in the subsequent pre- and series development of the product.

Acknowledgement

This work was created during my time as a doctoral student at the IPEK – Institute for Product Engineering at the Karlsruhe Institute of Technology (KIT), in cooperation with the MAHLE group.

I would like to express my special thanks to Univ.-Prof. Dr.-Ing. Dr. h. c. Albert Albers for the scientific supervision of this thesis. The joint discussions at the Institute in Karlsruhe, at MAHLE in Stuttgart, as well as the online meetings, helped sharpen my focus, provided new impulses and taught me to convey insights clearly through the precise use of language. Furthermore, Prof. Albers set the right tone for a highly focused research environment characterized by extraordinary interpersonal relationships, both at the Institute and within the cooperation between KIT and MAHLE. I would also like to thank Univ. Prof. Dr.-Ing. Thomas Vietor for accepting the co-supervision, for his interest in my research and for his valuable advice.

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Claas Luca Kürten

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List of Abbreviations

AC	Alternating Current
ACQ	Acquisition Process Group
AD	Advance Development
ALM	Application Life Cycle Management
ATA	Analytical Torque Control Algorithm
B2B	Business-to-Business
CPS	Cyber-Physical Systems
CS	Connected System
DC	Direct Current
DMM	Digital Model Master
DRM	Design Research Methodology
ECU	Electric Control Unit
EE	Hardware Design Team
EESM	Externally Excited Synchronous Machine
EM	Electric Machine
EMT	Electric Motor Dyno Testbench
EPSS	Electrical Power System Simulation
ETDS	Electric Traction Drive System
FPGA	Field-Programmable-Gate-Array
G1	Product Generation 1
HiL	Hardware-in-the-Loop
HWE	Hardware Engineering Process Group
IEESM	Inductive Externally Excited Synchronous Machine
INCOSE	International Council on Systems Engineering

IPEK	Institute of Product Engineering
KaSPro	Karlsruher Schule für Produktentwicklung
KPI	Key Performance Indicator
KS	Koppelsystem
LUTA	Look-up-Table Based Control Algorithm
MBSE	Model-Based Systems Engineering
MCT	MAHLE Magnet-free Contactless Transmitter
MECH	Mechanical Design Team
MiL	Model-in-the-Loop
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
P-HiL	Power-Hardware-in-the-Loop
PMSM	Permanent Magnet Synchronous Machine
PS	Phase Shift
PWM	Pulse Width Modulation
R&D	Research and Development
SE	Systems Engineering
SGE	System Generation Engineering
S-HiL	Signal-Hardware-in-the-Loop
SiD	System-in-Development
SiL	Software-in-the-Loop
SIM	Simulation Team
SPICE	Software Process Improvement and Capability dEtermination
SPL	Supply Process Group
SW	Software Team
SWE	Software Engineering Process Group
SYS	Systems Engineering Process Group

TC	Test Configuration
TRL	Technology Readiness Level
VAL	Validation Team
WLTC	Worldwide Harmonized Light Vehicle Test Cycle
XCP	Universal Measurement and Calibration Protocol
XiL	X-in-the-Loop

Symbols

a	Automotive provider
AV_n	Attribute Variation of Generation n
$\cos \varphi$	Power factor of the electric machine
CV_n	Carryover Variation of Generation n
$E_{i,j}$	Engineering Generation j of System Generation n
η_{ETDS}	Efficiency of electric traction drive system
G_n	Generation currently in development
I_a	Current of phase a
I_{AC}	Effective phase current
I_b	Current of phase b
I_c	Current of phase c
I_d	Stator current in d-axis (direct axis)
I_{DC}	Direct current of the power supply
$I_{DC,MCT}$	Direct current at MCT supply
I_q	Stator current in q-axis (quadrature axis)
I_r	Rotor current
L_{dd}	Stator self-inductance in direct axis
L_{dr}	Mutual inductance between stator d-axis and rotor
L_{qq}	Stator self-inductance in quadrature axis
L_{qr}	Mutual inductance between stator q-axis and rotor
L_{rd}	Mutual inductance between rotor and stator d-axis
L_{rq}	Mutual inductance between rotor and stator q-axis
L_{rr}	Rotor self-inductance
n	Electric machine speed

ω	Angular frequency
p	Product line
p	Number of pole pairs
P_{DC}	DC-power
P_{mech}	Mechanical power
Ψ_d	Magnetic flux linkage in the stator d-axis
Ψ_q	Magnetic flux linkage in the stator q-axis
Ψ_r	Magnetic flux linkage in the rotor
PV_n	Principle Variation of Generation n
R_n	Reference System of Generation n
R_s	Stator resistance
R_r	Rotor resistance
Tq	Torque
U_{AC}	Effective phase voltage
U_d	Stator voltage in d-axis
U_{DC}	Power supply voltage
$U_{DC,MCT}$	MCT supply voltage
U_q	Stator voltage in q-axis
U_r	Rotor voltage
v	Product variant

1 Introduction

The transformation in the automotive industry accelerates the development and adaptation of development and validation procedures. To be competitive, efficiency of development processes must be increased by reducing both development cycles and costs (Kerga et al., 2016). Furthermore, most established automotive companies must adapt their product portfolio to meet the demand for vehicle electrification. In order to foster innovations beyond the existing product portfolio, Advance Development¹ (AD) teams are employed. However, new technical solutions increase the development risk, as the developing entity lacks knowledge and information regarding the technical solution (Fricke et al., 2000).

To address these risks and to reduce development times model-based validation approaches are utilized (Düser, 2010; Etzold et al., 2019; Lemaire et al., 2015; Thomke & Fujimoto, 2000; Wagener et al., 2007). Furthermore, virtualization of design and validation is aspired to increase the flexibility in a fast-changing market environment (Thomke & Reinertsen, 1998). However, the desire for virtual validation is contradicted by the stakeholders' skepticism about the credibility of non-physical prototypes (Gausemeier et al., 2013).

In order to increase the decision-makers' confidence or credibility of virtual or mixed virtual-physical test setups, continuous, objective evaluations of their technical suitability are necessary. However, Yan et al. (2018) as well as observations in AD indicate, that the assessment of models is often based on the engineers' experience (Kürten et al., 2022). Especially in AD, where test setups are initially developed, changed frequently and testing activities are mainly described as commissioning, the results from physical tests are rarely reflected back to the models. This is a result of both, a strong fixation of the stakeholders on physical prototypes and a need for high additional resources to evolve and document testing activities.

¹ The term "Advance Development" (German: "Vorausentwicklung") will be used in this thesis for the description of research and development activities which can be located before typical product predevelopment activities. However, similarities and overlaps of these activities exist.

This thesis is focused on the development of a detailed understanding of the challenges of validation in AD and the development of methodical support to address these challenges. Based on the model of SGE – System Generation Engineering by Albers (Albers, Bursac et al., 2015), the contribution of AD to product development is to be identified. Furthermore, the thesis addresses the development of methodical support for continuous and objective evaluation of technical uncertainties regarding model-based test setups. The developed methodology particularly addresses the traceability and consistency of testing activities to enhance the transparency and comparability of test results. Thereby, the aim is to enrich the available references for the subsequent product development regarding both the System-in-Development and its validation environment. The methodical support was developed and evaluated within the research cooperation between the IPEK – Institute of Product Engineering and the “Corporate Research and Advanced Engineering” department of MAHLE. All projects involved were focused on the development of mechatronic systems, in particular electric traction drive systems.

This thesis is structured in seven chapters. In Chapter 2 the state of the art regarding the modeling of mechatronic systems, system development as well as system verification and validation within the model of SGE – System Generation Engineering is described. Subsequently, the research motivation, objectives and methodology are presented in Chapter 3. Furthermore, the research environment in which the majority of the research took place is outlined. To sharpen the understanding of the considered research field and to derive the requirements for methodical support, the results from the descriptive studies are presented in Chapter 4. In Chapter 5, the developed approach to support the model-based validation of mechatronic systems in AD is explained. Furthermore, the iterative development and evaluation of several methods to support the engineers is presented in detail. In Chapter 6, the developed approach and its methods are applied and initially evaluated in two case studies. Chapter 7 contains an overview of the key results of the thesis and provides an outlook on further, connected research needs.

2 State of Research

2.1 Modeling Mechatronic Systems

In this chapter, a general understanding of systems, modelling and the functional context of mechatronic products is presented. The cited literature serves as a basis for the developed methods and tools.

2.1.1 Understanding of Systems and Products

Modern transportation vehicles are assembled out of hundreds of interconnected systems. To deal with the development complexity of such mechatronic systems, a common understanding within the participating disciplines is needed. Systems theory is meant to explain structure and behavior across these disciplines and thus promotes system thinking (Flood & Carson, 1988).

A system is defined as a “combination of interacting elements organized to achieve one or more stated purposes” (ISO/IEC/IEEE 15288, 2015). To describe systems, Ropohl (2009) combines three different perspectives in his work on general system theory. The identified functional, structural and hierarchical concepts are displayed in Figure 2.1.

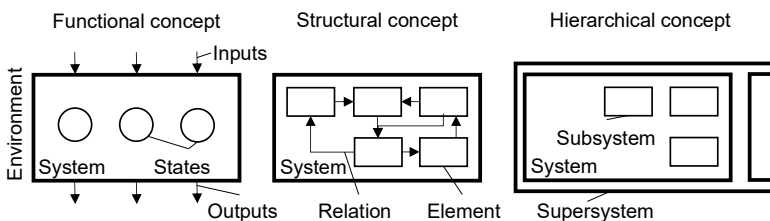


Figure 2.1: System Perspectives adapted from Ropohl (2009, p. 76)

According to the **functional** view, the system is considered as a black box to describe the behavior from an external perspective. Depending on internal states the system transforms inputs into outputs. The link between the inputs and outputs is described by functions. (Ropohl, 2009, pp. 75–76)

The **structural** concept focuses on the relations between the elements within a system. The relations and interactions between the elements define the properties and behavior of the system. Consequently, different arrangements of similar elements may result in different systems. The effect that properties can be observed only in the system as a whole but are not apparent with the elements itself is described as emergence. (Ropohl, 2009, p. 75)

The **hierarchical** view extends the structural concept by considering the elements of a system as systems itself. As a result, the regarded system consists of several subsystems while it can be viewed as part of a supersystem. Thereby, different descriptions from holistic to detailed system analysis are enabled. (Ropohl, 2009, p. 77)

The views of Ropohl allow to consider the concept of holism which can be explained by Aristotle (2009, 1045a.8–10): “The whole is greater than the sum of its parts”, Leonardo da Vinci: “Everything is connected to everything else” (Kinsman, 1989, p. 223) and Alexander von Humboldt: “Everything is interconnected and interdependent” (Doherr & Baron, 2012). However, in engineering the application of this concept is neither practical nor economical, it has to be understood as subject to a specific purpose instead (Albers & Lohmeyer, 2012).

An accumulation of components which are complex enough to be regarded as systems itself is described by **system-of-systems** (Horváth, 2012). System-of-systems are characterized by an operational and managerial independence of the systems. This describes the ability of the decomposed systems of a system-of-system to usefully operate separately (Maier, 1998). This system-of-system approach incorporates Ropohl’s concept of wholeness (Albers & Lohmeyer, 2012, p. 411).

Based on the described understanding of systems, every product can be understood as a system itself. Hence, multiple perspectives for the development of products can be integrated. A **product** is further characterized by the following three features (Albers, Basedow et al., 2020; DIN EN ISO 9000, 2015; VDI 2221 Blatt 1, 2019):

- Products are the results of developments and its realizations.
- A product can consist of any combination of material systems and/or services and/or business models.
- Products provide (socio-economic) benefits and can be offered to a customer.

Consequently, not every system can be understood as a product itself.

2.1.2 Mechatronic Systems

"[Mechatronics is] the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes" (Harashima et al., 1996). In many applications, the ability to obtain information on the system and its environment allows an improvement of the functionality. Mechatronic systems aim for constant and automatic optimization by gathering information via sensors and processing these to adapt the actors of the system accordingly. (VDI 2206, 2004)

According to the presented system understanding mechatronic systems can be structured into several subsystems. In general, a mechatronic system consists of a basic system, sensors, actors and information processing units. The environment as part of the supersystem has to be considered as well. A distinction between material flow, energy flow and information flow is usually made to describe the relations between the respective subsystems (Pahl & Beitz, 2013).

Basic information processing units consist of deterministic logic circuits. More complex processing units contain "intelligent" programmable and thereby reconfigurable logic circuits. When interconnected mechatronic systems are connected with global digital networks ("the cyberspace"), they are described as Cyber-Physical Systems (CPS) (Graessler & Hentze, 2020, p. 315). "CPS are integrations of computation with physical processes" (Lee, 2008, p. 363). The computational processes can be performed locally on embedded systems or on cloud-based computation systems (Broy, 2010). Most modern cars are equipped with multiple interconnected mechatronic systems and integrated into a network of connected vehicles and thus are examples for CPS. "[CPS] must meet requirements of openness, connectivity, increased software-implemented functionality, flexible configurability, dependability, and resilience, all in a cost-effective way, and during all phases of their lifetime" (Reussner et al., 2023, p. 83). To handle complexity, decomposition of the system on different abstraction levels and the definition of different views are necessary.

2.1.3 Electric Traction Drive Systems

The transformation and electrification of the automotive industry is apparent (Cornet et al., 2021; Simonazzi et al., 2022). With vehicle electrification, mainly the energy storage system and the drive train change significantly. Diesel-, or gasoline-tanks are replaced by high-voltage batteries or hydrogen storage systems. In battery electric vehicles, internal combustion engines are replaced by electric traction drive

systems (ETDS). In Figure 2.2, a schematic of the drive system layout of battery electric vehicles is illustrated.

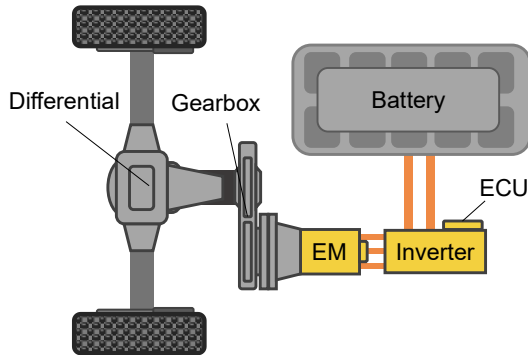


Figure 2.2: Schematic Drive System Layout of a Battery Electric Vehicle, Electric Traction Drive System Highlighted in Yellow

The displayed drive system connects the energy storage system with the vehicle's wheels and consists of the electronic control unit (ECU), the power inverter, the electric machine (EM), the gearbox and the differential. In this thesis the transmission and the differential are not regarded as a part of the ETDS (yellow) due to their equal operation in conventional powertrain systems.

A key driver for the development and optimization of ETDS is the system's efficiency. While the efficiency of ETDS exceeds the efficiency of conventional system setups with internal combustion engines, the energy density of storage systems such as the battery is significantly lower compared to conventional ones such as gasoline tanks. Consequently, increasing efficiency of the ETDS directly affects the necessary capacity of the energy storage system and thus results in cost reductions or an increase of driving range. As one of the most important technological objectives, the efficiency of the ETDS can be calculated based on Equation 2.1.

$$\eta_{ETDS} = \frac{P_{mech}}{P_{dc}} \tag{2.1}$$

P_{mech} describes the mechanical power at the motor shaft (Equation 2.2) and P_{dc} describes the electrical power at the inverter input (Equation 2.3).

$$P_{mech} = 2 \cdot \pi \cdot Tq \cdot n \quad 2.2$$

Where Tq is the mechanical torque measured at the shaft and n is the machine's mechanical speed.

$$P_{dc} = U_{dc} \cdot I_{dc} \quad 2.3$$

Where U_{dc} is the battery voltage and I_{dc} is the output current of the battery.

2.1.4 System Modelling

When observing, interpreting and conceptualizing a description of a (physical) system, a model of the system is created. Thus, a model is a simplified abstract of a more complex reality. In general, models are representations of systems, phenomena, or processes. (*Modelica Association Project FMI*, 2020; Podnieks, 2018; Stachowiak, 1973; VDI 2206, 2004)

To deepen the understanding of models, several characteristics are presented in the following. According to Stachowiak (1973) a model is characterized by three principal features:

- (1) **Representation** feature: Models are always models of something, namely, they are representations of natural and artificial originals, which can themselves be models again (Stachowiak, 1973, p. 131).
- (2) **Reduction** feature: Models generally do not capture all the attributes of the originals they are representing, but only those attributes that seem of relevance to the particular model creators and/or model users (Stachowiak, 1973, p. 132).
- (3) **Pragmatic** feature: Models are not assigned per se uniquely to their originals. They fulfill their replacement function: a) for certain – cognitive and/or acting, model-using – subjects, b) within certain time intervals, c) under the restrictions of specific operations (Stachowiak, 1973, pp. 132–133).

Models are representations made for one or more individuals and to perform specific functions at a certain stage. Ideally the purpose of models is well defined by model creators and always known to model users. Alike Stachowiak, Rothenberg et al. (1989) express the need for a referent / original (1), whether it is existing or not, against which the model can be validated. Furthermore, the importance of the specified models' purposes is underlined and consequently, limitations in the models' application are shown (2)/(3). To name a few common purposes, models are representations to help understand or analyze, define or specify, communicate or visualize, verify or validate systems (Walden et al., 2015). Application of models found in literature vary from organizational, processual, or mental models to analytical, phenomena or physical models. In addition to the mentioned principal features, Rothenberg et al. (1989) add the "cost-effectiveness" attribute to describe models:

- (4) "It is more **cost-effective** to use the model for this purpose [defined by (2)/(3)] than to use the referent itself."

Coherent with the model's purpose, the usage of a model might be justified by the non-availability of the referent, or rather a sufficient setup to integrate the referent, as well as any cost benefit in terms of money and time.

2.1.5 Model Complexity and Uncertainty

When modelling systems, trade-offs between the model's complexity and uncertainty must be made. To understand or determine the complexity of a system, Lindemann (2009) identified several criteria based on Ropohl's (2009, p. 76) system description¹:

- number, types, and diversity of **elements**
- number, types, and diversity of **relations**
- system **dynamics**
- number and types of **states**

The number, types and diversity of elements within the system and outside of the system as well as their relations affect the complexity. Furthermore, the number and type of states as well as the systems dynamic (transition between states) have an impact on the complexity.

¹ See Chapter 2.1.1

Uncertainty arises due to a lack of knowledge or due to a lack of definition. The lack of knowledge refers to the absence of information or the insufficiency of the system's understanding. Such a lack is, among other things, addressed by seeking relevant information or engaging in knowledge generating activities such as validation. A lack of definition is described as the absence of clear, precise or agreed-upon decisions or specifications. In product development decisions and definitions depend on the basis of problem-specific knowledge. However, knowledge generating activities need specifications. With the lack of definitions, these activities can only be initiated by creating estimations or hypotheses. (McManus & Hastings, 2005)

Models are created by abstracting complex issues and focusing on the defined purpose. The modelling process often involves making simplifications and rough assumptions, for example regarding boundary conditions. Multiple models with different points of view are utilized to analyze a system. Thus, a reduction of the complexity is achieved. However, with the lack of knowledge, for example regarding the relation between separated elements, abstraction leads to higher uncertainty.

2.2 System Development

With the understanding of the general system theory presented in Chapter 2.1.1, product engineering can be understood as a system itself. According to modeling characteristics, the models of system development presented in the following chapters are built up for specific purposes. Thus, the considered models are focusing only on sections of the product life cycle and represent only a few of many views in product engineering (Wynn & Clarkson, 2018).

2.2.1 Product Life Cycle Model

In the literature, many models of product life cycles exist. In general, the product life cycle can be divided into two phases: the product engineering² phase and the product operation phase. Whereas the product engineering phase stretches from the idea to the start of series production, the product operation phase includes production, distribution, use and return. (Albers & Gausemeier, 2012; VDI 2221 Blatt 1, 2019)

² "Product engineering" – translated into German as: „Produktentstehung“

Within this thesis, the focus is set on the engineering phase, which can be divided up further. According to the cycle model of product engineering by Gausemeier et al. (2012), three main cycles exist within the product engineering phase: strategic product planning, product development³ and the design of the production system (see Figure 2.3). However, these cycles are not meant to be performed sequentially.

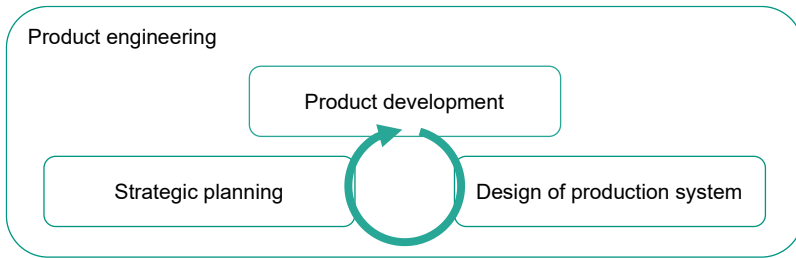


Figure 2.3: Product Engineering Cycle adapted from Gausemeier et al. (2012)

During **strategic planning**, an economic foundation for a product is provided (Albers & Gausemeier, 2012). Thereby every aspect of successful innovations⁴ is considered. Starting with the identification of potentials with the help of scenarios or trend analysis, the search for technical solutions to address these potentials is initiated (Fink et al., 2001; Hirschter et al., 2018). The elaboration and selection of technical solutions is supported by creativity techniques (Amabile, 1996; Mumford, 2000). In-depth market analyses are utilized to evaluate the economic value of the identified potentials and its possible technical solutions. To support and guideline the strategic product planning, business plans and product profiles⁵ are often utilized.

Based on strategic product planning, **product development** initiates the design of the product concept. Subsequently the domain specific design is initiated for mechatronic systems (VDI 2206, 2004). Nowadays, the modeling and simulation of the system and subsystems supports system development and integration. Thus, virtual prototypes shape product development. To model and document the product

³ "Product development" – translated into German as: „Produktentwicklung“

⁴ See Chapter 2.2.2

⁵ See Chapter 2.2.3

design, Systems Engineering⁶ is used. Within the development of embedded systems, the Automotive SPICE (Software Process Improvement and Capability dEtermination) reference model⁷ is used as a common guideline.

The **design of the production system** is closely connected and interacts with the product development (Albers, Lanza et al., 2022). In general, four aspects of the design of the production systems are considered: workflow planning, work equipment planning, workplace planning and production logistics (Albers & Gausemeier, 2012). Product engineering is understood as cyclical interactions of planning, engineering and production tasks, which are interconnected through validation⁸.

2.2.2 Innovation

For mechatronic products, market competition intensifies as industrial trends like shortening life cycles and rising customer needs for individualization persist while new players emerge in a globalized market (Braun et al., 2020; Kadam & Apte, 2015; Sabadka et al., 2019; Wahren, 2004, p. 235). Innovations enable competitive advantages and thus support sustainable success for companies (Coskun Samli & Weber, 2000). Technological progress and breakthroughs provide the potential to address customer or consumer needs (Klappert, Schuh, & Aghassi, 2011, p. 6). To achieve market success, multiple factors must be considered. Based on Schumpeters (1927) understanding of innovations, Albers, Heimicke et al. (2018) present a three-element innovation model (see Figure 2.4).

⁶ See Chapter 2.2.7

⁷ See Chapter 2.2.6

⁸ See Chapter 2.2.3

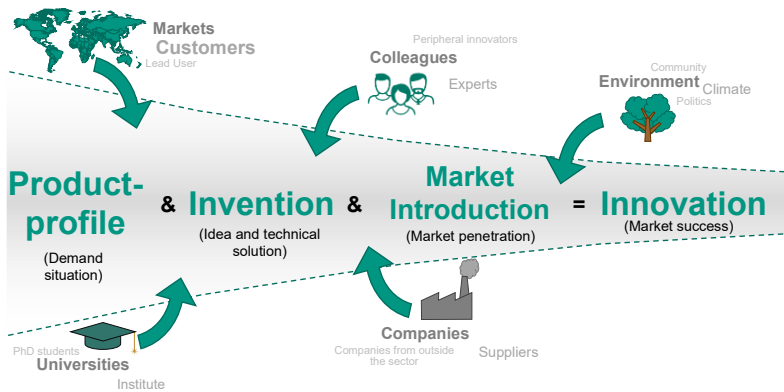


Figure 2.4: Three-Element Innovation Model adapted from Albers, Heimicke et al. (2018)

Thereupon, an innovation is the result to a successful market penetration of an invention, which satisfies a need situation in the market. To describe and clarify the addressed needs, product profiles⁹ can be used. The term “invention” includes both the ideation and realization of a system. An invention can be described as the implementation of a new combination which differs more than only gradually from the existing one. Typical inventions are new products, processes or services. However, also new system characteristics, new organizational or business structures are regarded as inventions. Besides the type of systems, the degree of novelty and the scope of the novelty are also considered when characterizing innovations. Only by achieving economic relevance on the market, inventions evolve into innovations. (Albers, Heimicke et al., 2018; Hauschildt et al., 2016; Schumpeter, 1927)

⁹ See Chapter 2.2.4

2.2.3 The ZHO¹⁰-model or Advanced System Triple

Building on the basic systems theory, product engineering can be understood as the continuous transfer of an initially vague system of objectives into a particular system of objects implemented by the operation system (Albers, 2010; Ropohl, 1975, 2009).

The **operation system** consists of all necessary resources in the form of developers, budget, tools etc. for product engineering. The operations are structured according to methods and processes, thereby objectives as well as objects arise from the operation system.

The **system of objectives** contains all explicit objectives of a system or product that is to be developed, including the planned attributes, states and functions as well as their relations at a certain time. Thus, stakeholder needs, requirements as well as restrictions on the system which is to be developed are expressed. Furthermore, the system of objective comprises the explicit documentation of the information required for the realization of the system to be developed. Based on the objectives, the operation system designs solutions which constitute the **system of objects**. Besides the solution itself, the system of objects contains all developed artefacts i.e., documents, simulations and prototypes. The system of objectives and the system of objects are connected solely by the operation system. (Albers & Braun, 2011, pp. 16–17)

Furthermore, product engineering is understood as an iterative process. The continuous enlargement and concretization of the objectives and objects during the development process is described by the extended ZHO-model which is displayed in Figure 2.5.

¹⁰ German abbreviations:

Z - "Zielsystem" translated: system of objectives,

H - "Handlungssystem" translated: operation system and

O - "Objektsystem" translated: system of objects

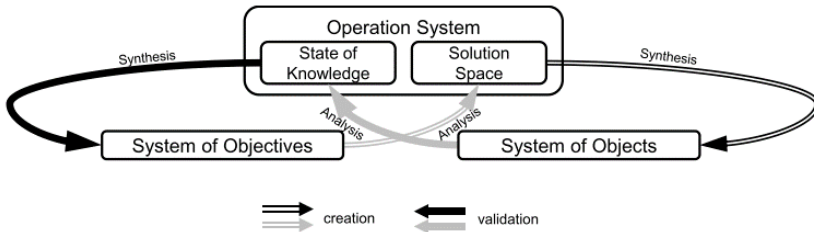


Figure 2.5: Advanced System Triple Approach (Albers et al., 2013, p. 3)

Albers et al. (2012) add the activities analysis and synthesis to the ZHO-model to refine the interrelationships of the system triple. Analysis describes actions aiming at understanding existing systems and thus, generates knowledge, while synthesis describes actions aiming at creating new systems, both objectives and objects (Lohmeyer, 2013, p. 102). The solution space is analyzed under the constraints of the system of objectives. The design or creation of objects inside this solution space is a synthesis activity. The analysis of the designed system of objects to extend the knowledge and the synthesis of objectives are both part of the validation. The synthesis activity may thereby represent the refinement, revocation, extension or addition of objectives. The development of systems/products is considered complete when the developed objects sufficiently match the objectives. (Albers et al., 2013)

2.2.4 Modelling Objectives in Product Profiles

Based on the ZHO-model, development tasks are a result to a mismatch between the system of objectives and the system of objects. Consequently, the relevance of choosing the “right objectives” is of high interest (Hall, 1962). According to Albers, Dumitrescu et al. (2018) the development of product profiles, which visualize and express the central objectives, belongs to the most important activities of product engineering. Product profiles include the model of “[...] benefits that makes the intended provider, customer and user benefits accessible for validation [...]” (Albers, Heimicke et al., 2018, p. 255). Thereby, the solution space for the design of a product generation is specified without describing the solution itself. Within the product profile, the solution space, is among other things, described by reference products and limited by boundary conditions. Thus, the product profile is a part of the system of objectives. To express a product profile, Albers, Heimicke et al. (2018) provide a product profile scheme, which is displayed in Figure 2.6.

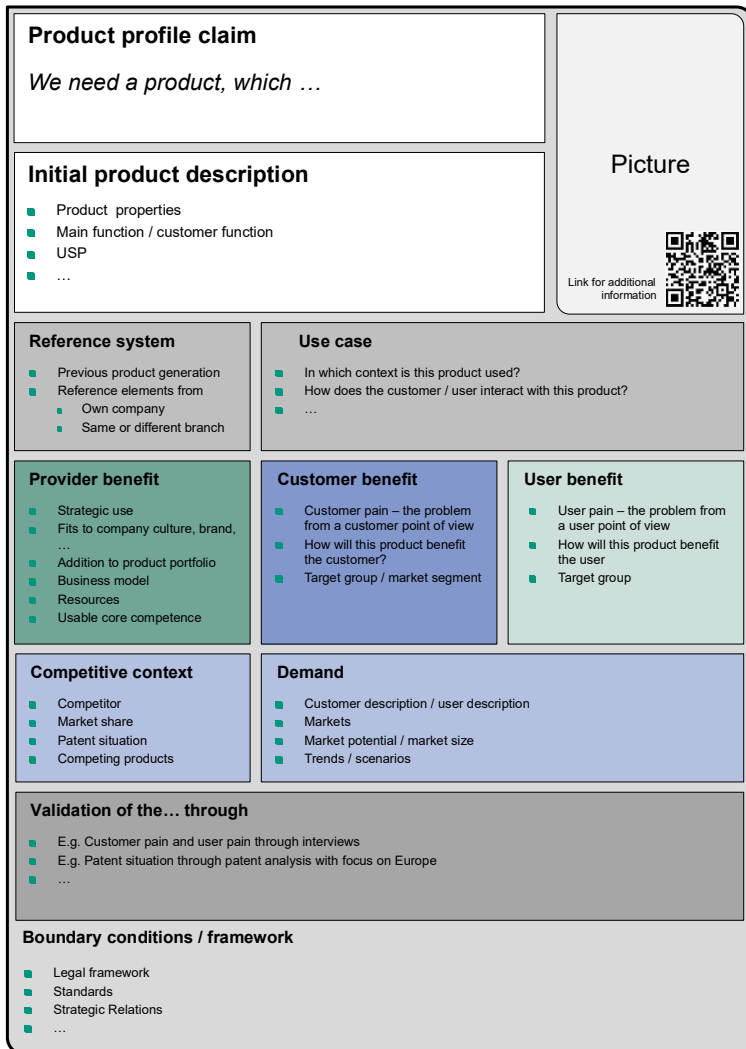


Figure 2.6: Product Profile Scheme (Albers, Heimicke et al., 2018)

As key elements of the product profile, “the number of benefits will be understood as a set of products and services, which are offered with the purpose of being sold to a customer and to provide benefits for him directly or indirectly – e.g. for users taken into account by him or for his customers” (Albers, Heimicke et al., 2018, pp. 255–256). Additionally, information regarding the potential use cases, the competitive context and the product demand are modelled within product profiles. In total, the product profile scheme consists of 12 modules. The validity of the considered sub-modules of the product profile might vary from vague hypotheses to empirically proven.

2.2.5 Research and Development within Companies

A crucial factor to companies’ success is the ability to regularly generate innovations (Chapter 2.2.2). As described, an invention needs to address a customer or consumer demand. In Figure 2.7 interactions between demand and supply within product engineering are displayed.

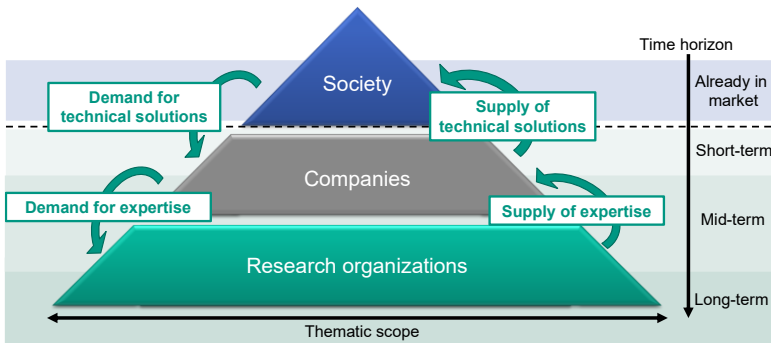


Figure 2.7: Demand and Supply Chain within Product Engineering adapted from Albers (2018)

In the present market economy, every product is legitimated by a demand within the society. A benefit for the society is created when technical solutions (products) address existing problems or specific needs. To meet these needs within the society, companies are dependent on the creativity and expertise of their employees. This demand for expertise is met by research organizations, which provide both the education of personnel as well as the documentation of research findings.

Since the late 1980s the importance of activities upstream of the product development phase to the success of innovation is stressed. Cooper (1988) states, "that new product success and failure is often decided before the new product project even enters the product development phase" (Cooper, 1988, p. 237). To support the integration of expertise from research organization into companies and to foster innovations, companies often establish separate research and development (R&D) departments. The separation of the R&D department from the series development department allows and facilitates higher creativity of the developers due to their independence of the concurrent (series) product development (Hilt, Wagner, Osterlehner et al., 2016; Ili et al., 2012; Schröder, 2010).

The tasks of these R&D departments include the idea generation, product definition and project evaluation (Murphy & Kumar, 1996). The key objective is a functional analysis and evaluation of the technical feasibility to such an extent that their suitability for series development can be demonstrated (Allmann, 2007; Hilt, Wagner, Ordnung et al., 2016; Ili et al., 2012). Through the early verification and validation of new product ideas and concepts by the R&D department, the risks for series development can be reduced. The gained knowledge as well as the generated results within R&D departments are typically transferred to the series development departments in the form of personnel, specifications of the identified customer need as well as virtual or physical prototypes (Stapel et al., 2009; Voigt, 2008, p. 412).

2.2.6 Modeling and Assessing Product Development Processes in the Automotive Industry

Process models, guidelines and approaches support the development of systems by guiding developers. Such models are designed to create clear, common objectives and to ensure that high-quality goals are achieved efficiently. Often, established procedures are abstracted in order to provide situation-specific support. (Lindemann, 2009)

In Figure 2.7, dependencies between different players are displayed on a macro level. Within the company layer a high competition can be observed while at the same time, the globalized supply chains create mutual dependencies. Standardization of systems and processes through norms and standards helps to establish trustful relations between companies. Moreover, conformity to development methods and standards is often seen as a level of quality (Zimmer et al., 2016).

For mechatronic systems, the guidelines VDI 2206 (2021) and VDI 2221 Blatt 1 (2019) are widely established and utilized as a basis for the development within companies. The so-called “V-model” provides a generic overview for the connection of tasks in the development of mechatronic and cyber-physical systems. The macro cycle within product development is displayed in Figure 2.8.

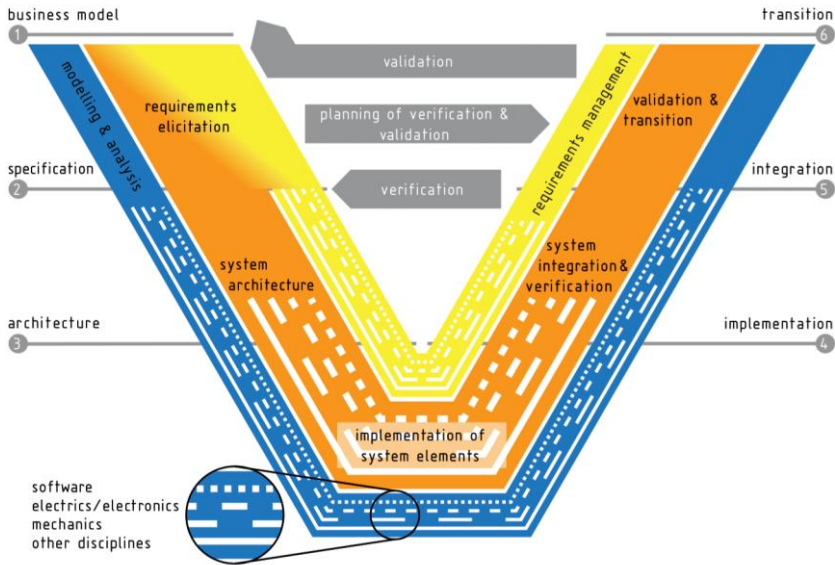


Figure 2.8: V-Model – Connection of Tasks in Interdisciplinary Development of Mechatronic and Cyber-Physical Systems (VDI 2206, 2021, p. 22)

According to the V-model, product development is described as an iterative procedure of system designing and system integration. The model consists of three visually parallel but interacting strands. The middle strand represents the core tasks of system development: requirement elicitation, system architecture, implementation of system elements, system integration and verification, validation and transition. The inner strand represents requirements engineering, while the outer strand emphasizes the modelling and analysis of the system and its subsystems. Additionally, six checkpoints are visualized which should support the developers in tracking the progress of the system development. (VDI 2206, 2021)

The basis for all displayed activities is a business model which is shown at the top left of the V-model. The business model is specified through requirements. Based on these requirements concepts of the physical and logical characteristics of the future product are described. The overall functions are divided into subfunctions and subsequently the intended operating principles as well as solution elements are designed. (VDI 2206, 2021)

Within the interdisciplinary development of mechatronic systems, the solution concepts are concretized within the different domains. Furthermore, detailed calculations and designing are done domain-specific. Thereby, the isolation of subfunctions on the lowest subsystem level is aspired. After assuring functionality on a domain level, subsystems are integrated stepwise into the system to analyze interactions and interdependencies. Each integration is accompanied by the verification of the defined properties and functions. Between the left and right thigh of the V-model the verification and validation activities¹¹ are indicated. (VDI 2206, 2021)

For the development of mechatronic systems and especially software systems within the automotive industry, a common process model is established. Furthermore, the process assessment is used to evaluate the supplier's development quality. The Automotive SPICE Process Reference Model is displayed in Figure 2.9.

¹¹ See Chapter 2.4.1

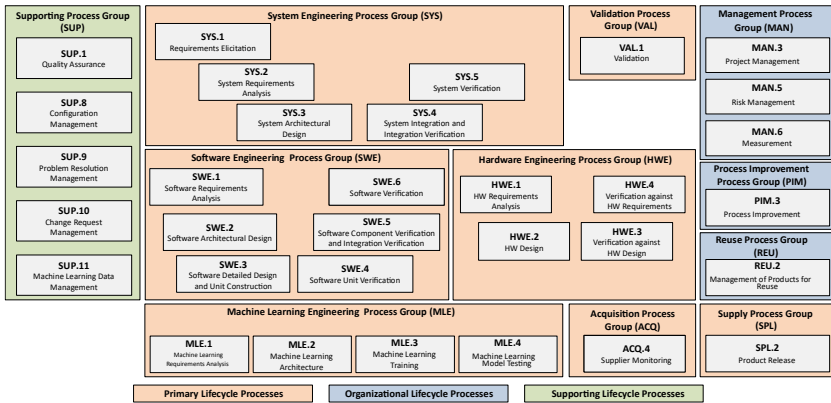


Figure 2.9: Automotive SPICE Process Reference Model (VDA QMC Working Group 13 / Automotive SIG, 2023)

The model can be divided into process categories: primary life cycle processes, organizational life cycle processes and supporting life cycle processes. Each process is characterized by a purpose statement, which contains the specific function objectives of the process in a particular environment. Furthermore, specific process outcomes, base practices and output work products are defined for each process. (Zimmer et al., 2016)

When a customer acquires products from a supplier, the primary life cycle processes may be used by both the customer and the supplier. In this case, the acquisition process group (ACQ) is of high relevance for the customer and the supply process group (SPL) for the supplier. The systems engineering process group (SYS) is of high relevance for both parties to address the elicitation of requirements, the definition of the systems architecture and the verification on system level. In addition, the software engineering process group (SWE) might be relevant for the supplier to address the management of software requirements, software architecture as well as the implementation, integration and software testing. The same applies to the hardware engineering process group (HWE) with regard to hardware development. With version 4.0 of the Automotive SPICE, the Validation Process Group is introduced with the purpose to “provide evidence that the end product, allowing direct end user interaction, satisfies the intended use expectations in its operational target environment” (VDA QMC Working Group 13 / Automotive SIG, 2023, p. 58). The other process groups can be employed to support and organize processes. (VDA QMC Working Group 13 / Automotive SIG, 2017, 2023; Zimmer et al., 2016)

Within the competitive automotive industry, a sufficient level of process conformity must be achieved and documented by the suppliers in order to be considered by the manufacturer when awarding development contracts. Elementary aspects of process conformity are the consistency¹² and traceability of the activities carried out. Traceability represents the formal relation between the elements, which must be available bidirectional.

2.2.7 Model-based Systems Engineering

According to the International Council on Systems Engineering (INCOSE), Systems Engineering (SE) describes an interdisciplinary, iterative and comprehensive approach for the realization of systems (Walden et al., 2015, p. 11). SE focuses on the definition of system requirements and functionalities and systematically supports the design and validation of the system. SE includes both technical and management processes and thus addresses several challenges of system development: “operations, cost and schedule, performance, training and support, test, manufacturing and disposal” (Walden et al., 2015, p. 11). SE highlights the system development as a whole and strives for a centralized exchange within interdisciplinary development teams. (ISO/IEC/IEEE 15288, 2015)

Furthermore, model-based Systems Engineering (MBSE) is defined as “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” (Walden et al., 2015, p. 189). The key idea of MBSE is providing and funneling information regarding the system and its development in a system model. Document-based approaches where management of information is difficult to maintain, synchronize and or access are thereby replaced (Beihoff et al., 2014). The SE process can be subdivided into activities regarding requirements engineering, system architecture modeling as well as verification and validation (Fritz et al., 2020).

The central outcome of the MBSE process is the system model (Friedenthal et al., 2015). The system model consists of a detailed model of the problem and solution space. It includes user and system requirements as well as the systems architecture. The system architecture incorporates multiple perspectives such as, for example the physical structure and the functional description of the system and relates their elements to one another. Different perspectives are used to manage complexity and

¹² See Chapter 2.4.6

allow modularization. Based on the system's architecture, the physical system can be decomposed into its subsystems and system functions can be broken down into subfunctions according to the hierarchical concept¹³. System architectures are commonly implemented in the modelling language SysML. (Dumitrescu et al., 2021; Friedenthal et al., 2015; Holt & Perry, 2019; Krause et al., 2021)

In Figure 2.10, the central levels of system architecture and abstraction according to Pearce and Hause (2012) are displayed.

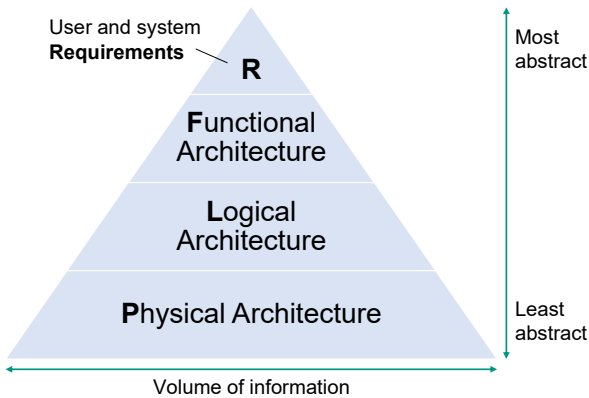


Figure 2.10: Level of System Architecture and Abstraction adapted from Pearce & Hause, 2012, p. 10

The requirements viewpoint contains all stakeholder needs (e.g., use cases) and therefore the requirements for the considered system. It describes what the system must achieve and acts as a starting point for the traceability of the content in other viewpoints. The functional architecture represents a solution-independent description of the system functionalities. Within this viewpoint, functions can be further decomposed and information exchange between the functions is documented. The logical architectural elements are represented within the logical viewpoint. Thus, a component independent solution description is realized, that allows reusability of functions within different system variants. The physical

¹³ See Chapter 2.1.1

architecture defines a specific design of the system, which corresponds to the logical architecture. Therefore, all subsystems, their functions, interfaces and connections are modelled in detail. (Pohl et al., 2012)

The system model represents a platform for all disciplines in a common language with the purpose to gather and extend the system understanding (Beihoff et al., 2014). Furthermore, the system model is meant to support the documentation of verification and validation activities in interdisciplinary projects. Typically, findings regarding the systems elements are attached to the systems description within the physical architecture model. Thereby, the system model represents a central platform for knowledge storage and exchange between developers from different domains (Alt, 2012). Moreover, with a thorough system model the effect of changes on any level can be traced to all system elements.

Despite the advantages described above, MBSE does not yet seem to be widely established in industrial practice (Gausemeier et al., 2013). This appears to be due in particular to a lack of user focus and a lack of acceptance of existing MBSE approaches (Huth & Vietor, 2020). To address these hurdles and to support the validation in product development, several methods to support MBSE are available. For example, the object oriented systems engineering method by Friedenthal et al. (2012, 431-519), the systems modelling toolbox by Weilkens (2014), the functional architecture for systems method by Lamm and Weilkens (2014), the conceptual design specification technique for engineering of complex systems by Gausemeier et al. (2012), or the comprehensive model-based systems engineering methodology to support validation by Mandel (2024).

2.3 The Model of SGE – System Generation Engineering

The model of SGE – System Generation Engineering by Albers is an explanatory model for the development of new systems (Albers, Kürten et al., 2022; Albers & Rapp, 2022). It describes fundamental phenomena in product engineering and acts as a basis for the research and development of new methods and procedures to support product development (Albers, Haug et al., 2016). The model is based on two basic hypotheses (Albers, Bursac et al., 2015; Albers, Rapp et al., 2020; Albers, Rapp et al., 2019):

- 1) “every development of a new system is based on a reference system” (Albers & Rapp, 2022, p. 29)

- 2) “based on the reference system a new system is developed by a composition of three different types of variation of subsystems: carryover variation, attribute variation and principle variation” (Albers & Rapp, 2022, p. 30)

Consequently, the development of new systems or products can be described as the development of new generations G_i . The reference system R_i , which is the basis for the development of new generations, consists of elements of already existing or planned socio-technical systems as well as the related documentation. These elements can be, for example, preceding products, products of a competitor or corresponding parts and documentation. The developers of a new system consider both physical systems such as analyzed products (e.g., benchmark) as well as virtual systems, such as simulations, descriptions, requirements or test results for the reference system. (Albers, Rapp et al., 2019)

With the model of SGE – System Generation Engineering by Albers, the development of one specific generation G_i can be mathematically modeled as the sum of different variations of subsystems, which are part of its reference system R_i :

$$R_i \xrightarrow{V} G_i = CV_i \cup AV_i \cup PV_i \quad (i \in \mathbb{N}) \quad 2.4$$

The index $i = n$ describes the system generation which is currently in development. According to the mathematical description (Equation 2.4), three different types of variations are defined (Albers, Bursac et al., 2015; Albers, Rapp et al., 2020):

- Carryover variation (CV_i): to minimize development efforts and risks, subsystems from the reference system are carried over to the new system with no or at most changes at the interfaces due to the integration into the system.
- Attribute variation (AV_i): to fulfill the desired functionality within the new systems, attributes of subsystems from the reference system are at least partially altered while elements and links within the subsystem are preserved in principle.
- Principle variation (PV_i): based on the subsystem from the reference system, elements as well as links between them are changed, added or removed.

Based on these three types of variation or their composition, the development of the new generation can be systematically planned. The share of the variation types can indicate potential risks for the new development as attribute and principle variations tend to entail higher uncertainties than most carryover variations. (Rapp, 2021)

An example for the application of the Model of SGE – System Generation Engineering is given below (Figure 2.11). In this example, the MAHLE Magnet-free Contactless Transmitter (MCT) is regarded as the System-in-Development (SiD). The SiD mainly consists of the primary electronic (Figure 2.11 right, lower part), the rotating transformer, a rectifier printed circuit board (PCB) and the rotor (Figure 2.11 right, upper part).

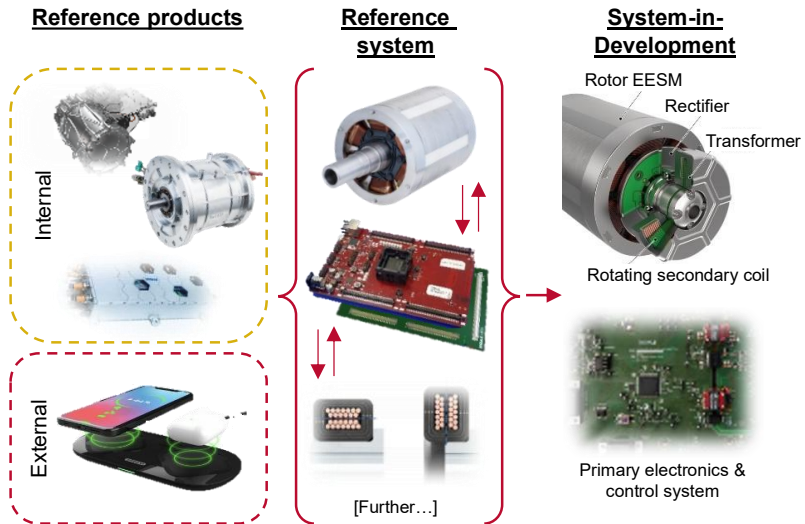


Figure 2.11: Reference System of the MAHLE MCT Described within the Model of SGE – System Generation Engineering

For the development of the new system, many reference products exist in and outside of the developing entity (in this case MAHLE). For example, 48 V traction drive systems, EMs and a DC¹⁴-to-DC converter are regarded as internal reference products. The wireless charging technology which is widely spread across consumer electronic products can be described as a reference which is not part of the entity's product portfolio.

¹⁴ DC: direct current

Among other things, the reference system of the new system development includes the rotor of an externally excited synchronous motor (EESM), which is carried over (CV) to the development of the new system. Additionally, the control unit as well as its control algorithm of the DC-to-DC converter are regarded as reference system elements. The control algorithm is adapted (AV) to control the MCT. For the design of the rotating transformer, stationary transformer concepts from consumer electronic wireless chargers are part of the reference system. These concepts are changed and adapted to fulfill the requirements regarding the rotating system and the different power level. According to the model of SGE – System Generation Engineering the development of the MCT can be described by the shares of CV, AV and PV. As a result to the high shares of new development (AV & PV), the development uncertainties and risks are rated as high. Furthermore, MAHLE's R&D department is responsible for reducing these uncertainties by demonstrating technological feasibility in order to enable successful product development.

2.3.1 Engineering Generations within the Model of SGE – System Generation Engineering

In industrial practice, product development processes are structured by phases, milestones, gates, sprints or other methods (Albers et al., 2012; Albers, Heimicke et al., 2019; Cooper, 1994; Ponn & Lindemann, 2011; VDI 2206, 2021; VDI 2221 Blatt 1, 2019). In addition, companies are planning development processes across products in order to exploit synergies (Albers, Haug et al., 2016). Based on Ropohl's (2009) system theory, interdependencies and reuse of systems across products can be modelled using the model of SGE – System Generation Engineering by Albers. Therefore, product portfolios can be differentiated in different product lines (p), product generations in different product variants (v) or product functions in different subfunctions (Fahl et al., 2019).

Based on the fractal character of the model of SGE – System Generation Engineering by Albers, the development of product generations can be modelled as well as the intermediate stages in the development of a product specific product generation (Albers, Kürten et al., 2022). Within the model of SGE – System Generation Engineering by Albers, these intermediate stages in the development of a system/product generation, are described and modelled by Engineering Generations ($E_{i,j}$) (Albers, Haug et al., 2016). In Figure 2.12 an example of the product portfolio and its directly connected development paths of an automotive provider modelled in the Model of SGE – System Generation Engineering is displayed.

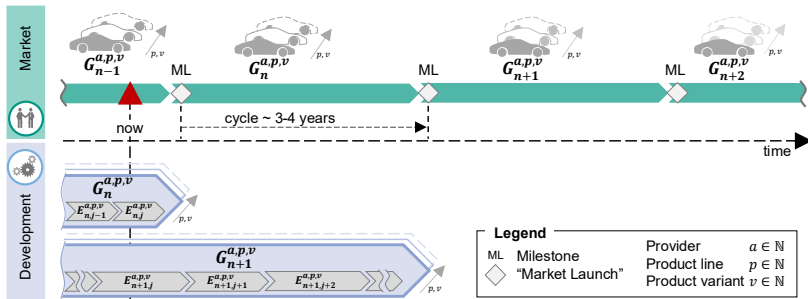


Figure 2.12: Exemplary Modeling of Product Development Process in the Model of SGE – System Generation Engineering adapted from Albers, Fahl et al. (2020)

The excerpt of the product portfolio of an automotive provider (a) in Figure 2.12 demonstrates consecutive generations of a specific product variant (v) within one product line (p). Further product variants and product lines which are in the market are indicated schematically, as well.

According to the nomenclature of the model (Albers, Fahl et al., 2020), the product generation, which will be launched next on the market is indicated as G_n . The product generation which is on the market is designated as G_{n-1} . In the automotive industry a typical market cycle lasts three to four years. Consequently, every generation $G_{n-1}^{a,p,v}$ of each variant (v) in each line (p) of a provider (a) will be superseded by a new generation $G_n^{a,p,v}$. The development of subsequent generations ($G_{n+1}^{a,p,v} / G_{n+2}^{a,p,v} / \dots$) is illustrated, as well.

The lower part of Figure 2.12 represents the schematical structure of the development of the subsequent generation $G_{n+1}^{a,p,v}$ by Engineering Generations $E_{i,j}$. While the first index (i) refers to the considered product generation (in this case G_{n+1}), the second index ($j \in \mathbb{N}$) analogously describes the Engineering Generation at that time. In this example, the current Engineering Generation of the considered product generation which is in development is designated as $E_{n+1,j}^{a,p,v}$. As the development of an Engineering Generation can be understood as the development of a system, every Engineering Generation can be modelled in the model of SGE – System Generation Engineering. According to Equation 2.4, every Engineering Generation is based on a reference system and thus, can be depicted as the sum of carry-over, attribute and principle variations. Especially in development projects with a high share of AV and PV the continuous assessment

of the state of the intended customer, user and provider benefits, which are modelled within the product profile¹⁵, can be planned and ensured by Engineering Generations. Thus, with the use of Engineering Generations customer orientation can be increased. (Albers et al., 2017; Albers, Fahl et al., 2020; Albers, Haug et al., 2018; Albers, Haug et al., 2019)

2.3.2 Product Generation 1 – G1

According to the Model of SGE – System Generation Engineering, the development of a new system is always based on a reference system¹⁶. Hence, a new combination of existing systems can result in an invention¹⁷. To model product engineering processes, product generations (and Engineering Generations) are used within the model of SGE – System Generation Engineering. Companies are aspiring to continuously extend their product portfolio by introducing new products.

If a company begins a new development path completely from scratch, so that no predecessor generation exists as an element in the reference system, the term “Product Generation 1 (G1)” is used within the model of SGE (Albers in Yan, 2020). Moreover, no system architecture predecessor exists within the reference system. These development paths often differ from the development of successive product generations. In Figure 2.13 seven indicators for the prospective classification as G1 are given (Albers, Ebertz et al., 2020).

¹⁵ See Chapter 2.2.4

¹⁶ See Chapter 2.2.7

¹⁷ See Chapter 2.2.2

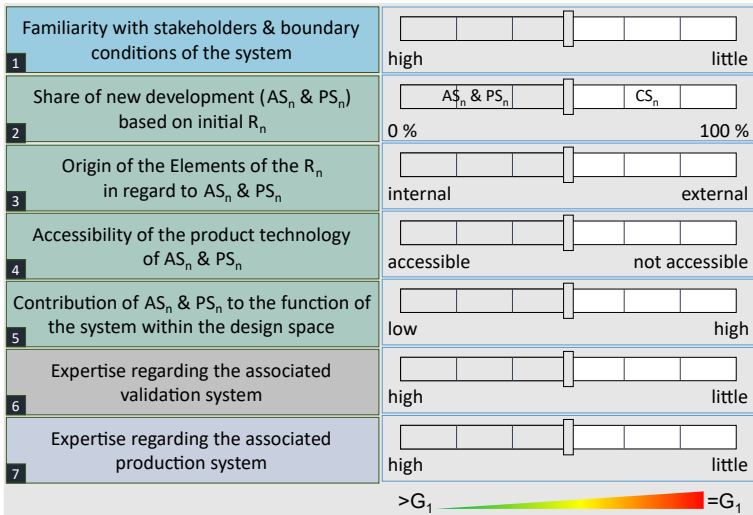


Figure 2.13: Systematics for the Classification of Product Development in regard to their Characteristics of Product Generation 1 translated from Albers, Ebertz et al., 2020

The first indicator is the familiarity with stakeholders and boundary conditions of the system. A low degree of familiarity and awareness with the relevant stakeholders is a characteristic for the development of a G1. As a consequence, the maturity of the within the product profile described demand as well as the users, customer and provider benefits is low. Furthermore, the stakeholders include suppliers and employees. Boundary conditions include for example market regulations, legal restrictions and registered patents.

The second criterion represents the scope and degree of novelty (principle and attribute variations) based on the initial reference system. Aligned with the understanding of inventions, a G1 is associated with a high share of attribute and principle variations.

The third and fourth indicators describe the sources of the reference system elements as well as their accessibility. G1 developments are characterized by limited experience of the developing entity with the reference system elements. It is concluded that neither explicit elements of the system of objectives and resource system nor the accompanying knowledge is sufficient if relevant reference system elements originate primarily from external sources (Albers et al.). Accessibility of

reference system elements depends, among other things, on the maturity of the technology.

Within the fifth criteria, the contribution of the varied sub-systems/components to the function of the system is evaluated. For example, major changes to the appearance of the system are likely to have a smaller impact on the functionality than only small changes to the system which realizes the central function of the system. However, for the evaluation of development risks and uncertainties, all variations to the system must be considered as interdependencies between the systems cannot be neglected.

The sixth and seventh criteria reflect the extent of experience with the corresponding validation and production system, describing the experience with methods, tools and structures for system validation and production.

The classification as a G1 at an early stage typically triggers the adaptation of development procedures to address known challenges. The observed effects as well as potential countermeasures to each of the seven indicators are described in detail by Albers, Ebertz et al. (2020). As a countermeasure in the case of a high share of new development, difficult access to technology and limited experience with the validation system, AD or pre-development activities are often initiated.

The fractal concept of the model of SGE – System Generation Engineering by Albers can of course also be applied to the understanding of G1 developments. While the system or subsystem development can be classified as a G1, the supersystem does not necessarily have to be a G1. For example, the development of components such as the electric motor of a vehicle can be described as a G1 development, while the development of the supersystem, in this case the vehicle, is described as the next generation of an existing system.

2.4 System Verification and Validation

According to Albers “the central activity in product engineering is validation” (Albers, 2010). This chapter is devoted to present the understanding, meaning, importance and activities of validation.

2.4.1 Definition and Understanding of Verification and Validation

In product engineering, verification and validation describe two “different stages of ensuring the required system properties” (VDI 2206, 2004).

Verification

“Generally demonstrating the truth of statements. Transferred to technical systems, it is to be understood as meaning checking whether the way in which something is realized (for example a software program) coincides with the specification (in this case with the description of algorithms). When checking the validity of a program, reference is also made in this connection to program verification. The verification is generally realized in a formal manner. In everyday language, verification is the answer to the question: Is a *correct* product being developed?” (VDI 2206, 2004, p. 117)

Verification is thus focused on the formal comparison of the systems properties, behavior and previously defined requirements. “[Verification is] providing objective evidence, that the system, software, or hardware and its associated products [are] conform to requirements [...]. [Furthermore,] verification of interim work products is essential for proper understanding and assessment of the [...] product(s).” (IEEE Std 1012-2016, p. 26)

Validation

“Originally checking the validity of a measuring method in empirical social research, i.e. the extent to which test results actually register what is intended to be determined by the test. Transferred to technical systems, it is to be understood as meaning testing whether the product is suitable for its intended purpose or achieves the desired value. The expectations of the technical expert and the user come into the equation here. Validation comprises, for example, checking whether the description of an algorithm coincides with the problem to be solved. It generally does not have to be carried out in a formal manner. In everyday language, validation is the answer to the question: is the *right* product being developed?” (VDI 2206, 2004, p. 117).

Accordingly, validation includes the activities of evaluation, objectification and verification. The criteria or requirements used for verification must be extracted from (often subjective) needs or demands and then must be continuously evaluated regarding their suitability. A main challenge of validation is to provide evidence that

the system satisfies the intended use and the users' needs (IEEE Std 1012-2016, p. 26).

According to Albers (2010, p. 5) “[...] only in validation knowledge evolves [...]”. In regard to the ZHO-model (Chapter 2.2.3) validation is the continuous comparison and evaluation of the designed (synthesized) systems (O) and elaborated (modeled) objectives (Z) through the operation system (H). That the developed system meets the objectives or moreover the demands and needs can only be assured by continuous validation.

2.4.2 The Pull Principle of Validation

Validation is often assigned to the final phase of the development process. In accordance with the V-model, validation activities are “pushed” with the availability of models and prototypes. With the so-called “push-principle” of validation the methods, tools and test set-ups are defined subsequent to the system's design. Thereby, these “secondary” development activities are associated with considerable effort and are carried out only after the design of the models and prototypes. Furthermore, the developed models are prone to miss their intended usage as the validation activities are only conducted after their development.

With Albers, Matros et al.'s (2015) “pull-principle” of validation, a different model of integrating validation activities in the product development process is proposed. According to the “pull-principle”, knowledge gaps initiate validation activities and thus, further activities are demanded (“pulled”) due to the need for validation. These “pulls” include the design and development of the needed systems (“primary” activities). That is why the SiD is designed simultaneously to the development of its validation environment. Moreover, a sequential, iterative validation is realized instead of a final validation only after the development of the models or prototypes. Based on the identified knowledge gaps, specific objectives for the validation activities are derived. The therefore relevant system elements can be identified, or their development triggered. These elements include both necessary systems of the SiD as well as the required systems for the validation, such as experimental setups. Hence, by focusing the development on only the required elements of the test set-ups which are relevant to achieve the specific objectives, effectiveness and efficiency are increased. The artefacts which are generated by validation activities are always associated with specific knowledge gaps. As a result, the development process is coordinated by and centered around the knowledge generating activity – validation. (Albers, Matros et al., 2015)

2.4.3 Approaches Towards Effective Validation of Mechatronic Systems

Since the 1990s, the computational support of designers by simulations and tools has rapidly grown and is nowadays widely established (Banks, 1998; Eigner et al., 2014). At the same time, the verification of product properties and functions is still highly dependent on physical prototypes. In general, a differentiation between the verification of single sub-systems or components and the entire system or product is common (VDI 2206, 2004, p. 39). As the entire physical system is only available towards the end of the development process, system verification is likely to be postponed until that stage.

With Thomke and Fujimotos (2000) introduction of the **frontloading**-concept, the idea of continuous verification and validation by “digital mock-ups” emerged. To increase the development performance, they propose to shift investigations to identify and solve problems from the end of the development to earlier phases (e.g., before the existence of physical prototypes). The aim of frontloading is to avoid costly redesigns and delays toward the end of the development process. Frontloading ideally results in reduced costs and a shorter time-to-market. (Lee et al., 2018; Thomke & Fujimoto, 2000)

Therefore, simulation and modeling tools are needed. With the aid of models and simulations, engineers can analyze the system’s properties, functions and behavior before physical prototypes are available. The concept of virtual prototyping aims to create a digital representation or simulation of the system which is to be developed. Thus, virtual prototyping provides a holistic view of the system and is used for the evaluation of different design alternatives. The success of the systems verification and validation based on these virtual models is dependent on the validity of the models¹⁸ itself. The development of complex systems often involves multiple disciplines such as design, software and hardware. Within these interdisciplinary teams, multiple models and simulation tools are created and used to consider discipline-specific views. Despite increasing computational power, multi-physics and comprehensive system simulations are often limited to higher levels of abstraction. Furthermore, the prediction and modeling of interferences and interdependencies between the sub-systems is often exceeding not only the scope of such simulations but also the scope of developers knowledge. (Jensen et al., 2016; VDI 2206, 2004)

¹⁸ See Chapter 2.4.5

To address these problems, numerous testing techniques exist which incorporate the usage of simulations, models, prototypes or system mock-ups but differ in scope and the level of abstraction compared to virtual prototyping. For example, Model-in-the-Loop (MiL), Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL) are common approaches which were mainly designed for the development of embedded systems and are now widely used in the field of product development.

The **Model-in-the-Loop (MiL)** approach describes a purely virtual test configuration where both the developed system and the environment are simulated. Thereby, the systems functionalities and behavior can be analyzed simultaneously to the design phase. MiL allows to evaluate different variants or designs at an early stage and thus can aid to avoid costly design changes in the later development phases. However, these MiL evaluations highly depend on the model's quality. With Stachowiak's (1973) understanding of models¹⁹ it becomes obvious that models are rarely able to consider all aspects simultaneously. In automotive development projects functional models as well as implementation models exist (Bringmann & Krämer, 2008). Functional models are meant to describe, understand and evaluate the systems physical behavior on a system level. These models are transformed into implementation models during the development process which are designed to meet the requirements (Bringmann & Krämer, 2008). (Schäuffele & Zurawka, 2016)

The **Software-in-the-Loop (SiL)** approach is, as the name suggests, a software specific testing approach where the software is again executed in a virtual test configuration. With the SiL approach the software code which will run on the target hardware is executed on an emulated hardware. SiL often follows MiL testing to identify potential errors due to the code implementation on the target hardware. Even though real-time capability of SiL is not necessary, the performance of the code on the target hardware can be evaluated. (Bringmann & Krämer, 2008; Oshana & Kraeling, 2013; Schäuffele & Zurawka, 2016)

The **Hardware-in-the-Loop (HiL)** approach describes the integration of physical (hardware) systems into a virtual environment. Using (analog and digital) sensors and actuators the interactions of the systems with its environment are modelled. This closed-loop interaction between the system and its environment facilitates the assessment of the system's input and outputs on both communication and power level. Furthermore, a differentiation between Signal Hardware-in-the-Loop (SHiL) and Power Hardware-in-the-Loop (PHiL) configurations are common (Faruque et

¹⁹ See Chapter 2.1.2

al., 2015). On SHiL level, the exchange between the system and its environment is limited to the exchange of signals without significant power transfer. These setups are typically used for the initial test of ECUs. The main target is the investigation of the corresponding reaction of the ECU (output signals) to the emulated feedback signals from the system's environment (input signals). On PHiL level, the interactions of the SiD with its adjacent systems are not only limited to signals but also include the exchange of power. In addition to the adjacent systems, power sources or sinks are needed to generate or absorb the SiD's power. In this case, the power sources and/or sinks act as Koppelsystems²⁰. (Bringmann & Krämer, 2008; Faruque et al., 2015)

2.4.4 IPEK-X-in-the-Loop Approach

The **IPEK-X-in-the-Loop (XiL) approach** according to Albers et al. (2008) describes the fundamental concept in the validation of subsystems to integrate the subsystem into the overall system and its environment (Albers, Behrendt et al., 2016). The "X" is defined as the system which is the center of the validation activities. All interacting systems of "X" are described as **Connected Systems (CS)**. With the IPEK-X-in-the-Loop Framework Albers, Behrendt et al. (2016) integrate both the representation of different system characteristics (virtual or physical) of "X" and the CS as well as the consideration of all system levels. Thereby, continuous prototyping is supported and the importance of physical or mixed virtual-physical prototypes is emphasized. The underlying concept thus enables continuous validation starting from the very beginning of the development process.

In Figure 2.14 multiple dimensions and system levels are schematically displayed for the example of an automotive system.

²⁰ See Chapter 2.4.4

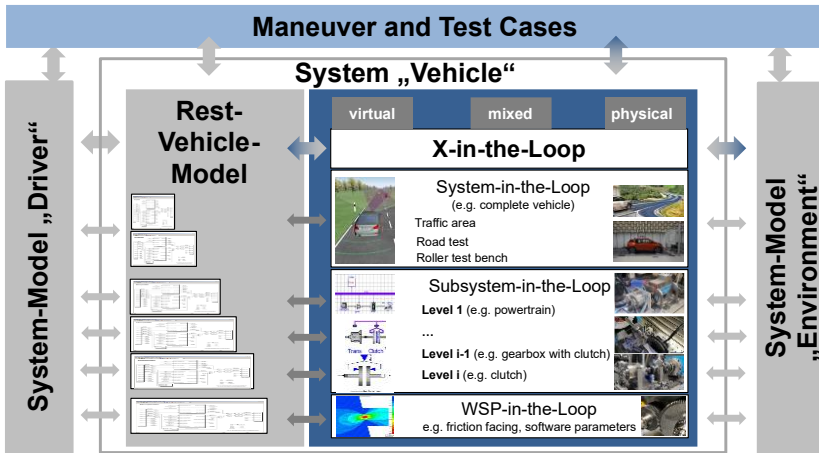


Figure 2.14: IPEK-X-in-the-Loop-Framework according to Albers, Behrendt et al., 2016

The scope of the investigated system is defined by the objective of the validation activities. In most cases, X is the same as the (sub-)system for which the developer is responsible and which properties and functions are meant to be verified. In this case, the X is called the **System-in-Development (SiD)**. As displayed in Figure 2.14, the scope of “X” can vary from a single working-surface-pair to an entire vehicle. When the objective of the validation activities is more focused on knowledge generation with respect to a (sub-)system, “X” is called System-under-Investigation. The System-under-Investigation can be part of the SiD or represent any of the CS. (Albers, Behrendt et al., 2016)

Besides the scope of the system the framework allows to model both the SiD (or Sul) and the CS in any form, be it virtual, mixed virtual-physical or physical. To overcome potential incompatibilities between the different systems, **Koppelsystems (KS)** are added. The KS are supposed to be designed in such a way that they do not add any model behavior relevant to the validation activity, but merely enable and support the desired systemic behavior of the models involved (Albers, Pinner et al., 2016; Yan, 2020). Within the IPEK-XiL Framework three types of Koppelsystems are considered: virtual-virtual, physical-physical and virtual-physical. To negate undesired behavior of the KS, KS itself may include additional

models which are specifically designed to compensate the undesired system influences.

The presented XiL approach integrates the validation of the different system levels²¹ as well as the validation approaches (MiL, SiL, HiL) which allows a holistic description of the validation activities. The specific design of different interacting models (including SiD, CS and KS) addressing a validation objective²² is described as Validation Configuration or **Test Configuration (TC)**. For the planning, execution and analysis of validation activities the architecture of TCs can be illustrated as displayed in Figure 2.15.

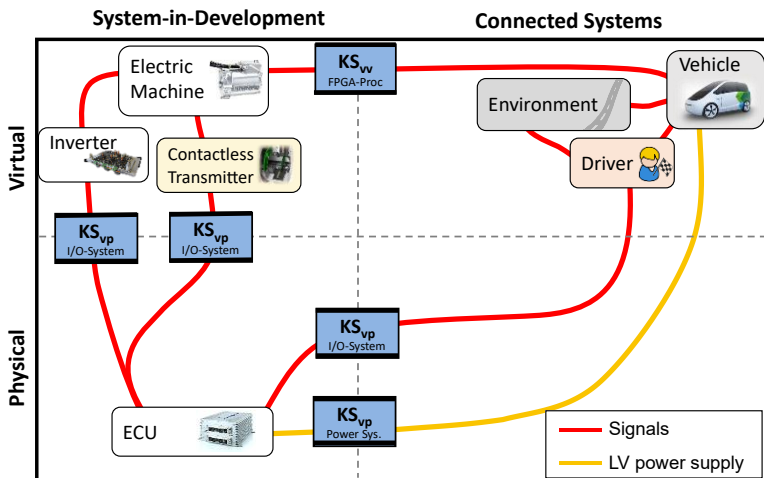


Figure 2.15: Architecture of a Representative Test Configuration at the Advance Development Department of MAHLE (Kürten et al., 2022)

In general, the shown scheme allows to distinguish between systems of the SiD and CS as well as between virtual and physical forms. In the displayed example, the SiD, an ETDS, is split into a physical ECU and virtual models of the inverter, traction motor and contactless transmitter. In this case, all connected systems are emulated.

²¹ See Chapter 2.2.6

²² See Chapter 5.1.1

Several KS are implanted to connect the systems and to overcome incompatibilities between these systems. For example, the KS between the physical ECU and the virtual inverter includes digital input output (I/O) converters.

Every TC is specifically designed to meet the requirements of the defined validation objective. The sum of all elements, models, processes and methods at a certain degree of the products maturity can be described as the **validation environment** (Albers, Mandel et al., 2018).

2.4.5 Modeling, Verification and Validation of Simulation Models

An extensive industry study by Gausemeier et al. (2013, 39) has shown that a key challenge in using virtual or mixed virtual-physical TCs is the lack of the stakeholders confidence in the simulation results. This confidence in simulations and models is also referred to as model validity, -maturity, -quality, -accuracy or **-credibility**. Although many validation theories for simulation models exist (Durst et al., 2017; Sargent & Balci, 2017), the assessment of modeling uncertainties is often based on the modelers experience (Yan et al., 2018). The objective evaluation of models is an additional activity during the development and validation of the system which is represented by these models. Figure 2.16 displays the general modeling process according to Schlesinger et al. (1979) and Sargent (2010).

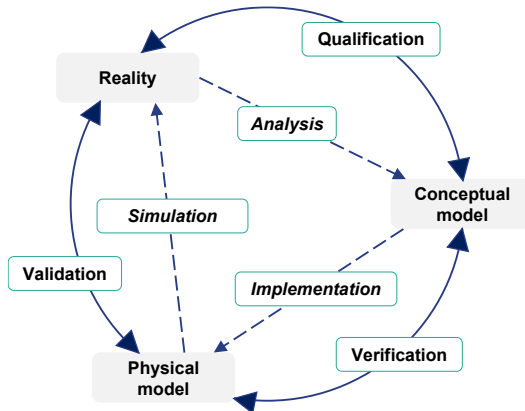


Figure 2.16: General Modeling Process adapted from Schlesinger et al. (1979) and Sargent (2010)

With the specific analysis about the system in reality, a conceptual model is derived. The properties, functions and behavior of the system in reality are often described by requirements. The conceptual model is a description of the reality and thus, consists of illustrations and of laws of nature or mathematical equations (Klemmer et al., 2011; Schlesinger et al., 1979). The qualification of the conceptual model describes the definition and refinement of the model's application purpose as well as the evaluation of its adequacy regarding the domain of application (Sargent, 2010; Schlesinger et al., 1979).

Based on the conceptual model, the modeling approach can be chosen and subsequently a computational model can be implemented (Murray-Smith, 2015). With the introduction of abstract modeling languages like MATLAB / Simulink, the boundaries between the conceptual model and the computerized one are blurring (Klemmer et al., 2011). The computational models are verified regarding their representation of the conceptual model (Sargent, 2010). With the execution of the computational model, the reality is simulated. To validate the simulation results, observations or measurements of the system in reality are necessary (Sargent, 2010). The modeling and validation of models is a continuous, iterative process (Oberkamp et al., 2004).

For utilization of models within the process of validation of the SiD, the models' accuracy must be determined to establish credibility (Danquah et al., 2020; Oberkamp et al., 2004) and to avoid an overrating of the models' ability (Lindemann, 2009, p. 11). Many approaches and methods that support the evaluation of models exist. However, "no theory has been agreed upon to date for how V&V of simulation environments should be performed" (Durst et al., 2017, 2). Many approaches and methods (e.g.: Dona and Ciuffo (2022); Murray-Smith (2015); Sargent (2010); Viehof (2017)) are based on Carson's (2002) "Model Verification and Validation" approach, which is explained in detail.

Carson's Framework for verification and validation consists of three activities (Carson, 2002, p. 56):

1. Testing face validity
2. Testing input parameter variations
3. Comparing model predictions and past performance of the actual system

In the early stages of the modeling process, often real systems to compare the model to are not available yet. Testing face validity means examining the model's behavior and output measures of performance for given scenarios (Carson, 2002). The extend of the face validity check is always limited to the tester's understanding

of the real system (Murray-Smith, 2015, 95 ff.). Evaluating the model's behavior over the widest range of expected input parameter variations provides insight over the boundaries and limits of the models. Outliers or significant changes can be indicators for model's uncertainties. These kinds of tests are also known as parameter sensitivity analysis. With the availability of the actual system in reality, the comparison of model predictions and the measured performance/behavior of the actual systems are enabled. Conventional validation methods promote a binary understanding of model validity. Either the model is able to accurately represent the physical origin, or it fails to do so (Easterling, 2001). However, with the model complexity in present use cases the distinction of the uncertainty within the intended use should be aspired (Oberkampf et al., 2004; Sankararaman & Mahadevan, 2015). Carson proposes repeating all available measurements within the computational model and using statistical measures to evaluate the model's ability to represent the actual system. In the field of automotive simulation models, for example Klemmer et al. (2011), Murray-Smith (2015), Viehof (2017), Danquah et al. (2020), Dona et al. (2022) follow the idea of the detailed statistical evaluation of the models accuracy.

2.4.6 Model Consistency and Continuousness

Due to the models' flexibility, in many applications, the initial modeling purpose is adjusted or extended. Moreover, models are continuously refined based on new findings regarding the system in reality. Two key challenges for the development of complex systems within interdisciplinary teams are modeling continuousness and consistency. Consistency is referred as the quality that all models, which represent the same system from different viewpoints or with different granularity, "do not contain any contradictions" (Albers & Lohmeyer, 2012, p. 412). Continuousness can be subdivided into horizontal continuousness which means that models can be used in different TCs throughout the product life cycle and vertical continuousness which addresses the continuousness of models independent from the level of abstraction or granularity (Albers et al., 2012; Albers & Lohmeyer, 2012; Lohmeyer, 2013). The understanding and challenges of consistency in the view-based development of CPS is the subject of the collaborative research center 1608 – "Convide"²³.

²³ CRC/SFB 1608 – Convide: <https://www.sfb1608.kit.edu/index.php>

2.4.7 Finding Suitable Test Configurations

The use of virtual and mixed physical-virtual TCs increases the flexibility of validation activities. However, the definition and design of a suitable TC must be carried out individually and regularly for each validation objective during the development process (Albers, Behrendt et al., 2016). Paulweber and Lebert (2014) specify the following criteria for choosing suitable components for the design of TCs: cost, reproducibility, accuracy and flexibility. The schematic of Yan et al.'s (2018) systematic approach for the assessment and selection of suiting TCs is displayed in Figure 2.17.

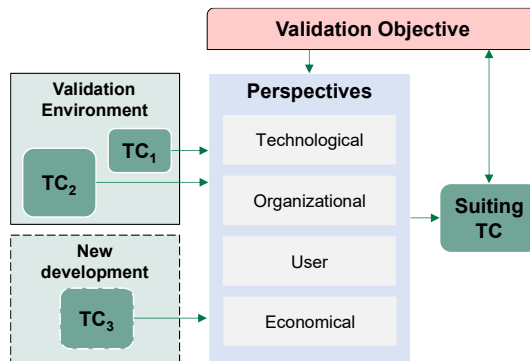


Figure 2.17: Assessment and Selection of Suiting Test Configurations adapted from Yan et al. (2018)

Based on the validation objective, the different perspectives and criteria can be used to evaluate and select a suiting TC. Thereby, existing TCs can be reused, adapted or entirely redesigned to match the requirements which are derived by the validation objective. In a first step, necessary constraints are regarded to narrow down the selection process. Subsequently, further, rather soft, criteria are considered. To support the selection process, the following four perspectives can be used (Yan et al., 2018):

- Economical perspective: Includes, among other things, the cost for development, procurement, commissioning, maintenance, and operation of the regarded TC.
- User perspective: Describes the usability during operation as well as the necessary system knowledge regarding the SiD as well as the CS and KS.

- Organizational perspective: Covers the time for modeling, transportation or commissioning. Furthermore, reusability, flexibility and strategic orientations can be considered.
- Technological perspective: Takes in the technological readiness level, reproducibility, safety for people and systems as well as dynamics of systemic interactions.

The presented approach addresses the systematic identification and documentation of knowledge regarding the validation environment. Thus, transparency and traceability of decisions regarding the selection of TCs are increased. To support this documentation of knowledge regarding the systematic assessment of TCs, Mandel et al. (2020) propose to use MBSE. Thereby, connecting the experience and knowledge of existing TCs with the present validation objective. As a result, reuse and further development of existing TCs for the usage in subsequent development phases is facilitated.

3 Research Objective and Research Approach

3.1 Motivation

The development of complex mechatronic systems or CPS is usually subdivided into multiple domains and often distributed among multiple companies. Furthermore, the integration of software and hardware subsystems into a mechatronic system is often accompanied by challenges (Bellalouna, 2009). The integration of all subsystems into a fully functional physical product is usually the responsibility of the company that introduces the product to the market. However, all development partners, especially these developing subsystems, need to consider system interfaces and interactions between systems for the validation of their SiD (Albers et al., 2014). Consequently, for the development of new systems different validation strategies are utilized. In the automotive industry physical demonstrators such as concept cars allow comprehensive testing under close to operational conditions. However, the built-up of physical demonstrators is cost extensive and time consuming or otherwise these demonstrators might lack technological maturity and complexity. Thus, model-based development and validation approaches are utilized to consider interdependencies between the subsystems starting from the beginning of the development process. Shortening the development cycles of mechatronic systems is often seen as a key factor for product/companies' success (Hundertmark, 2013, p. 204; Lindemann, 2009; Wahren, 2004, 235 ff.). Therefore, the shift of validation activities towards earlier development phases is pursued¹. Consequently, virtual or mixed virtual-physical TCs are utilized extensively (Albers, Behrendt et al., 2016; Albers & Düser, 2009). However, when seeking development decisions, physical prototypes are mainly seen as the only source for trustworthy results (Gausemeier et al., 2013, 39; Hilt, Wagner, Ordnung et al., 2016, p. 1501).

Compiling and identifying a suitable validation environment for the concurrent validation needs is a complex procedure. Based on a specific validation objective, different perspectives must be considered. Organizational, user and economical perspectives can be evaluated objectively by the available resources in time,

¹ See Chapter 2.4.2

personnel and funds (Yan et al., 2018). However, the evaluation of the technical perspective is rather challenging and associated with uncertainties. Especially in the AD phase, where systems and TCs are often initially built up, technical uncertainties regarding both the SiD and the TCs are high. Newly developed TCs are subject to different uncertainties regarding the technical behavior. In particular, interactions between virtual and physical subsystems might be affected by the TC itself. Uncertainties regarding the effects of model reductions on the systems' interaction are difficult to foresee for newly developed systems. In addition, incompatibilities between inputs and outputs of different models must be met by Koppelsystems to enable the exchange of information (Albers, Pinner et al., 2016). Besides possibly known properties of the Koppelsystems itself, which can be ideally compensated, undesired or non-neglectable influence on the system's behavior must be investigated.

To address the stakeholder's tendency to rely on physical prototypes, these uncertainties need to be evaluated transparently and objectively. Thus, the continuous comparison and identification of deviations between the system's behavior within its application environment and within the build-up TCs must be carried out. Thereby, needed measures to improve the TCs suitability can be derived and the credibility of these can be increased. The scope of the necessary evaluation also depends on the Technology Readiness Level (TRL)² of the SiD. For example, in early phases of the development, higher uncertainties and some model limitations might be permitted to fulfill the validation need for knowledge generation. However, for qualification and certification, evidence of validity of the used TC is demonstrated by extensive evaluations only. Observations in the industry have shown however, that the evaluations of TCs are often subjective and based on the engineers' experience (Yan, 2020, p. 113). To enable objective and continuous analysis and classifications systematic support needs to be established.

3.2 Research Objective and Methodology

The aim of this thesis is to understand the specific challenges in the utilization of model-based validation approaches in AD and based on this, to develop methodical support that facilitates continuous system validation. Furthermore, the methodical support should facilitate the development of flexible validation environments and

² Defined by European Commission (2013); Mankins (1995)

thus aspires to enhance the efficiency of product validation in the subsequent pre- and series development.

Up to now, no common procedure for the verification and validation of models has been established. In order to make high use of model-based approaches and the virtual or mixed virtual-physical TCs, a common approach for the evaluation of the technical perspective regarding the suitability of TCs in regard to the validation objective needs to be developed. The utilization of X-in-the-Loop approaches increases development speed and efficiency, thus the basis for a flexible validation environment needs to be set within AD and transferred accordingly to pre- and series development. In particular, the contribution of AD to product development should be allocated within the Model of SGE – System Generation Engineering.

In order to achieve this objective, three research questions are elaborated:

- 1) What specific challenges do automotive suppliers face when validating mechatronic systems in Advance Development?
- 2) Which methods enable consistent and traceable validation from idea generation to functional prototypes in Advance Development?
- 3) How can Test Configurations be analyzed and classified systematically in order to identify strengths and misconceptions in the used models?

The procedure for addressing the above research questions is oriented based on the Design Research Methodology (DRM) according to Blessing and Chakrabarti (2009) and the described research methodology by Marxen (2014). In an iterative process, findings from empirical research and experimental studies are used to specify the research objectives and refine the proposed methodology. Accordingly, in Figure 3.1 the structure of the work and its elements are shown.

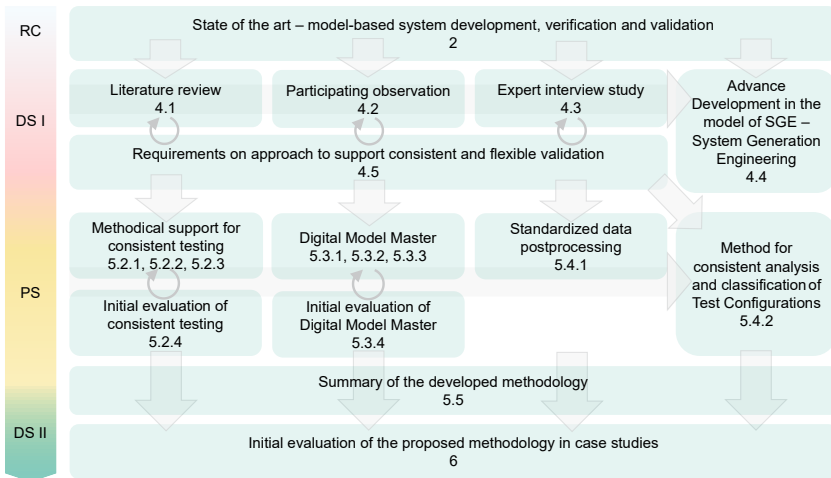


Figure 3.1: Structure of Research based on Design Research Methodology according to Blessing and Chakrabarti (2009) and Marxen (2014)

In the context of the research clarification (RC), the relevant state of the art in research on model-based system development and validation is described in Chapter 2. To further specify the research need and objective, the first research question aims at developing a deepened understanding of the challenges of validation activities in AD. To address this matter, a systematic literature review (Chapter 4.1), participating observations (Chapter 4.2) as well as an interview study (Chapter 4.3) at the AD department of an automotive supplier are conducted. Based on these different research methods, requirements for the needed support (Chapter 4.5) are derived within the Descriptive Study I (DS I). Additionally, the deepened understanding enables the allocation and generalized description of AD within the model of SGE – System Generation Engineering (Chapter 4.4) which facilitate transferability of the understanding and the developed support.

Subsequently, within the Prescriptive Study (PS) a heuristic design support is developed. The approach to support consistent and flexible validation in AD is presented to answer the second research question. To facilitate applicability an overview of the used terminology within this thesis is given in Chapter 5.1. Based on the identified requirement for the methodical support, the developed methodology includes three methods. The methodic support for testing (Chapter 5.2) and the Digital Model Master (Chapter 5.3) are designed to increase traceability and consistency of validation activities. The method for consistent analysis and

classification of TCs (Chapter 5.4), which is based on the developed methods for traceability and consistency, addresses the third research question.

The initial evaluation of the developed support (Descriptive Study II – DS II) is conducted at the AD department of the automotive supplier MAHLE. Several case studies to examine the specific methods (Chapters 5.2.4, 5.3.4) as well as the overall approach (Chapter 6) are performed. The iterative design and evaluation of the proposed methods according to Marxen (2014) is schematically indicated in Figure 3.1.

The intention of the research cooperation between the IPEK and MAHLE is to directly address identified problems at the application of methods and processes within the industry. Consequently, the Prescriptive Study as well as the Descriptive Study II are partially conducted as Action Research. “Action research is an iterative process involving researchers and practitioners acting together on a particular cycle of activities, including problem diagnosis, action intervention, and reflective learning” (Avison et al., 1999, p. 94). By this approach, theoretical methods and processes of the KaSPro³ are combined with the practical applications and problems in the described research environment⁴. The presented methodology is developed and evaluated as described by action research characteristics, by continuous iterations of planning, acting, observing and reflecting. The strengths of action research that should be emphasized are also its greatest weaknesses. The direct link between research and application allows for tailor-made solutions to problems, the transferability of which must, however, be carefully examined. In order to address this risk, the applied approaches should, if possible, have a high degree of carryover variation in regard to existing methods and processes of the KaSPro.

³ “The basic research concept of the IPEK for the development of the KaSPro - Karlsruhe School for Product Development is the parallel research on methods and processes of the PGE - product generation engineering combined with the research for synthesis and validation of new technical systems” IPEK - Institut für Produktentwicklung am Karlsruher Institut für Technologie (KIT) (2020) (<https://www.ipek.kit.edu/english/Institut.php>).

⁴ See Chapter 3.3

3.3 Research Environment

The primary environment for the conducted research is the “Corporate Research and Advanced Engineering” department of the MAHLE International GmbH. Based in Stuttgart, MAHLE is a leading global development partner and supplier to the automotive industry. In 2023 MAHLE employed around 72.000 people and achieved about 12 billion euro in sales. The company’s product portfolio is subdivided into “Electronics and Mechatronics”, “Thermal Management”, “Filtration and Engine Peripherals”, “Engine Systems and Components” and “Service Solutions”. In 11 research and development centers, about 5.700 people are employed. The AD department in Stuttgart is set up to proof concepts for new technologies and products as well as to develop new methods and processes for the worldwide product development. By design, this development path has the tendency to fulfill many of the characteristics of the G1 development according to the model of SGE – System Generation Engineering. An example for the characterization of an AD project as a G1 can be found in (Albers, Ebertz et al., 2020, 12 f.). In terms of processes, the activities of the AD department are located upstream of the predevelopment and its subsequent series development departments. Affected by the transformation within the automotive industry, changes to the structural and strategical organization were observed during the research project. As a reaction to shortening development cycles, the usual timeframe of AD projects was reduced in 2022 and thus proximity to customer demands and series development was strengthened. (MAHLE GmbH, 2022, 2024)

4 Descriptive Study on Development and Validation in Advance Development

To obtain a deeper understanding of the characteristics and challenges of the development and validation in AD, descriptive studies are conducted. In Chapter 4.1 the design and the results of a systematic literature review are presented. In Chapter 4.2 the insights of a participating observation within the AD department of the MAHLE GmbH are outlined. Based on the literature review and the participating observation, interviews with experts of the AD department at MAHLE GmbH were conducted and evaluated (Chapter 4.3).

The results of the investigations are concluded in Chapters 4.4 and 4.5. In order to allow transferability, a generalized description of both the characteristics and challenges in AD are presented. In Chapter 4.4 the characteristics of development paths are analyzed and the interdependencies between these paths and the product development path are described. To sum up the descriptive studies, requirements on methodological support for validation in AD are derived in Chapter 4.5.

4.1 Systematic Literature Review

Scope and depth of literature regarding validation in AD and predevelopment of suppliers in the Business-to-Business (B2B) segment is limited. The existing work is used to deduce and narrow down the challenges of the considered area. Consequently, the systematic literature review is designed to briefly outline concurrent trends within the automotive industry, to highlight challenges of the B2B relationship and its effects on validation activities as well as to explain the challenges of validation within AD projects.

In a first step, a keyword search is carried out to obtain an overview of the existing work within the research area and to derive suitable search terms (see Appendix A). In the second step, the systematized search terms are used for searches and review according to the top-down method. To limit search results, time restrictions and Boolean operators are used. After the initial screening, relevant literature is selected by cross-reading.

4.1.1 Concurrent Trends within the Automotive Industry

The research period is characterized by economic uncertainties. Based on the contemporary political decisions regarding environmental and climate protection (PE/66/2022/REV/1, 2023; Paris Agreement, 2016), the transformation of the automotive industry is accelerated (Dijk et al., 2016; Fleming et al., 2019; Simonazzi et al., 2022). Also, the global Covid-19 pandemic as well as the Russian war of aggression on Ukraine destabilize the international markets (Bardt, 2020; Coffman et al., 2023; Mans, 2022). Moreover, global supply chains experience major disruptions (Grundmann et al., 2020). As a result, long lasting trends regarding transnational operations and production strategies are questioned and examined in the new context (Proff et al., 2021). Especially the European automotive sector is affected. For example, electricity costs, which account for a significant proportion of production costs, are significantly higher in Europe than in the United States and China (Cornet et al., 2023).

On a technological level, four central trends have been identified: e-mobility/alternative powertrains, autonomous driving, connected cars and shared mobility (Grundmann et al., 2020). At the core of these trends are the further increasing demand for individual mobility and the desire for technological solutions to reduce greenhouse gas emissions. With the introduction of new technologies like battery electric or fuel-cell electric vehicles and new business models, the existing hierarchies in the automotive industry are restructured.

4.1.2 Challenges Regarding Business-to-Business

As a result, two opposing tendencies to changes of the value generation chain can be observed. Over many years, Original Equipment Manufacturers (OEM) have shifted their focus on the customer relationship, transferring more and more of the development of technical subsystems to suppliers (Flik et al., 1998; Grienitz et al., 2013; Krcal, 2008; Pfäfflin et al., 2019; Sturgeon et al., 2008). However, with the comparatively lower design complexity of ETDS compared to combustion drive systems, a reverse trend can be observed (Fleming et al., 2019; Proff et al., 2021; Robinet, 2022).

Regardless of the distribution of the shares in the value chain, there is a mutual interdependence between the OEMs and the suppliers (Voß, 2008). The market behavior as well as strategic decisions affect all development parties. For example, the OEMs pursued two main strategies to overcome the decline in sales during the 2008 financial crisis: shortening the period until market introduction and increasing diversity of product variants. These changes by the OEM are automatically

propagated to the suppliers. To meet the approaches of modular development platforms by the OEMs, suppliers need to increase the flexibility and modularity of their products as well. Furthermore, OEMs and suppliers are seeking closer cooperation to improve development speed. (Gierl & Gehrke, 2004; Hundertmark, 2013)

Ongoing globalization is putting immense cost pressure on the automotive supply industry. As a result, several strategies for the cooperation between the OEMs and suppliers can be observed. Besides process-, niche or value-/reputation-based strategies, innovation and cost leadership strategies are widely spread (Gierl & Gehrke, 2004, 212 ff.; Hundertmark, 2013, 201 ff.). In the case of the cost leadership strategy, suppliers achieve economies of scales by catering the same or similar variants of the product to multiple OEMs. A prerequisite for cost leadership is a high degree of flexibility with regard to development and production in order to be able to meet the differing requirements of the OEMs. In the case of innovation leadership, suppliers have to make high upfront development investments in order to attract customers. Additionally, the ability to quickly modify the presented prototype to the customers' requirements is essential for the role of the innovation leadership (Allmann et al., 2006).

4.1.3 Challenges Regarding Advance Development

The objectives of AD or predevelopment activities differ greatly from those within series development (Murphy & Kumar, 1996). As described in Chapter 4.4, AD projects are initiated based on the brief description of a problem space and the identified beneficiaries of a possible technical solution. A direct link to a specific product is not yet drawn (Albers, Kürten et al., 2022; Taguchi & Cariapa, 1993). The organizational independence from the series development offers a high degree of freedom regarding the development. In general, the systems in development of AD projects are most often described as novelties. Based on the model of SGE – System Generation Engineering, all systems are based on references. Moreover, parallels between the activities in the AD and the characteristics of a G1 can be drawn. Figure 2.13 shows the indicators that describe G1 identified by Albers, Ebertz et al. (2020). These characteristics are used to structure the results of the literature research regarding the challenges in AD.

While the objectives of AD projects are to demonstrate the technical functionality, most often by the help of prototypes (Stapel et al., 2009), and to evaluate the financial viability, the objectives and requirements of the system in development are not sufficiently defined yet. Entities try to increase their acquaintance with the stakeholders and business conditions (1). The identification of stakeholders as well

as the evaluation of their requirements present a central challenge in AD projects (Allmann, 2007; Richter et al., 2019b; Stapel et al., 2009, p. 142). Furthermore, Richter et al. (2019a) state that these projects are characterized by “at least partly unknown and frequently changing objectives and interfaces of the system in development” (Richter et al., 2019a, p. 419). These uncertainties are both a result of the unfamiliarity with the stakeholders and the high shares of new development (as in AV and PV) (2). In addition, attribute and principle variations are accompanied by concept changes within the development phase. As a result to the, comparatively to series development, low degree of rigidity and maturity of the modelled stakeholders, objectives and requirements at the AD, frequent changes occur (Hilt, Wagner, Osterlehner et al., 2016; Klappert, Schuh, Möller et al., 2011; Richter et al., 2019a).

With the idea of extending the existing product portfolio, AD departments face the challenge that the origin of reference system elements are often external (3). The transfer of knowledge to the developing entity faces several hurdles (4). To start off, a general opposition regarding unknown technologies or innovation in most companies cannot be denied. Or as Schumpeter (1912, p. 108) identified, even “the most up-to-date firm has a persistent resistance to change”. If the technology to be used has not yet been widely applied but is mainly discussed within research projects, the accessibility for companies is limited. Especially when the research findings are limited to research papers, the reproducibility and application in an industrial context is challenging (Kempf et al., 2022). Another hurdle is posed by legal issues. For example, patents on the considered technology/application have to be identified and the company's own development must be adapted accordingly (Hauschildt, 1999; Hilt, Wagner, Ordnung et al., 2016).

According to Albers, Ebertz et al. (2020) a G1 is also characterized by comparatively low experiences with the validation (6) and production system (7) of the SiD. However, the production technology and moreover an efficient production of the system is a key success factor for companies (Albers, Lanza et al., 2022; Schröder, 2010, p. 162). Hilt, Wagner, Ordnung et al. (2016, p. 1499) conclude that new “technologies fail mainly before the first sample”. However, extended time resources for AD projects don't guarantee success (Hilt, Wagner, Ordnung et al., 2016). The importance of early customer integration and early system validation is stressed by Albers et al. (2014). Consequently, the design and development of the system, its validation environment and the production system are needed simultaneously.

4.1.4 Conclusion of Literature Review

To foster innovations, companies support the integration of external expertise (e.g., from research organizations) by establishing separate research and development departments. The literature review has shown that the common obstacles companies are facing when striving for innovations can be classified into four groups (Cooper, 1988; Hilt, Wagner, Ordnung et al., 2016; Murphy & Kumar, 1996):

- 1) **Technological:** When striving for innovations, new technological solutions are often aspired. The proof for technical feasibility is one of the main challenges. The uncertainty can be assessed with the help of the model of SGE – System Generation Engineering. The uncertainty regarding the technical feasibility increases with the share of new development (AV & PV).
- 2) **Market:** AD projects are initialized based on certain challenges or problems within the society. Such projects strive for technical solutions which address these challenges. However, there is a high uncertainty whether the proposed solution meets a widespread demand. Often, missing or insufficient demand hinder the success.
- 3) **Economical:** The extension of the existing product portfolio is accompanied by high costs. Besides the development of the system itself, production and market costs must be considered, as well.
- 4) **Juridical:** In globalized markets, development speed is essential for success. As every system is based on references, ambiguous patent situations must be clarified.

Based on these challenges, Hilt, Wagner, Ordnung et al. (2016) derived three key factors for the success of these developments:

- 1) **Communication between Advance Development and series development:** The development and integration of new systems into a company's product portfolio is a joint effort. A common understanding of the objectives and requirements as well as the technical solution are essential for success. However, insufficient time and overload of developers often lead to insufficient documentation.
- 2) **Transparency about risks and uncertainties:** In the early phase of system development, changes happen. The common awareness of rigidity and maturity of objectives as well as the developed systems are crucial for success.
- 3) **Physical Prototypes:** Tests with physical prototypes are very important for risk reduction and for the conviction of stakeholders. Simulations and mixed virtual-physical setups are used to provide the needed flexibility. However, the credibility of these virtual approaches highly depends on their evaluation based on physical prototypes.

4.2 Participating Observation at the Advance Development Department of MAHLE

With the start of the research project in April 2019 the author conducted a participating observation in the “Corporate Research and Advanced Engineering” department of the MAHLE group. The observation continued for about one and a half years. It therefore includes observations from both solely on-site development activities and hybrid working forms after the start of the Covid-19 pandemic. The observations can mainly be divided into two phases. Especially in the beginning of the observations, unstructured and explorative conversations with engineers within and outside the department were conducted to build up a general understanding of the challenges. Problems and discussions within the development projects were documented using key words and parallels between the different projects were analyzed. After extensive exchange with the developers and having developed a general overview, the author participated in various validation activities. The results of these observations are divided into the analysis of the AD process and the investigation of the model-based validation approach.

4.2.1 Observations Regarding the Advance Development Process

As a supplier within a B2B relationship, the systems which are developed can also be described as subsystems of a supersystem or as systems which are part of a system-of-systems (ISO/IEC 21839:2019). As a consequence, the SiD is subject to both stakeholder needs within and outside of the developing entity. To understand the challenges which are specific for the very early development phases of an automotive supplier, the AD process is investigated in detail. In Figure 4.1 the influences of the interactions between supplier and customer on the AD process are schematically visualized.

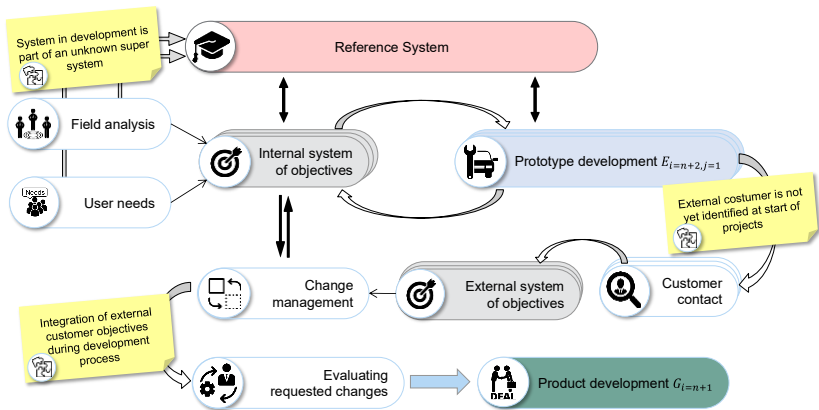


Figure 4.1: Simplified Visualization of the Observed Challenges within the Development Process in the Advance Development Department of MAHLE

The interactions between supplier and manufacturer can be described as follows: Based on the field analysis and the identified user needs, an initial system of objectives is generated. According to the model of SGE – System Generation Engineering, the system of objectives is thereby based on a reference system. The product profile¹ can be used to express the innovation’s potential. As part of the participating observation, the author used the product profile scheme (alike Figure 2.6) to model and visualize the internal system of objectives. Moreover, several peculiarities were observed in the AD process of the automotive supplier.

Firstly, the system of objectives does not yet include comprehensive business plans for the commercialization of the developed system. In scope are the identification and validation of a number of benefits as well as the ideation and technical implementation. Secondly, potential customers aren’t part of the development projects from the beginning. In order to generate a competitive advantage within the industry, customers are only contacted after the conception and production of first prototypes. In terms of the Model of SGE – System Generation Engineering, these initial ($j = 1$) prototypes are Engineering Generations ($E_{i,j}$) which contribute to the development of a new generation which are either subsequent ($i = n + 2$) to the

¹ See Chapter 2.2.4

generation which is currently in development and will be introduced to the market next ($i = n + 1$) or, less common, lead to the introduction of an entirely new generation ($G1$)². Moreover, the attraction of the customer to potential products increases significantly with the existence of physical prototypes. The attraction of potential customers initiates a new development sequence. Customers' interests are linked to new (external) systems of objectives which generally differ from the internal system of objectives of the supplier. Thus, the goal of negotiations is starting to find common objectives. The supplier needs to evaluate the risks associated with the requested changes by the customer. Only if both partners (supplier and customer) agree on a common system of objectives, joint developments are initiated. Furthermore, the observations have shown that customers are highly tentative to start joint predevelopment projects without the existence of physical prototypes which match most of the customers' demands.

4.2.2 Findings Regarding Advance Development Process

As a supplier within a B2B relationship, the system in development is thereby part of a yet unknown supersystem. Consequently, the identification and modelling of different stakeholders is essential to ensure that the SiD addresses multiple and often conflicting requirements. These models of potential users and customers serve as a foundation for structured verification and validation activities. In Figure 4.2 the immediate connections between the developed system of the automotive supplier and the customers as well as the users are illustrated.

² See Chapter 2.3

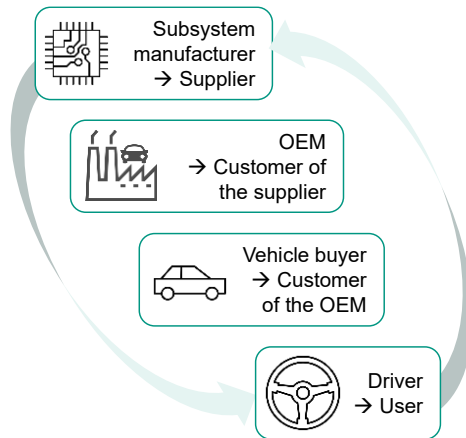


Figure 4.2: Modelling of Customers and Users in the Role of the Automotive Supplier

For a subsystem of a vehicle, the proximate customers are OEMs or other suppliers, which integrate these subsystems into their system. The customers of OEMs are the vehicle buyers, who may be for example private individuals, companies or public institutions. The users of the developed vehicles are drivers and passengers. Besides these immediate connections, further external stakeholders like regulatory entities or internal stakeholders like aftermarket or series development can be identified and modelled to further specify the supplier's, customer's and user's benefits³.

The models of potential customers are subject to the general model properties⁴ and thus do not cover all customers' perspectives. In order to validate the SiD and convince potential customers, it is necessary to create an application-oriented representation of the customer. For the purpose of the system validation, ideally the SiD is integrated into an existing physical supersystem to evaluate the anticipated user, customer and supplier benefits. In the example of the automotive supplier, the integration of the developed system into an existing car or concept car can serve as

³ See Chapter 2.2.4

⁴ See Chapter 2.1.2, Stachowiak (1973)

the basis for an application-oriented verification. However, the usage of existing physical supersystems is accompanied by two major drawbacks. A high investment in resources to acquire and modify such physical supersystems is needed. In addition, the SiD is specified and often optimized for the selected supersystem only. Thus, the flexibility to address multiple different customers might be neglected. Thus, virtual customer models are utilized. These models are based on the analysis of multiple relevant physical supersystems and thereby represent a synthesized model of different customers.

Customer models in the context of automotive system development can be constructed to either encompass generalized requirements such as the smallest common installation space across all customer supersystems or to address specific needs of individual customers, potentially excluding others. The selection and structuring of such models by the supplier is a critical component of the validation process, as each requirement, whether generic or customer-specific, must be systematically evaluated for its impact on system design.

A central objective in AD is the comparative assessment of alternative design solutions. The internal customer, typically the predevelopment department, often mandates the exploration of conflicting requirements to guide strategic decision-making. For instance, an eTDS may be conceptualized with a focus on maximizing performance, potentially at the expense of cost efficiency, or conversely, optimized for cost while accepting trade-offs in performance. These divergent design directions underscore the necessity of traceable customer models to support continuous validation and ensure alignment with both technical feasibility and stakeholder expectations.

Verification and validation activities allow iterative feedback loops of both the customer model as well as the utilized simulation models. The IPEK-X-in-the-Loop approach enables the investigation of the SiD's behavior and its interconnections with the environment, surrounding systems, supersystem and user. These setups including virtual customer models enable the systematic evaluation of customer requests, supporting refinement, rejection or derivation of system requirements (Albers et al., 2014). In addition, gaps or inconsistencies within the simulation models representing the surrounding systems, supersystems and users can be identified and thereby accelerate decision-making and reduce development risks.

Observations have shown that the uncertainty regarding the future customer and their objectives remains high despite the modeling at the beginning of the process. Therefore, the demand for high flexibility regarding the potential supersystem is embedded in the system of objectives. A trade-off between system flexibility and

cost-efficiency must be solved. On the one hand, the supplier benefits can be increased when developing flexible system structures which are able to fulfil the needs of multiple customers. On the other hand, flexibility has a high impact on the development resources in cost, personnel and time.

The system development in the AD department can be described with the support of the ZHO-model. Based on the initially defined (internal) system of objectives, first prototypes are designed within the operation system and thus constitute the system of objects. With the publication of results based on the first physical prototypes, customers are attracted and included in the development process. Before starting joint supplier-customer development projects, common systems of objectives must be defined. Therefore, the supplier faces two main challenges. On the one hand, convincing customers of internally defined objectives requires a deep system understanding and extended validation of the identified user needs. However, the customer-specific user groups in the automotive industry impede this approach. On the other hand, when accepting customer demands, required changes to the existing system lead to certain development risks. The ability to quickly evaluate and agree to customer demands is therefore decisive for the suppliers' success in a highly competitive market. However, the system models required for this are typically used for the initial design only and subsequently miss sufficient maintenance and validation.

4.2.3 Observations Regarding Model-based Validation Approach

To deepen the understanding regarding the usage of the model-based development and validation approach, methods, procedures and documents were analyzed within the participating observation. In the AD projects, the needs and objectives within the validation teams evolve with the maturity of the developed system as well as its environment. From proof of concepts up to first qualification tests, a broad variety of testing tools, strategies and methods are utilized.

The observations have shown that a high share of the capacity within the validation teams is directed onto the set-up and commissioning of suitable TCs. As the AD department focusses on the further extension of the existing product profile of the company, the type of the systems that are to be developed change in such a way that the reuse of existing TCs is often not possible without modifications. Moreover, due to the high degree of novelty of the SiDs, the objectives of the AD projects specifically include the development and evaluation of new TCs. During the research period the development and inauguration of a testing environment for hydrogen-based propulsion systems was observed. Furthermore, in accordance with the

Action Research approach⁵ the author was part of a group of engineers, who developed simulation models, software real-time in the loop TCs as well as a PHIL TC. Additionally, the development of TCs within the AD department and the transfer to the subsequent series development departments at different locations was noticed.

As a result, a high share of validation activities is not only intended to generate knowledge regarding the SiD but also regarding the TC. Furthermore, validation activities within the AD are characterized by frequent changes to the setups. Either the SiD or the CS and KS change due to the uncertainty and novelty of both. Due to the dependency of stakeholders on test results of physical prototypes, only limited resources are spent on the investigation and evaluation of models or mixed virtual-physical TCs. As a general observation, the usage of virtual or virtual-physical TCs sometimes does not exceed the extended commissioning phase when physical setups are available. Structured comparisons of test results from different TCs are rarely conducted. Moreover, the usage of virtual prototypes depends on the experience and trust of the responsible engineers.

As a part of the participating observation, a targeted document and test data analysis has been conducted. To visualize the existing challenges of the model-based validation approach in the AD department, a comparison of test results from two different TCs is given. The starting point for the displayed results is a common description of the testing procedure, which is usually stored within an application life cycle management (ALM) tool. Subsequently, the responsible test bench engineers conduct the implementation and execution at the test bench on site. The preparation, analysis and comparison of the measured data is associated with different obstacles. To name a few, the recorded signals have configuration-specific names, sampling times and are stored in various file-formats. The comparison of the logged measurements at two different TCs are displayed in Figure 4.3.

⁵ See Chapter 3.2

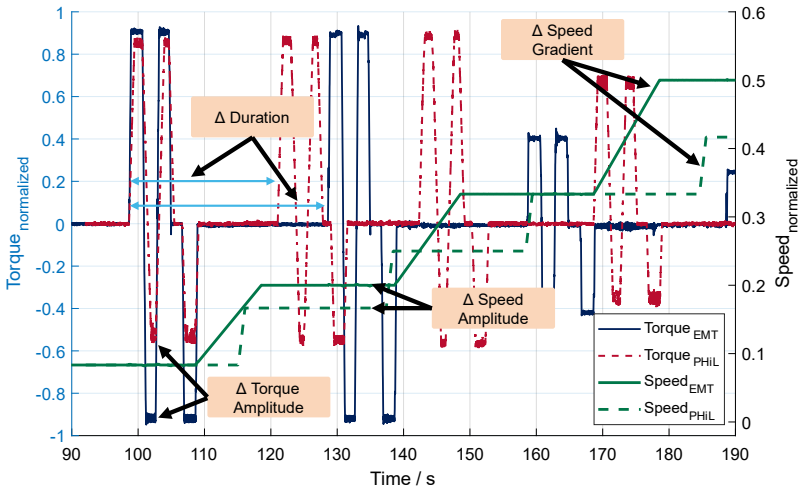


Figure 4.3: Example for Observed Inconsistencies of Test Results Between Different Test Configurations: Torque and Speed Behavior of EM over Time

The measured torque (blue and red) of the EM is shown on the left y-axis, machine speed (green) on the right y-axis. Although the test results are based on the same test description, different behavior of the SiD within the two TCs is apparent. To name a few examples, differences in amplitudes, gradients, limits and lead times are apparent. The deviation in the speed characteristics is a result of different implementations of the system stimulation at the two TCs. Besides the variety in test bench control tools, different test bench operators are responsible for the interpretation and implementation of the described test procedure.

4.2.4 Findings Regarding Model-based Validation Approach

In AD customer models are utilized to design the SiD and enable verification and validation of the SiD. To address the importance of validation in the development process, the planning and development of a suiting validation environment is started in parallel to the design phase of the SiD. Confronted with a high share of new development and the required flexibility, the development of a suiting validation environment requires extensive resources itself. Focusing on knowledge generation, flexibility is often prioritized over consistency. TCs are modified regularly to suit the needs. Consequently, the consideration of test standards and the automation of

testing is therefore often postponed. While the AD is focused on the functional verification of the SiD and the built-up of a flexible validation environment from component to system level, subsequent predevelopment activities are directed towards the acquisition of customers and the validation of customer specific designs.

As a result of heterogenous TCs, comparability of results from different TCs is associated with high effort. Furthermore, inconsistent and non-traceable test input and output data as well as modeling and parameter data hinder comparability. However, only with consistent testing and consequent back-mirroring of results, a stringent development of the validation environment can be achieved. In addition, quickly evolving and frequent changes to the systems and its environment increase uncertainty regarding the suitability of the several TCs for validation activities. However, the credibility of the validation environment consisting of simulation models, mixed virtual-physical test setups and physical prototypes is essential for the success of customer acquisition and system development. Thus, detailed traceability of the test steps and used systems as well as the testing equipment is necessary to evaluate and compare the results based on different testing activities.

4.3 Expert Interview Study on Challenges in Advance Development

To enhance the understanding of the specific challenges of validation within the AD, nine problem-centered expert interviews were conducted. On the basis of the systematic literature review and the participating observations within the department, an open interview guideline was designed (see Appendix B). The interview guideline was initially designed to target four aspects: "general challenges within Advance Development", "uncertainty regarding the supersystem", "changes to the system of objectives", "conception and development of the validation environment".

The interviewed experts were required to participate in active as well as past development projects for mechatronic systems. All experts have at least four years of experience in AD projects. Furthermore, all experts are or were responsible for the planning and execution of validation activities. Due to the Covid-19 pandemic the semi-structured interviews were held via telephone and lasted between 45 and 75 minutes. To avoid misunderstandings, the interviews were conducted in German. Prior to the interview, the interviewees were shown a short overview of the used terminology in order to establish a common understanding. With the consent of the interviewees eight of the conducted calls were recorded and then transcribed with

the interviewees remaining anonymous. In one case, the interview transcript was created based on notes taken during the interview.

The evaluation of the transcribed data is based on a qualitative content analysis according to Gläser and Laudel (2009). The analysis and evaluation of the transcribed interviews follows the procedure shown in Figure 4.4.

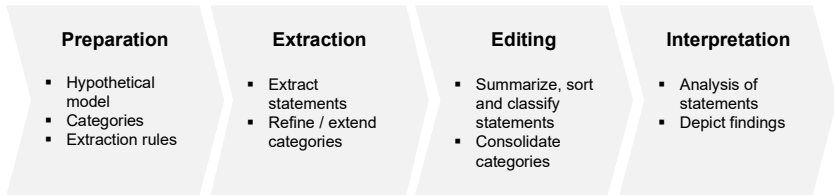


Figure 4.4: Procedure of Qualitative Content Analysis adapted from Gläser and Laudel (2009, p. 203)

In preparation of the content analysis and based on the literature review as well as the participating observation, a hypothetical model was drafted. Thus, 12 categories were derived, and nine extraction rules defined. The extraction was structured according to the interview guideline and the experts' current position (stakeholder, project manager, validation engineer) within the department. During the extraction, the categories were refined and extended. After the extraction, the statements were sorted, classified and summarized. As a result, six central categories were consolidated which are show in the Table below.

**Table 4.1: Categories for Expert Interview Extraction
adapted from Renner (2022, p. 55)⁶**

#	Category
K1	Internal organizational and structural influences
K2	Documentation within the development project
K3	Initial definition of the system of objectives
K4	Changes to the system
K5	Validation activities within the project
K6	Validation environments within the project

With the refined and concentrated categories, the statements were analyzed in depth and the challenges in AD were depicted. The results of the extensive analysis are displayed in Appendix B. The most relevant challenges are discussed in the following Chapters. (Renner, 2022)⁶

4.3.1 Management of Objectives and Requirements Regarding User, Customer and Supplier Benefits

All interviewees see a major challenge in dealing with the objectives and requirements regarding the SiD in AD projects. Especially in the context of the supplier in a B2B environment, technology development projects (described as AD projects) are rarely done jointly with defined customers. “A general challenge during the advanced engineering phase is the fact, that we don’t have a real customer yet”⁷. Instead, potential customers are identified and modelled by the supplier itself. The uncertainty regarding the stakeholders often results in a wide “range of requirements, [...] that you can’t really do justice to [...] any solution [...]”⁷. At the same time, the customer orientation is described as essential. Otherwise “you end up with something [...] that [the series development] [...] doesn’t want to take over because it actually totally misses the point.”⁷ Unlike the predevelopment of an OEM,

⁶ Co-supervised thesis (unpublished)

⁷ Translated from Experts in the Corporate Research and Advanced Engineering Department of MAHLE International GmbH (2020)

the supersystem of the supplier is not yet entirely defined or identified. Therefore, the planning capability with regard to the later application is insufficient. As a result, the level of detail regarding the requirements especially on domain level is often described as not satisfactory for design and verification.

4.3.2 Identification of Reference System Elements

According to the interviewed experts, there have not been any predecessor generations within the company which could serve as a reference for the development of the considered systems. However, similar systems or products could be identified. “We primarily performed benchmarks. [...] we knew that there was a [product] from [a competitor] that we could buy. We mainly used this product as a reference [...]”⁸

The consequences were mentioned in many aspects of the development process. Development activities start without specification sheets from customers which is unusual for a supplier. Moreover, objectives, requirements, and specifications must be identified, evaluated, and defined by the developing team itself. Even though the use case is described relatively precisely, a major difficulty for an automotive supplier lies in breaking down the objectives and requirements in detail. “We didn’t commit to one vehicle but tried to form a reasonable combination. [...] The bottom line is that it’s not very customized, but rather that it represents the function in such a way that it can be adapted to as many customers as possible.”⁸ However, there is the risk, that “[...] you would like to generate a jack of all trades [...]. In other words, a product that [...] can cover everything [...] this makes it even more difficult to define such a product in detail [...]”⁸

Even though the systems developed are not general novelties to the market, the interviewed experts see a major hurdle in the accessibility of knowledge regarding the development of these systems. This is primarily due to the fact that these systems are considered new for the developing entity.

4.3.3 Frequent Changes - Flexible System

The interviewed experts agreed on the fact that all system developments are affected by changes. The system development is described as an iterative process

⁸ Translated from Experts in the Corporate Research and Advanced Engineering Department of MAHLE International GmbH (2020)

where the gathered knowledge about the system leads to adaptations or refinement on the previously defined objectives and requirements. However, in the context of the development within the AD of the automotive supplier both, the strategic decisions by the management as well as the appearance of potential customers often result in major changes: "So, at the requests of both the management and the customers, it was decided to quit this development approach and to start from scratch, so to speak [...]"⁹. This citation underlines, that only in an ideal case, the initially internally defined supersystem and specifications exactly meet the expectations of potential customers.

With that in mind, one of the objectives of the AD path is to generate the necessary flexibility to establish the company's ability to quickly adapt the developed system to specific customer needs. Multiple experts mention a conflict between a high degree of flexibility and a straightforward system development. A high system flexibility is equivalent to high uncertainty. Nevertheless, the planning of verification and validation activities often are dependent on a higher degree rigidity of requirements. Sometimes simplifications are made when setting up the test environment, which happens concurrently with the system development: "[The test bench] was ordered and purchased for a specific application, and there was never any talk of maintaining flexibility here so that it could then be used extensively for other customer projects."⁹

The main objective, a prove of the technical feasibility, is customer independent. But at the same time the attraction of potential customers is essential for the product's success. According to the experts, in the case of direct customer contact during the development stage, developers and management lose sight of their primary goal: generating knowledge. The interviewed experts explicitly mention the fear of losing the customer as a reason, why the documentation of alternative solutions might be postponed or, in the worst case omitted.

4.3.4 Interdisciplinary and Interdepartmental Development

All of the interviewed experts have a high level of experience with interdisciplinary development projects. Nevertheless, each expert mentioned some difficulties due to the interdisciplinary character. The still present domain centered mindset is seen as one of the biggest hurdles. "People have a very strong tendency to think in their faculty and not in a more holistic, system approach [...]"⁹. As a result, the

⁹ Translated from Experts in the Corporate Research and Advanced Engineering Department of MAHLE International GmbH (2020)

coordination and communication of development activities is described as complicated. In particular, the lack of documentation of changes and their effects on the various subsystems is criticized by the experts. At the same time, they agree on a high importance of detailed documentation to enable a successful cooperation and handover to pre- and series development. In general, a low acceptance of the MBSE approach and its tools was observed by the experts: "But there you also have to say that [the documentation] [...] of course also depends on the people involved."¹⁰. As possible reasons for the low acceptance, the interviewees cite both a lack of competencies (or understanding) and a lack of capacity (especially time). The experts mention a potential fear of not being able to perform primary development tasks when being occupied with documentation tasks.

4.3.5 Verification and Validation Activities in Advance Development

All experts stressed challenges considering the verification and validation activities in AD. One of the main challenges is the high degree of novelty regarding the system in development and therefore lacking experience with the associated validation environment. According to the experts: "[...] the greatest difficulty [is] that you are developing a product and its test benches more or less in parallel."¹⁰ They also mention a high pressure to demonstrate first results. As a consequence, simplifications regarding the validation objectives must be made: "We simply strapped such a motor onto a test bench [...] in Slovenia, ran it at a certain speed and at some point said: Look at the phase current, it works [...]. For us, it's always the situation that we receive the money from the management and have to justify what we do with it."¹⁰

A key challenge is the prioritization of the validation activities according to the system objectives. Multiple validation needs must be expressed in corresponding validation objectives¹¹. Tradeoffs between short term results and sustainable knowledge generation must be made. While the acquisition of testing equipment is often seen as a long-term task due to high delivery times, early acquisitions are prone to high uncertainties regarding the system. "Because the requirements were so vague, it was not possible to specify concrete test cases [...]."¹⁰ However, without

¹⁰ Translated from Experts in the Corporate Research and Advanced Engineering Department of MAHLE International GmbH (2020)

¹¹ See Chapter 5.1

system relevant test cases, requirements for the validation environment can hardly be determined.

Regarding the specification and design of the validation environment, the statements of the experts indicate that the first principle of the model of SGE – System Generation Engineering is applicable. “We had no hardware in the loop or even component test benches [suitable for this specific SiD]. We then started with our colleagues in Slovenia, who had a test bench [...] then we continued at the University of Stuttgart, again with a motor test bench with the same problem: We simply never managed to get a stable DC supply with the currents at the voltage level. [...] In the end, that actually was the trigger to design and build our own motor test bench.”¹² Both the experiences within the company as well as with the external test bench are regarded as reference system elements for the design and development of the new test bench. Besides the physical setup, references regarding models must be identified and employees must be trained. The experience regarding both the execution of test as well as interpretation of test results has to be established. “Then there is a problem and then one person says: your test bench does not work. And the other person says: your product does not work. So, which one is true?”¹² All experts highlight the need for sufficient validation of the TCs. However, many see a conflict in the low degree of automation due to the high share of commissioning tests in AD.

There also is a need for a highly flexible validation environment because the ability to quickly adapt the developed system according to the customer needs is seen as crucial for product success¹³. Virtual or mixed virtual-physical validation configurations are suitable to provide such flexibility. The experts describe the initially developed test benches as “Bastelprüfstände”¹⁴, where early tests are conducted solely manually, and the configurations are often adapted continuously. These test benches are essential for early and fast knowledge generation and thereby represent an essential role in the concept of continuous validation. However, the credibility of these approaches is described as insufficient for convincing both internal stakeholders as well as customers. Moreover, the build-up models are often

¹² Translated from Experts in the Corporate Research and Advanced Engineering Department of MAHLE International GmbH (2020)

¹³ See Chapter 4.3.3

¹⁴ Experts in the Corporate Research and Advanced Engineering Department of MAHLE International GmbH (2020)

the entities' first models and simulations regarding the considered systems and thus, seek for model verification by physical testing.

4.3.6 Conclusion on Expert Interviews

The interviewed experts described AD as a particular phase of product engineering. AD projects often aim for knowledge generation regarding systems that are still unknown to the entity. Thus, the identification and accessibility of reference system elements is challenging. At the same time, a sophisticated system understanding is needed to comprehend and derive the needed functionalities and requirements without the customer. Due to the novelty of the system to the entity, more challenges arise while simultaneously developing the system and building up suiting TCs. Additionally, the experts underline that the system of objectives is subject to frequent changes. These changes can originate based on first test results, internal decisions or customer requests. That is where the search for an ideally flexible system and a validation environment that is able to cover the different applications starts. The usage of simulations and models provides to some degree the needed flexibility. However, the experts mention that stakeholder and customer demands can rarely be satisfied by simulation results. Physical prototypes are needed for convincing customers and to increase credibility of simulations and models.

4.4 Advance Development in the Model of SGE – System Generation Engineering

The purpose of creating a benefit to society is seen as the basis for all development activities (Albers, 2018). The development and market launch of a specific product generation usually aims at creating an immediate benefit within society. However, there are development paths whose results or deployments are not directly offered or cannot be directly offered on the market. As one example, the empirical study within AD has shown that the results of these projects are used as references by pre- and series development teams for the development of one or more product generations. Besides these upstream development paths, the results of further development paths can represent higher-level artifacts for the development of specific product generations. These artifacts are often deployed as modules or in the sense of system-of-systems and thus can be integrated into different, parallel product generations.

To further investigate the characteristics and interdependencies of these, often organizationally separated, development paths, an expert study has been

conducted (Albers, Kürten et al., 2022). Four case studies in different companies¹⁵ and research organizations¹⁶ were examined in detail. In Chapter 4.4.1 a representative model of the AD based on the model of SGE – System Generation Engineering is used to describe the characteristics. Subsequently, the interdependencies between the analyzed development paths are depicted and thus the findings on how these development paths contribute to a benefit within the society are explained (Chapter 4.4.2).

4.4.1 Case Study – Generalized Description of Development Paths

Within the case study on development paths, a data collection was conducted drawing on participating observations within the research environments. Besides the trigger and main objectives of these development paths, the results and the “definition of done” were analyzed. Furthermore, the used reference system elements were examined. (Albers, Kürten et al., 2022)

The subsequent exemplification of the analyzed aspects is a result of the participating observation within the AD department¹⁷. The data collection and analysis of the further case studies can be found in Albers, Kürten et al. (2022).

To promote and facilitate innovative thinking of employees and to generate new product ideas that expand the company's existing product portfolio, MAHLE dedicates and gathers activities to observe competitors and the respective research landscape in company-wide innovation hubs. A systematic evaluation of the thereby generated ideas is the basis for the strategic decision to further investigate these ideas within the AD department.

The main objective of AD projects is to examine these ideas for their technical functionality and to evaluate potential benefits. The scope of these projects explicitly excludes a dedicated strategy for market launch. Moreover, the objective is aimed at generating knowledge and providing prototypes as a basis for the subsequent

¹⁵ "Advance Development projects" at MAHLE GmbH, "Modular Developments" at TRUMPF GmbH & Co. KG, the "Development of Display and Operating Concepts" at Porsche AG

¹⁶ "Research Projects" at IPEK - Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT)

¹⁷ See Chapter 4.2

predevelopment and series development projects. As part of the project transfer from AD to product predevelopment, collaborative development activities were observed. A distinctive “definition of done” within the AD is not defined. However, within the process description TRL 4¹⁸ is defined as the earliest, and TRL 6¹⁹ as the latest start of transfer to product predevelopment.

The examined projects focused on the development of automotive traction system and its auxiliaries. The observations show that the results can be traced back to new product generations which start of production dates are usually set between four and eight years after the projects were initiated. In terms of time and the context of typical development cycles within the automotive industry, the activities of the AD can be assigned to the system generation G_{n+2} . Depending on the accessibility of the technology, or rather the maturity of research findings and existing systems (reference system elements), the prototypes are first implemented in an experimental environment and later in an environment close to the target application. Commonly, various prototypes exist as solely virtual, mixed virtual-physical or exclusively physical models. These prototypes are used for the early validation of the system in development and thus, to generate knowledge regarding the system as well as to determine to what extent the stakeholder needs are met.

The analysis of several case studies by Albers, Kürten et al. (2022) has shown that all development paths can be understood and described by the model of SGE – System Generation Engineering. In Figure 4.5 an abstract description based on the ZHO-model of the system development in AD is displayed.

¹⁸ Technology Readiness Level 4 (TRL 4): Lab Testing/Validation of Alpha Prototype Component/Process: Design, development and lab testing of components/processes. Results provide evidence that performance targets may be attainable based on projected or modeled systems. European Commission (2013)

¹⁹ Technology Readiness Level 6 (TRL 6): Prototype System Verified: System/process prototype demonstration in an operational environment (beta prototype system level). European Commission (2013)

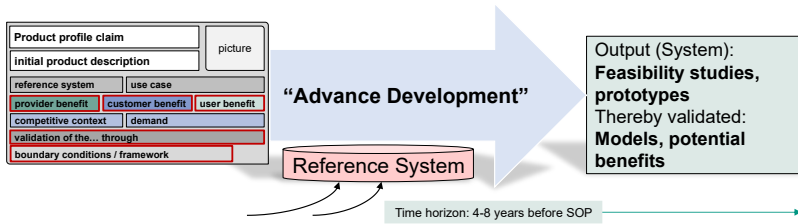


Figure 4.5: Characteristic Representation of the Development Path – Advance Development adapted from Albers, Kürten et al. (2022)

Figure 4.5 shows the observed development path and the corresponding reference system. On the left side, a simplified representation of the product profile template (see Figure 2.6) is displayed. On the right side, the central output and thereby validated systems are shown.

According to the data collection described above, only aspects of the product profile are examined in detail. The feasibility studies and prototypes primarily address the functionality of the regarded technology. Aligned with the three-element innovation model (see Figure 2.4), the main results of AD are the identification and initial description of the demands as well as the (initial) evaluation of the technical feasibility of the invention. Furthermore, the potential benefits of the system in development are assessed. In the case of the automotive supplier, the potential benefit for the provider itself as well as potential customers and users are examined. Meanwhile, many aspects of product development are yet neglected or only considered superficially, like marketing or production strategies.

A central outcome of the case studies regarding development paths is that the various development activities in the different paths can all be understood as system developments. Based on the two hypotheses and the fractality of the model of SGE – System Generation Engineering, a similar architecture and nomenclature can be applied to describe and model these paths. As a result, a common understanding can be established. This opportunity to unify and standardize processes in companies is beneficial for both research and companies. The common understanding allows a more extensive investigation of the interdependencies between different development paths and describes as well as visualizes their contribution to product development success.

4.4.2 Interdependencies between Development Paths

With the understanding and description model of the different development paths, the interdependencies between these system developments and their contribution as a benefit to society are analyzed. The case studies revealed that the results of the considered development paths represent systems that differ in scope, maturity, and character (Albers, Kürten et al., 2022). The outstanding common characteristic of the outcomes of the considered development paths is that these systems are not offered on the market. However, the observations have shown that they provide major contributions to the realization of benefits (Albers, Kürten et al., 2022).

In Figure 4.6, the observed development paths as well as their interdependencies in product engineering are displayed within the exemplified product portfolio of a modelled entity. Multiple product lines and variants are only schematically indicated for better visibility. Furthermore, only observed interactions between the different development paths are plotted (without claiming completeness).

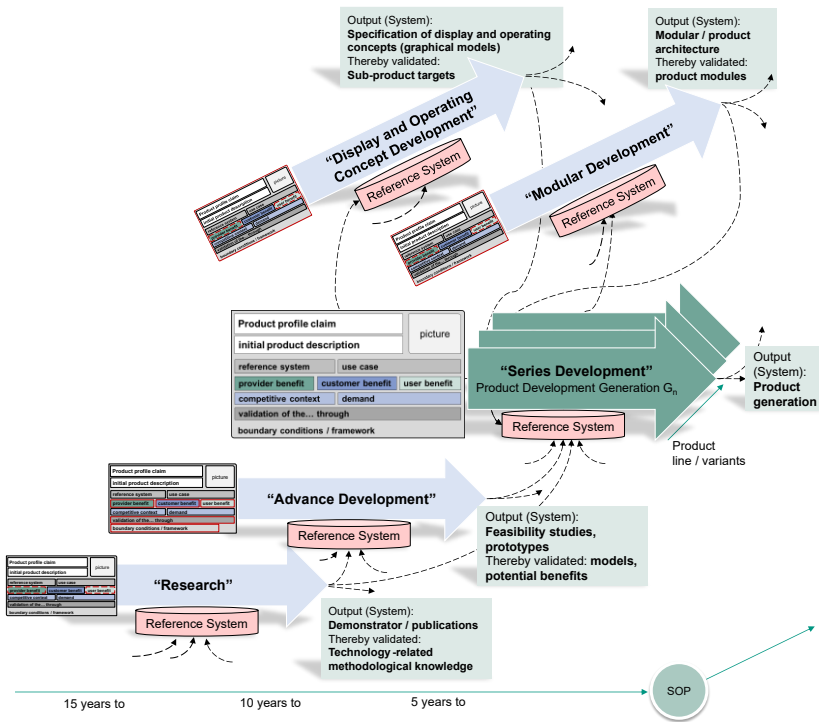


Figure 4.6: Interdependencies between Development Paths in the Model of SGE – System Generation Engineering by Albers (Albers, Kürten et al., 2022)

A fractal depiction of the development paths increases comprehensibility. All development paths are displayed as system developments similar to the described development path of AD at MAHLE GmbH (see Figure 4.5). With the detailed analysis of the considered development paths by Albers, Kürten et al. (2022) and years of research dedicated to product engineering in companies by the KaSPro²⁰ an approach to describe the displayed interdependencies in a generalizing way is presented. Based on the system triple, product engineering is described as an iterative process. Thus, the results of any system development can either contribute

²⁰ KaSPro: **K**arlsruher **S**chule für **P**roduktentwicklung

directly or indirectly to product development. Findings can either confirm or disprove hypotheses and thus promote or change paths taken. In both ways, the findings are expanding the knowledge base. Furthermore, development activities can be conducted upstream (e.g., AD) or in parallel to product development. Development activities can be planned and designed explicitly (e.g., modular development) or implicitly (e.g., research) to support product development activities.

Development paths and activities are driven by the need to generate a benefit. With the model of SGE – System Generation Engineering all activities can be linked by the utilization and provision of reference system elements. These many-sided interrelationships are schematically shown in Figure 4.6 with the help of the dashed arrows.

Several objectives to describe the existence of different development paths which are not directly related to a specific product generation can be identified. An organizational separation is often associated with a certain degree of freedom as tasks are dedicated to these paths which facilitates creativity. At the same time, higher development risks which are associated with a high degree of new development can be outsourced. Another motivation is the use of synergies by outsourcing the development of subsystems that can be reused across several product lines and variants.

4.5 Requirements on Methodological Support for Validation in Advance Development

The AD stage is described as a central element for successful innovations. The central activity in the development process is validation. For the validation of identified stakeholder needs (product profile) as well as for the validation of the technical invention a suiting validation environment is needed. However, due to the high share of new development within the AD projects, suiting TCs have to be developed simultaneously to the SiD.

Especially in the role of a supplier, high flexibility to react to changing system environments is needed. Initially produced prototypes which are designed based on a virtual customer model created by the developing entity rarely match all demands and requirements of actual customers. Flexible validation approaches like the IPEK-X-in-the-Loop approach are designed to continuously validate the SiD. The understanding of the interfaces and interdependencies between the SiD and potential supersystems, which represent the customers' systems, is essential for successful customer acquisition. The development of therefore needed modular

validation environments is associated with extensive resources and raises the demand for continuous validation of the TCs itself.

When setting up new TCs, validity of these configurations is essential for all further SiD related validation activities. Like the SiD itself, TCs should be analyzed for quality, integrity, correctness, consistency and **validity**. The development of systems as well as TCs are iterative processes, thus raising the need for **continuous** validation.

Especially test results in mixed virtual-physical TCs must be compared to the expected results. The origin of observed discrepancies must be determined. Either discrepancies are a result to the behavior of the CS/KS or a result to the behavior of the SiD. Only by comparing and validating continuously, unwanted behavior of SiD and TC can be identified (National Aeronautics and Space Administration, 2016).

The literature review, the participating observation as well as the conducted interview study express several challenges regarding consistent validation in AD. Within the following three chapters summarized answers to the first research questions are given.

4.5.1 Traceability of Validation Activities

In order to meet the challenges which are accompanied with distributed and interdisciplinary teams²¹, a common understanding and language is needed. By providing a common descriptive model and language, a mutual understanding of needs, activities and outcomes is fertilized. Moreover, by establishing a shared understanding, the transferability of applied methods to other system developments can be enhanced. In Chapter 5.1, the essential terms and concepts regarding the validation within this thesis are described.

With the unavailability of customer requirements, the developing entity must establish a system understanding to derive user and customer needs.²² Only with the comprehension of system interdependencies, functions and requirements can be derived sufficiently. Therefore, potential customers and users must be modelled. The traceability of validation activities to check and verify the deduced requirements

²¹ See Chapter 4.1.3, 4.2.3, 4.3.4

²² See Chapter 4.3.1

and functions, for example by system simulations, is essential. Only with full traceability, the developers can make use of conducted validation activities. Traceability allows the identification of raised uncertainties due to occurring changes (Martin et al., 2022) and enables a transparent communication about potential risks towards the customers.²³ Furthermore, documentation is necessary to address the challenges regarding the distribution and transfer of the acquired knowledge between AD and series development.²⁴ At the same time, the documentation allows reuse of requirements and their associated Test Runs over different engineering and system generations. Sufficient documentation fertilizes the consultation of these elements as references for further development projects.

However, the findings within the participating observations demonstrate irregularity in test input and output data.²⁵ Variations in test data are for example result to heterogenous testing tools, manual implementation and execution of tests and different interpretations by the engineers. Furthermore, in order to meet stakeholder demands, objectives were reshaped and focused on physical prototypes. In other words, resources of the AD teams are limited. Thus, methodological support must be designed in such a way that the effort to achieve traceability and reusability does not exceed the existing resources. The designed method should support traceability by giving engineers structured guidance when conducting testing activities. Furthermore, homogenization and automation of test execution and analysis is needed to reduce inconsistencies and enhance reusability as well as comparability (Haas et al., 2021).²⁶ In Chapter 5.2 methodological support for homogenization, automation and traceability of testing activities is addressed.

4.5.2 Consistency of Modeling and Parameter Data

The need for flexibility regarding the system and its validation environment²⁷ raises the demand for virtual or mixed virtual-physical TCs. The descriptive study has pointed out that in the context of the AD of an automotive supplier, these TCs must be built-up simultaneously to the development of the SiD. Consequently, their continuous validation is necessary. Validation of virtual or mixed virtual-physical TCs can only be achieved when comparability of test results between different TCs is

²³ See Chapter 4.2.2, 4.3.2, 4.3.3

²⁴ See Chapter 4.1.4, 4.3.4

²⁵ See Chapter 4.2.4

²⁶ See Chapter 4.2.4, 4.3.4, 4.3.5

²⁷ See Chapter 4.1.2, 4.2.1, 4.3.3

given. With the availability of multiple models, frequent changes to the system are accompanied by a high degree of maintenance to keep all models up to date. Thus, the model validation is associated with additional and extended effort for the repetition and analysis of comparable Test Runs in different TCs.²⁸ Besides a high degree of reusability and automation of Test Runs²⁹, consistency of all used modeling and parameter data is needed.

Especially for the identification and analysis of phenomena, traceability of the used modeling and parameter data is required. Yet, in dynamic and interdisciplinary development, consistent documentation and communication is described as challenging. Comprehensive documentation is often seen as an additional burden in already complex and time-consuming development processes. The interviewed experts observed non-sufficient communication of changes within the interdisciplinary development teams. On top of that, due to the Covid-19 pandemic distributed development was enforced, disrupting established ways of communication within the teams.³⁰

Methodological support needs to facilitate the exchange of modeling and parameter data. Furthermore, changing system functionalities or requirements must be propagated to the models accordingly. For the set-up of TCs, the execution of Test Runs and the analysis of test results, the used modeling and parameter data must be traceable and ideally consistent. Comparability of test results from Test Runs within different TCs must be given to evaluate the virtual and mixed virtual-physical TCs. Methodological support to enhance consistency of testing data is presented in Chapter 5.3.

4.5.3 Credibility of Test Configurations

The descriptive studies strongly indicate that stakeholders see physical prototypes as the only trustworthy source for decisions. Moreover, customers are more likely to be convinced when physical prototypes were used.³¹ In spite of that, suppliers need

²⁸ See Chapter 4.2.3, 4.3.5

²⁹ See Chapter 4.5.1

³⁰ See Chapter 4.1.4, 4.3.3, 4.3.4

³¹ See Chapter 4.1.4, 4.2.1, 4.3.5

virtual representations to cope with frequent changes of stakeholder demands and to start the validation of the SiD at early stages to shorten development times.³²

The interviewed experts pointed out that the uncertainties regarding the functionalities and requirements of the SiD often complicate or even impede the design of suiting TCs.³³ As a result, the design and construction of TCs within AD are continuous processes. As with the development of any new system, uncertainties exist which can only be addressed through validation. With the simultaneous development of both SiD and TCs, the identification and allocation of unwanted system behavior to either the SiD or the CS/KS is essential.

The validation of TCs and thereby a risk reduction can be achieved by continuous comparisons of testing activities within different TCs. Therefore, consistency and traceability of the input data as well as the utilized modeling and parameter data is needed.³⁴ Also, the evaluation of the credibility of the results is necessary. Transparency regarding the credibility of the utilized TC is both important for internal validation planning as well as for the communication of simulation results towards potential customers, for example. Although the flexibility of virtual or mixed virtual-physical TCs is considered to be immensely important, only limited resources for their development and evaluation are available. (Düser et al., 2023; Freyer & Düser, 2023)

The designed method needs to support the continuous evaluation of the used TCs to document and address the strength and weaknesses of the validation environment. A transparent and objective documentation of the validation activities regarding the TCs should enhance the credibility and thereby extend the flexibility for the development. In Chapter 5.4, an approach for continuous analysis and evaluation of TCs is presented.

³² See Chapter 4.1.1, 4.1.2, 4.3.3, 4.3.5

³³ See Chapter 4.3.5

³⁴ See Chapter 4.5.1, 4.5.2

5 Methodology for Consistent and Flexible Validation in Advance Development

Aligned with Atzberger et al. (2020, 466f.), Estefan (2008, p. 5), Gericke et al. (2017, p. 105) within the KaSPro the term methodology describes a collection of methods and process models, which fundamentally consist of activities, guidelines and tools. Within this chapter, the basic elements of the developed methodology are presented. In Chapter 5.1 a common understanding of the activities and elements, which are specifically addressed by the developed methods is established. The methodical support for consistent testing (Chapter 5.2) consists of a generic Test Run implementation method, a guideline to derive Test Runs based on use cases and a superordinate test automation tool, which enables identical system stimulation in all TCs. The Digital Model Master (Chapter 5.3) includes a method and tool to improve consistency and traceability of modeling and parameter data in virtual or mixed virtual-physical TCs. The method for the consistent analysis and classification of TCs presented in Chapter 5.4 builds on the methodical support for consistent testing and the Digital Model Master and complements the presented methodology.

This study employs the Action Research methodology¹ to iteratively develop and evaluate the components of the comprehensive methodology. Iterative activities, including problem diagnosis, action intervention, and reflective learning, were conducted with a group of applicant engineers to facilitate collaborative reflection and refinement of the methodology. The results of these iterative processes are detailed in the subsequent chapters. Chapter 6 presents an initial evaluation of the entire methodology in accordance with the descriptive study II of the DRM. Prior to the integration of the complete methodology, individual methods and guidelines underwent initial evaluations through case studies, which are documented in Chapters 5.2.4 and 5.3.4. Furthermore, these chapters aim to enhance comprehension by providing concrete application examples of the proposed methods, thereby illustrating their practical relevance. Making use of iterative evaluation and real word application, applicability of the developed methods is ensured.

¹ See Chapter 3.2

5.1 Validation in Advance Development

Validation is a continuous activity throughout the product engineering cycle. Therefore, depending on the perspective, maturity level or stage in the development process, different needs and objectives exist. **Validation needs** describe knowledge gaps or the lack of clear specifications/definitions regarding the planned and/or required system properties/behavior. Any validation need is thereby linked to elements of the problem space/product profile (e.g., stakeholder needs, use cases) as well as to the solution space (e.g., objectives, requirements, functions, architecture).

To meet validation needs under the constraints of product development processes (such as time and cost), specific validation objectives are defined. A **validation objective** determines the specific goal and purpose of a given validation activity. Thus, relevant elements for the defined validation activity are determined based on the corresponding elements which are linked to the validation need. Furthermore, the validation objective includes the definition of specific expectations or hypotheses regarding the validation activity. Based on the validation objective, requirements and boundary conditions on the TC can be derived.

5.1.1 Testing Definition

To further describe the activities in the context of validation, procedures like experimenting, examining, inspecting, evaluating, certifying or testing are used throughout the literature (DIN EN ISO 9000, 2015; IEEE Std 610.12-1990, 1990; ISO/IEC/IEEE 24765; ISO/IEC/IEEE 29119-1; Karthaus, 2020, pp. 62–70; National Aeronautics and Space Administration, 1970; VDI 2206, 2004; VDI 2221 Blatt 1, 2019).

Within this thesis, the focus is set on the validation activity “testing”. **Testing** is defined as an “activity in which a system or component is executed under specified conditions, the results are observed or recorded, and an evaluation is made of some aspect of the system or component” (IEEE Std 610.12-1990, 1990, p. 74; ISO/IEC/IEEE 29119-1, p. 10).

Testing fulfills two central roles in the development process. First, testing can help to understand a (new) technology or explore the design space and thus, improve the design of the SiD. Second, testing can generate information and knowledge regarding the test process, methods and environment. Thereby, testing can be valuable to both the development of the SiD as well as the test configuration. (Tahera et al., 2019, pp. 293–294)

Based on Albers, Behrendt et al. (2016), Ebel (2015), ISO/IEC/IEEE 24765 and ISO/IEC/IEEE 29119-1 a generic description model of the testing activity, its sub activities and artefacts is proposed as displayed in Figure 5.1.

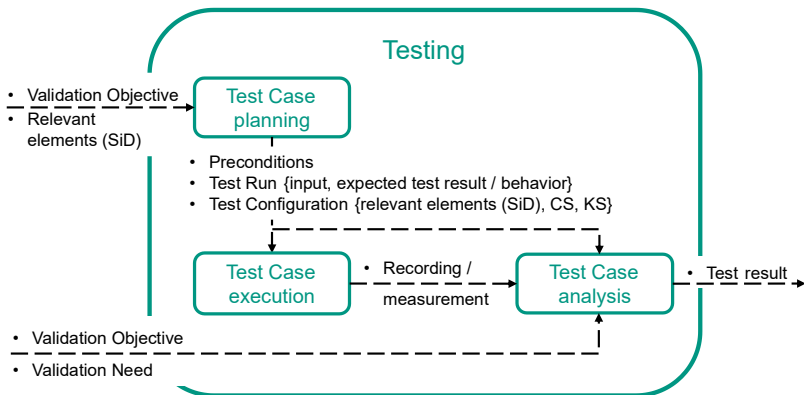


Figure 5.1: Description Model of the Activity “Testing”

During the product development process different needs arise and thus, different validation objectives are determined, which initiate and define the testing activities. In general, the testing activity includes the planning and execution of a Test Case as well as the analysis and interpretation of the test results. In Figure 5.1, the black arrows represent the artifacts necessary to perform the displayed activities (green). The design and realization of the described activities is often done iteratively.

When planning the Test Case, the validation objective and thus, the relevant elements are used to define the preconditions, the Test Run and the TC. The description of Test Cases is specifically addressed in Chapter 5.1.2. The outcomes of a Test Case execution are usually stored in recording or measurement files. For the analysis and interpretation of the Test Case, the engineers need to take the validation need and validation objective into account. The Test Case analysis is further investigated in Chapter 5.4.

5.1.2 Formalizing Testing Activities by Test Cases

Functional description models are used to plan, document and track validation activities. In standardized processes such as Automotive SPICE, Test Cases

constitute the focal point of testing activities. In Figure 5.2 elements of a functional Test Case description model based on ISO/IEC/IEEE 24765 and ISO/IEC/IEEE 29119-1 are displayed.

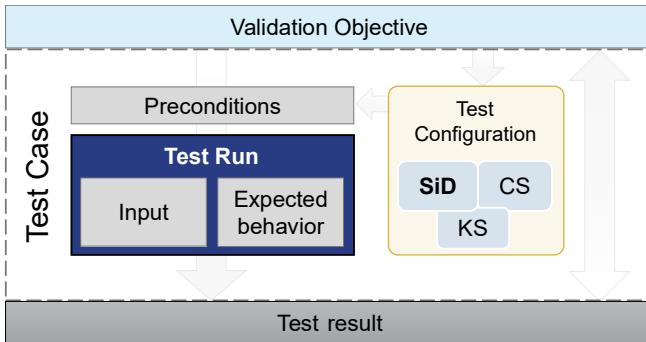


Figure 5.2: Test Case Description Model based on ISO/IEC/IEEE 24765; ISO/IEC/IEEE 29119-1, p. 10

A Test Case consists of a Test Run, the related preconditions, a defined TC and the test results. Even though a general procedure to define a Test Case cannot be described (Albers, Behrendt et al., 2016, p. 554), typical processes and interrelationships are explained below. (ISO/IEC/IEEE 24765; ISO/IEC/IEEE 29119-1)

Test Cases are formulated and depicted based on the previously identified validation needs and the subsequently derived validation objectives. Based on a specific validation objective, relevant elements of the problem and solution space can be identified. A Test Case can address either properties, functions and/or a system's behavior. For instance, these system attributes are specified in product profiles or requirement sheets.

ISO/IEC/IEEE 29119-1 differentiates between static and dynamic testing methods. Static tests involve analysis or evaluation of system properties without execution/stimulation. Dynamic tests involve execution or stimulation of the system by defined Test Cases. The scope of the suggested method is focused on dynamic tests. For the functional description of dynamic tests, technical functions can be used. According to Zingel (2013, p. 133), the term "technical function" explains the purpose of a system from a technical point of view (see Figure 5.3).

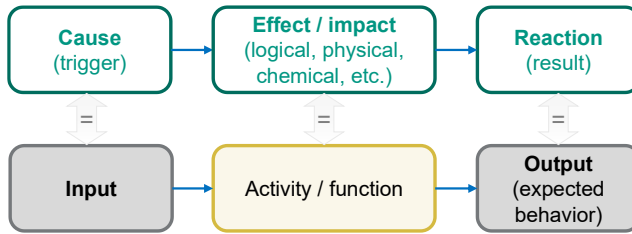


Figure 5.3: Understanding of the Term “Technical Function” adapted from (Zingel, 2013, p. 134)

As displayed in Figure 5.3, the stimulation (input) of a system, triggers a reaction (output). The relation between input and output can be described by the function (for instance, as an equation). System input can either be information, energy or material flow. The respective reactions can be time-discrete or continuous events. These reactions are measurable (results) and can serve as input for further functions.

A **Test Run** addresses product functions from a technical viewpoint by defining the inputs and expected behavior of the system. To represent a user interaction with the system, multiple product functions might be addressed. Thus, Test Runs can consist of multiple, consecutive system stimulations. Figure 5.4 shows an exemplified structure of a Test Run which addresses the system’s behavior.

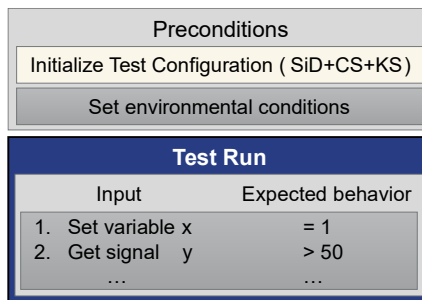


Figure 5.4: Structural Model of Preconditions and Test Run as part of a Generic Test Case

As displayed, in this case the input to stimulate the system is abstracted to the representation of set and get expressions of variables and signals of the system.

For example, within the first step the speed of the EM can be set to a desired value of 500 rpm and within a second step the EM stator temperature can be measured and compared to an expected value of 60 °C. Thus, a clear step-by-step instruction is given while, at the same time the abstraction level allows applicability and reusability in various TCs. The ability to address several requirements within a single Test Run represents a decisive degree of freedom for the developer of a Test Case. With the combination of several requirements, the efficiency of validation activities can be increased. However, a combination can also alter the system's behavior and have significant effects on the evaluation of the system. **Preconditions** include both the description of environmental conditions as well as the potentially necessary initialization of the TC.

Any Test Case includes a specific description of the **Test Configuration** (see also Figure 2.15). Based on the validation objective, the scope of the system (SiD / Sul) as well as the necessary interacting systems (as in CS and KS) are determined. Furthermore, the necessary form, either virtual, mixed virtual-physical or physical and the corresponding maturity of the systems to achieve the validation objective, can be derived.

With the determined system stimulations and the expected behavior, a list of the signals that are to be recorded/measured is defined. As a result to the execution of the Test Run, a detailed analysis and interpretation of the measured signals can be initiated. Part of the **test result** is the accordance of the system behavior in regard to the requirements. The analysis takes place under the consideration of the validation objective. Accordingly, the interpretation takes the strengths and weaknesses of the present TC into consideration. Additionally, the maturity of the SiD is taken into account during the test analysis. The test result is thereby subject to the engineer's analysis based on the present validation need and objective. By transferring the recorded system behavior into system properties, the test interpretation ultimately provides insights on the system (Ebel, 2015). It must be noted that the test results are always subject to the specific TC. Consequently, the TCs properties such as measurement accuracy, latency times and model reduction features must be considered and evaluated.

5.1.3 Validation of Test Configurations

Central objectives of AD projects are the knowledge generation and the building up of a broad understanding of system interdependencies between the SiD and its supersystem. In the case of an automotive supplier, the understanding of the supersystem is essential for a successful cooperation between the supplier and the OEM. In AD, when a new system is designed and validated for the first time within

the entity, the design and validation of a suitable validation environment is essential for development success. A key task for the supplier is to model and simulate the interfaces between the system and its supersystem as well as between the supplier and customers. In order to be successful in the globalized automotive supplier market, digital technologies and virtual TCs are widely spread within the development (Dumitrescu et al., 2021).

Throughout the whole product engineering cycle, from strategic planning up to product usage, different validation needs and objectives exist. To meet these challenges, model-based validation approaches like the IPEK-X-in-the-Loop approach are applied. Accordingly, many TCs are set up to meet the different needs and objectives. Prerequisite for the usage of any TC in validation of the SiD, but especially for TCs with high virtual shares, is an extensive validation of the TCs itself. The goal of AD projects specifically includes the development and validation of a flexible validation environment. To handle complexity regarding both the SiD as well as the VE and to organize and plan the validation activities, MBSE approaches are utilized. MBSE approaches specifically address the traceability of the activities to support the systematic knowledge generation regarding both the SiD as well as the validation environment (Mandel et al., 2020). MBSE systematically supports the documentation of validation activities and thus supports the reuse of existing TCs.

At the regarded research environment at the AD department of MAHLE, a flexible validation environment for the development of (parts of) ETDS are considered. The four TCs displayed in Figure 5.5 represent an excerpt of this validation environment.

	TC1: Model-in-the Loop	TC2: Signal Level HiL (S-HiL)	TC3: Power Level HiL (P-HiL)	TC4: Electric Motor Dyno Test Bench (EMT)
System	virtual	physical virtual	physical virtual	physical
Controller	ECU	ECU	ECU	ECU
Inverter	Inverter power electronics		Inverter power electronics	Inverter power electronics
E-Motor	E-Motor	E-Motor	E-Motor	E-Motor

Figure 5.5: Excerpt of the Validation Environment for Electric Traction Drive Systems at the Advance Development Department of MAHLE

In the displayed example the ETDS is divided into the subsystems controller, inverter and electric motor. Four different TCs are indicated (CS and KS are not shown for the sake of simplicity). The level of virtualization decreases from left to right. In TC 1 “Model-in-the-Loop” the entire system is emulated. In TC 2 “Signal Level HiL (S-

HiL) the controller/ECU is physically present while the inverter power electronics as well as the electric motor are emulated (Boog et al., 2019). As a further integration step the inverter is physically integrated into the TC 3 "Power Level HiL (P-HiL)". In TC 4 "Electric Motor Dyno Testbench (EMT)" the entire traction drive system is physically present. For the investigations regarding the supersystem, the emulations of further systems such as the gearbox, vehicle or auxiliaries are implemented and can be included in any TC if necessary.

Besides the objective in AD to verify the technological functionality of the SiD, a key enabler for a successful succeeding series development is the design and validation of a flexible validation environment. A validation environment consists of multiple TCs, like the ones displayed in Figure 5.5. The development of these TCs include an iterative process of modeling and validating CS and KS. For the evaluation and validation of the models and entire TCs, a high degree of consistency within the validation environment is needed to compare the behavior of physical and virtual systems. Furthermore, continuous exchange with potential customers is needed to iteratively refine and integrate the feedback into the customer models. As a result to the features of virtual systems, multiple models with different purposes exists for the same (sub-)system. An effortless exchangeability of models according to the IPEK-XiL-approach allows a high degree of flexibility for the testing activities. To enable comparability of Test Runs within different TCs methodical support for consistent testing is presented in the following chapter.

5.2 Methodical Support for Consistent Testing

Depending on the validation objective, Test Runs are performed in different TCs. The interdisciplinary development of mechatronic systems often leads to a non-simultaneous physical availability of the different subsystems. However, with virtual or mixed virtual-physical TCs, testing activities can begin before the physical availability of all subsystems. With only small changes to the SiD or with the presence of physical subsystems, Test Runs (or parts of it) are regularly repeated in different TCs to evaluate the changes. For example, the development of the control algorithm of an electric traction drive is initiated on a model level. The behavior of the developed algorithm is then assessed within a virtual TC. With the physical availability of subsystems such as the controller, inverter or EM, the already performed Test Runs in the virtual TC can then be repeated in a mixed virtual-physical TC. A mandatory prerequisite for the comparison of the system's behavior represented in different TCs is to conduct the stimulation of the system in the exact same way.

The method provides support to enable and ensure comparability of testing activities throughout the development process. Comparability is achieved through a superordinate test automation tool and with the consistent reuse of Test Runs in all TCs. A schematic overview of the Test Run structure embedded between the functional Test Case description and the TCs is displayed in Figure 5.6.

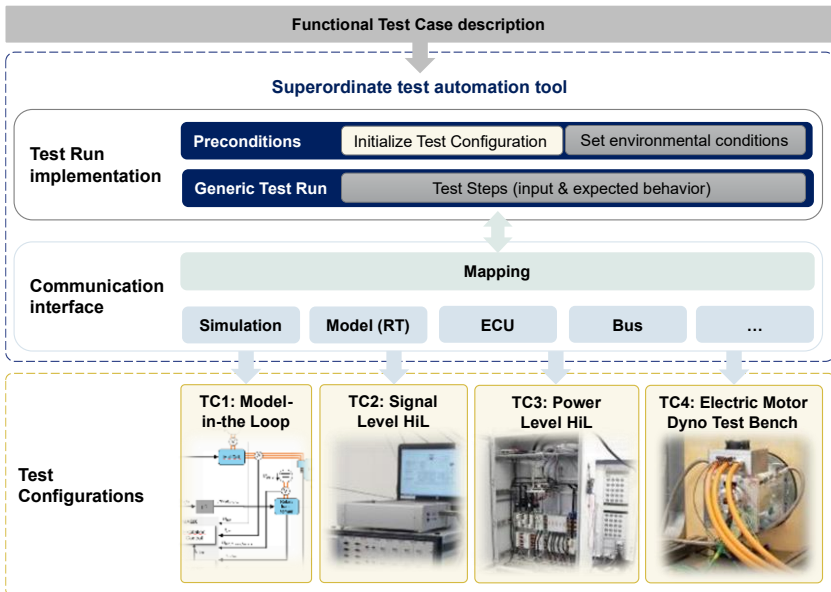


Figure 5.6: Connection between Functional Test Case Description and Test Case Execution with a Superordinate Test Automation Tool at Different Test Configurations: Structure of Test Run Implementation and Communication Interface for Mapping of Generic Signals to Used Interfaces

The implementation of Test Runs in the test automation tool is initiated based on the functional Test Case description. The methodical support consists of a guideline for Test Run formulation and implementation (Chapter 5.2.1) as well as the description and implementation of relations between the test automation tool and the TCs (Chapter 5.2.2). Thereby, the methodical support enables repeatability and comparability of the testing activities.

5.2.1 Generic Test Run Implementation Method

Proper execution of testing activities starts before the execution of the actual Test Run. A necessary prerequisite for the repeatability and comparability of test results are equivalent (and often stationary) starting operation points. To avoid unintentional dissimilarities, automation of the preparation and conditioning is recommended. However, depending on the setups, establishing these preconditions often varies from TC to TC in such a way, that a generic definition and execution of the procedure is not feasible.

With identical or at least comparable starting conditions the system stimulation can be carried out. Stimulations are often designed to reproduce user interactions with the systems². As defined in Chapter 5.1.1 within the Test Run the input (stimulus) and expected behavior of the system are defined. The stimulation and its expected behavior are usually defined in such a way as to address or check the fulfillment of requirements. With the definition of Test Runs, product functions are addressed from a technical point of view. This technical abstraction should be done TC-independent to achieve reusability of Test Runs. Test Runs can be further subdivided into sequential or parallel Test Steps. In general, Test Steps either describe the stimulation or the observation of system characteristics. The corresponding expectations concerning the system's characteristics that are linked to the input are also included in the Test Step. In Table 5.1 a generic structure for the formulation of Test Runs is given.

² See Chapter 5.2.3

Table 5.1: Generic Test Run Template – Excerpt of EM-Test Run

#	Operation	Sys. characteristic	Value	Time	Description	...
...						
11	Write/set	EM-speed	500 rpm	1 s	Speed up EM	
12	Read/get	EM-temp. stator	> 60 °C	Until reached	Check target temp.	
...						

The displayed template provides a translation of the human understanding into a machine-readable form. Each row represents a Test Step. Within the first column, the order of the Test Steps executed sequentially or in parallel is indicated. The “Operation” defines whether the system characteristic is stimulated or observed. The third column consists of the system characteristics description (as in the physical architecture of the MBSE-model). The “Value” and “Time” define the target behavior of the Test Step. The “Description” provides more detailed information on the purpose of the Test Step (in regard to the validation objective/requirements). As in any domain specific application the table can be extended as required. Moreover, such a generic formulation is also applicable to the initialization of the environmental conditions within the preconditions of the Test Case to ensure repeatability and comparability in different TCs. Columns one to five are necessary to allow execution of the Test Run within a superordinate test automation. The template creates a uniform understanding of the Test Runs for all project participants. Furthermore, it enables everyone to define such Test Runs, as the dependency on specific test software is eliminated.

5.2.2 Communication Between the Test Automation and the Test Configurations

For the execution of the mentioned generic Test Run structures, a translation of the generic description to the target system is necessary. As displayed in Figure 5.6 the communication interface between the test automation tool and the TCs consists of specific mappings and the usage of different application programming interfaces (API).

APIs provide standard commands for the execution of general operations. Thereby, the communication of different systems is simplified. In this case, the APIs enable unified communication between the test automation and the different test systems

of a TC. The standardization of the communication of test bench tools and test automation tools is driven by the ASAM XIL v2.2.0 (2017) standard and the subsequent ASAM XIL v3³ project. In Figure 5.6 several API targets are schematically displayed within the communication interface block. The standardization of the access of tools allows simultaneous and interchangeable communication with simulations, models, control units, Bus-systems and many more. For the communication of the test automation and the TCs within the AD of MAHLE, several APIs (e.g.: “ASAM ACI”, “ASAM XiL”, “dSPACE HIL API”, “Vector XIL API”, “NI VISA”, etc.) were developed, extended or applied with Python⁴ and ECU-Test⁵.

For each interface there is a specific mapping which translates the generic Test Step description (see Table 5.1) to the hardware or software of each system within the TC. In Table 5.2 a schematic list is given, where the generic descriptions of the system characteristics are mapped to the target variables and signals of the system within the TC.

Table 5.2: Mapping of Generic System Characteristics to Target Variables/Signals

Mapping	System characteristic	Target variable/signal
A	EM-speed	TestBench / LoadMachine / DesiredSpeed_rpm
	EM-temp. stator	CAN3 / GanterDAQ / T_2
	...	
B	EM-speed	Model / ElectricMachine / Speed_rpm
	EM-temp. stator	Model / ElectricMachine / Stator / Temp_1
	...	

A system characteristic such as the speed of an electric machine (EM-Speed) is stimulated identically while utilizing different APIs. As an example, the mapping for the EM speed at a MiL configuration (Mapping B for TC1 at Figure 5.6) and motor test bench configuration (Mapping A for TC4 at Figure 5.6) is described as follows:

³ <https://www.asam.net/project-detail/asam-xil-v300/>

⁴ <https://www.python.org/>

⁵ <https://www.tracetronic.de/produkte/ecu-test/>

Within the MiL configuration, the speed variable within the model is addressed via the XIL API, while within the motor test bench configuration the machine speed is controlled via the automatic calibration interface (ACI) of the load machine.

If a system is transferred from one TC to another, the mapping can be reused as long as the API remains the same. Over the course of a development process, a long list of system specific mappings evolves. The generic Test Step description and the mapping concept are designed in such a way that the same generic Test Run can be executed identically by the automation in two or more TCs.

5.2.3 Guideline to Derive Test Runs Based on Use Cases

According to the definition of verification and validation⁶, the result of a Test Case will provide information on whether the system meets the specifications and whether these specifications match the users' expectations. Furthermore, within IEEE Std 1012-2016 the essential purpose of verification and validation is described as to provide objective evidence for the systems conformity to requirements and the satisfaction of these requirements to meet the intended use and user needs.

Test Cases are representative models of a collective of use cases (Albers, Behrendt et al., 2016). According to Albers, Behrendt et al., 2016, 554 f. (2016), a general procedure for Test Run definitions cannot be described, as it is highly product- and use case-specific. Siller and Korotkiy (2011) present a requirements-based test strategy to derive Test Cases based on defined sets of requirements. However, within AD, contractually binding agreements on product functions or requirements between customer and supplier are not yet existent. Thus, testing activities need to represent user interactions with the system. However, Test Cases only have to represent as much as necessary in regard to the validation objective, both in terms of Stachowiak's model theory and the efficiency of testing (Berger, 2022). Thus, the development of Test Cases is often based on experience. To support a transparent formulation of Test Cases a guideline to support the derivation based on use cases is presented in the following (Taghavian, 2020)⁷. In Figure 5.7 a general overview and differentiation of the terms "Use Case", "Test Scenario" and "Test Case" is given.

⁶ See Chapter 2.4.1

⁷ Co-supervised thesis (unpublished)

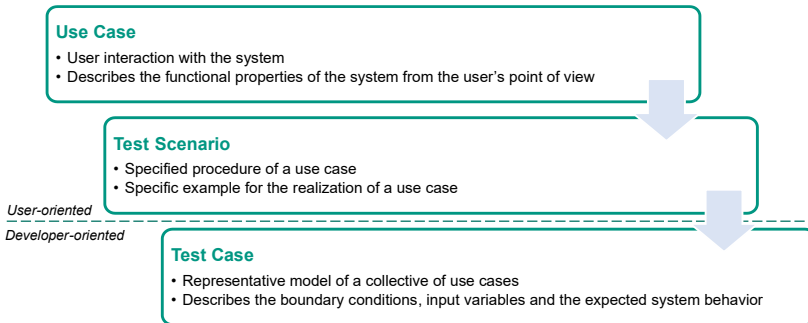


Figure 5.7: Overview and Differentiation of Use Case, Test Scenario and Test Case

A use case describes the user's interaction with the system from the user's perspective and is often formulated by verbs. An example of a use case could be the acceleration of a vehicle onto the Highway. According to Lamm and Weillkiens (2014) a use case consists of an activity which represents a system's function, an input/trigger of the activity and an output/cause of the activity. In the given example, pressing the accelerator pedal is the user input, accelerating the vehicle is the activity and the output is the increase in vehicle speed.

Test Scenarios describe concrete examples for the realization of use cases (Pohl, 2010). Furthermore, scenarios represent a specification of use cases that allow the user's interaction with a system to be clearly reproduced. Therefore, Test Scenarios add defined start and end states as well as system, boundary and environmental conditions. Additionally, these conditions must also be regarded as continuous and time dependent. With the example given, one Test Scenario specifies the vehicle acceleration from 50 km/h up to 100 km/h within 5 seconds at ambient temperature of 25 °C along with the further specification of the start/end states and other system, boundary as well as environmental conditions.

In contrast to use cases, which describe system functions from the user's point of view, Test Cases depict the execution of a technical function from a developer's perspective. From the user's perspective, the overall system is viewed as a non-decomposable, "atomic" system. Only with the understanding and technical background, the system can be decomposed into different subsystems. Test Cases consist of the relevant systems in regard to the validation objective. Additionally, Test Cases include criteria to evaluate whether the user's demand is fulfilled. A

guideline to derive Test Cases based on use cases and Test Scenarios is illustrated in Figure 5.8.

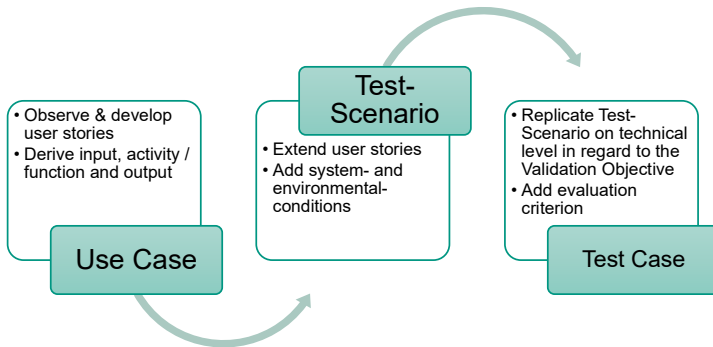


Figure 5.8: Guideline to Derive Test Cases based on Use Cases and Test Scenarios

The basis for developing use cases is a comprehensive understanding of how the user interacts with the product. User observations can be documented with user stories or user journeys (Brown, 2008). Methods like design thinking, customer interviews or questionnaires can support the creation of these user stories. A user story consists of a description of all interactions with the product. Moreover, for each interaction the input, activity/function and output can be derived and captured within the user story. As users have individual needs, a broad variety of different sequences of users' interactions with the product can be observed. However, there is a limited number of triggers, activities/functions and outcomes of the interactions which can be differentiated in use cases.

Test Scenarios can be used to depict the different combinations of the interactions, for example the change of start/end states or environmental conditions. Test Scenarios are used to further specify the user's interactions with the product. However, it must be noted that users usually think of only a limited number of scenarios. Consequently, for the investigation of Test Scenarios, either a large sample of users can be analyzed, or morphological analyses can be used to extend existing Test Scenarios. The specification of start/end states as well as systemic/environmental conditions can be captured within the user stories. In general, the number of possible Test Scenarios is very high.

With the transition from use cases and Test Scenarios to Test Cases, the perspective is shifted from the user to the developer. The developers' task is to replicate the relevant Test Scenarios on a technical level in regard to the present validation objective. Therefore, the system must be divided into its subsystems. Based on the validation objective, the SiD as well as its CS can be identified. Under consideration of the testing efficiency, Test Cases are often designed to cover a number of representative or worst-case Test Scenarios. With the detailed understanding of the user's interaction with the product (as in use cases and Test Scenarios) developers can derive requirements and thus evaluation criteria for each Test Step. The activities of deriving and refining requirements are subject to a continuous validation process.

A transparent documentation of the derivation process and consequent linking of Test Cases to use cases is the basis for an efficient system validation. Especially for the development of new product variants, a high share of requirements and Test Runs as of the reference product can be reused. However, for the development of new systems, reuse of requirements is prone to the risk of not meeting the user's needs.

Especially at an early stage of development, when few requirements have been formulated for the system, the guideline presented can support the derivation of further requirements and Test Cases. However, the derivation of Test Cases is particularly challenging in the role of the automotive supplier due to the uncertainty regarding the supersystem. Nevertheless, the systematic examination of the interaction between the user and the supersystem by the supplier is essential for the negotiation with the customer and the refinement of requirements.

5.2.4 Initial Evaluation of the Developed Methodical Support for Consistent Testing

The initial evaluation was conducted in a development project for ETDS at the AD department of MAHLE. The case study included two key roles: a software developer with six years of experience in software development and testing of mechatronic systems. His role included the allocation of relevant control signals and the analysis of the test results; a validation engineer with over ten years of experience in mechanical and mechatronics testing. His role included the implementation and execution of the test cases at two different TCs. The two engineers were instructed and supported by the author. The selection of participants was based on their experience and familiarity with the relevant elements. Data collection was conducted using a combination of observations, unstructured interviews and document analysis, focusing on the participants' experience and the effectiveness of the

developed method. Direct observations were made during the application of the developed method. Unstructured interviews were conducted with both participants to gather in depth insight into their experience with the methodological support. A thorough analysis of relevant documents was performed, including test case implementation, execution reports and analysis of test results. For the application of the methodical support a centralized location for the storage of Test Cases as for example a MBSE system model is required. Furthermore, a superordinate test automation tool such as ECU-Test is required for the implementation and execution of the Test Cases. The knowhow to establish the communication of the test automation tool with the TCs, for example with the given APIs is a further prerequisite. This knowhow was established and provided by the author prior to the case study.

For the initial evaluation of the developed method and tools an application example of a Test Case which addresses the rotor current control is given. The Test Case addresses a requirement regarding the stability of the rotor current in response to sudden changes to the stator current I_d . An extract from the generic Test Run implementation within the utilized test automation ECU-Test is displayed in Figure 5.9. The preconditions of the Test Case include the initialization of the systems, a communication check and the reaching of a reference operation point.

#	Action / Name	Parameter	Expectation / Value	Comment
65	Loop	len(n_set)	-> set_value_counter	loop defined setpoint list
66	Generic-Write: setSpeed_rpm	PHYS(rpm)	n_set[set_value_counter - 1]	ramp up EM-Speed
67	Wait	2 s		wait for stabilization
68	Generic-Read: Speed_rpm	PHYS(1/min)	n_set[set_value_counter - 1] +/- 3%	check speed with 3% tolerance
69	stimulate EM currents			set target currents
70	Generic-Write: set_id_A	PHYS(A)	ld_test[set_value_counter - 1]	
71	Generic-Write: set_lq_A	PHYS(A)	lq_test[set_value_counter - 1]	
72	Generic-Write: set_if_A	PHYS(A)	lf_test[set_value_counter - 1]	
73	Wait	timestep in s		

Figure 5.9: Extract from a Generic Test Run Implementation within the used Test Automation Tool ECU-Test to Analyze Rotor Current Control

In the Figure above, five Test Steps are shown. After the ramp-up of the EM speed (row 66 & 67) the expected speed is checked with a tolerance of $\pm 3\%$ (row 68). Subsequently, the commands to set the stator and rotor currents are executed (row 70-72). Within this implementation, the desired and expected values are stored in parameter lists (e.g.: “n_set”).

The TC consists of the physical ECU and virtual real-time models of the MCT, inverter and EM (alike the SiD in Figure 2.15). The real-time models are implemented on a Field-Programmable-Gate-Array (FPGA) which is controlled by a dSPACE system. For the communication with the ECU a universal measurement and calibration protocol (XCP) is established using a Bus network, which is controlled with VECTOR CANape⁸ software. Consequently, two communication ports are configured between the test automation and the TC. Relevant excerpts of the two mappings associated with the Test Run above are shown in Figure 5.10.

Name	Mapping type	Target
<ul style="list-style-type: none"> ▼ ECU <ul style="list-style-type: none"> setId_A setIq_A setIr_A 	CALIB	GenericECU/FOC_fidCmd_P
	CALIB	GenericECU/FOC_flqCmd_P
	CALIB	GenericECU/RCC_fSetIfCmd_P
<ul style="list-style-type: none"> ▼ EM_Data <ul style="list-style-type: none"> setSpeed_rpm 	MODEL	Plant model/Model Root/MDL/MECHANIC/Open_Loop_Speed[rpm]/Value

Figure 5.10: Excerpt of the Mapping Between the Superordinate Test Automation Tool (ECU-Test) and dSPACE (Model) / Vector (Calib) Systems

The generic names used in the generic Test Run implementation (Figure 5.9) are displayed on the left. Furthermore, the mapping includes two targets. The first is the ECU (Calib), where the target address refers to messages of the XCP. The second points to a path within the real-time model of the EM on the FPGA.

The generic approach enables the independent implementation of Test Runs in regard to the manufacturers of testing equipment and tools. Besides the reusability, the automation ensures comparability of Test Runs executed in different TCs. The initial applicants described the handling of the test automation tool as intuitive. The TC-independent structure shifts the main efforts for Test Run implementation from test bench control computers and operators to any developer in the back office and thus, can increase the test efficiency (Boog et al., 2021). However, the initial configuration of communication interfaces to the test equipment and tools is additional effort. To integrate all tools and unify the communication, new interfaces were implemented prior to the case study. These efforts can be declared as one-time efforts as existing interfaces can be reused across applications. The scope and

⁸ <https://www.vector.com/int/en/products/products-a-z/software/canape/>

limits of the Test Steps which can be implemented generically were refined iteratively to match all limitations of the testing tools within the validation environment. For example, the polling-cycle between the automation and the recipients must be considered for transient and fast operating Test Steps. If the execution time of the Test Steps is smaller than the polling cycle, test sequences must be transferred to the real time system of the tool which is acting as the stimulator.

To conclude the initial evaluation of the presented methodical support for consistent testing, a positive overall conclusion can be drawn. The generic implementation of Test Cases enabled reusability in all considered TCs and thus overall efforts for the testing activities were reduced. The utilized tool for the automation of the Test Case execution ensured flawless and repeatable system stimulations. In addition, further resources could be reduced or relocated by the automation of the Test Case execution. Long-term studies with a broad group of applicants to assess the persistence of the outcomes need to be conducted.

5.3 Digital Model Master

5.3.1 Method for Handling Modeling and Parameter Data

During the development and validation of mechatronic systems, numerous virtual and physical models are implemented and utilized. In Figure 5.11 the variety of models of the same subsystem as well as the different locations where the according parameter and modeling data are saved are illustrated. The models' purposes and thus, applications, scope and maturity differ within interdisciplinary teams. Among other things, models are utilized to characterize or describe systems, evaluate concepts, capture knowledge, develop and adjust designs or to support system integration and verification (Walden et al., 2015, 181f.). In terms of the application in the described process, models will either be characterized as descriptive models, which visualize or represent properties and interdependencies of the complex reality, or as simulation models which are used to analyze and predict the behavior of the reality. A simulation describes the implementation of any model in a specific environment and thereby allows the models execution over time (Engel, 2010; Walden et al., 2015, p. 181).

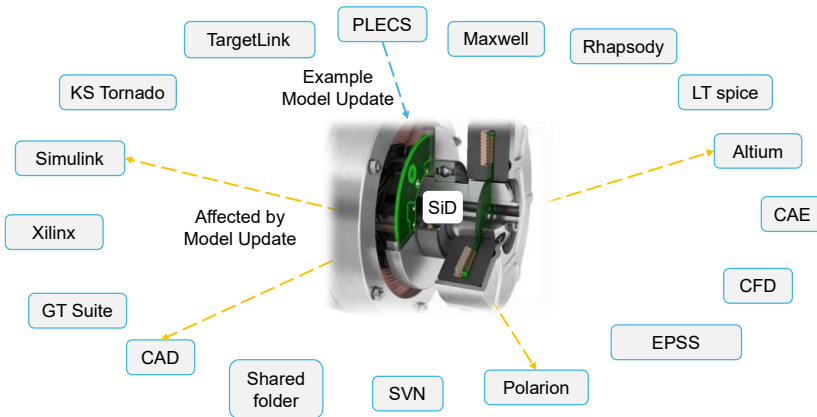


Figure 5.11: Excerpt of Virtual Models and Storage Location for Parameter and Modeling Data of the MAHLE Magnet-Free Contactless Transmitter⁹

The continuous knowledge generation by validation activities leads to adaptations or changes of the existing models. As the development and validation of all (sub-)systems are affected by the interacting systems, changes to the models can be both, the result to findings of the modeled system as well as the interacting systems. The interdependencies between models might lead to cascades of changes to multiple models (example indicated in blue and yellow arrows within Figure 5.11). With an iterative development and validation process, models are changed frequently. (Ewald et al., 2020; Pretschner et al., 2007)

To enhance the consistency of the system-related parameter and modeling data the Digital Model Master (DMM) is introduced (see Figure 5.12). The DMM serves as a unique platform for the exchange of system-related modeling and parameter data. Especially addressing interdisciplinary and distributed teams, the exchanged data can be accessed by all team members at all times during the development process. The DMM contains all data concerning system design as well as all behavioral model data. Starting at the beginning of the development process, the DMM serves as the

⁹ PLECS: Piecewise Linear Electrical Circuit Simulation, CAE: Computer-Aided Engineering, CAD: Computer-Aided Design, CFD: Computational Fluid Dynamics, EPSS: Electrical Power System Simulation, SVN: Subversion

only basis for modeling and parameter data. In highly complex systems, the development of TC is accompanied by the challenge of surveying available and most recent modeling and parameter data. With the DMM a single source of data simplifies development and analysis of TCs. Beyond the development of the system, the DMM also serves as a basis for a potential subsequent implementation of digital twins of the system (Stark et al., 2020). The following illustration (Figure 5.12) provides an overview of the concept of the DMM. (Kürten et al., 2021)

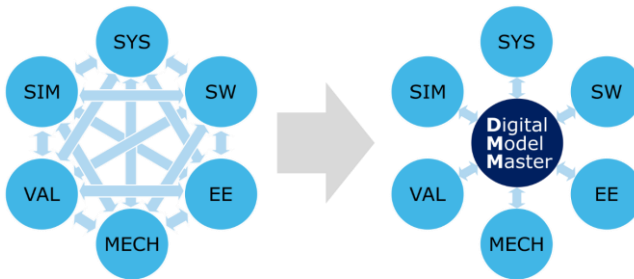


Figure 5.12: Digital Model Master Concept: From a Document-Centric (left) to a Model-Centric (right) Approach for Data Exchange between Domains of Mechatronic Systems (Kürten et al., 2021)

Building on the basic idea of MBSE, the goal is to shift from a heterogenous, document-centric approach to a consistent and interconnected understanding of the system. With the understanding of interconnectedness of the systems, the interactions between the (discipline specific) models are funneled by the DMM. Both, providing and accessing modeling and parameter data is enforced by the DMM. With the development of each Engineering Generation, an increase of the maturity level is aspired and thus complexity of the system, the interactions between the subsystems and its models rises. The DMM supports the documentation and handling of the used models' scope and complexity.

To elaborate on the exchanged data, an extract of the DMM data of an electric traction drive project at the AD of the MAHLE group is presented in the following. For example, the members of the mechanical design (MECH) team provide 3D-engineering data, technical drawings and mechanical parameter sets. Hardware design team (EE) distribute electric circuit diagrams and power electronics circuit models. Software releases, interface descriptions as well as controller flash data for rapid prototyping, debugging and diagnostics are covered by the software (SW) team. Simulation (SIM) and validation (VAL) team members are focused on system

variant parametrization as well as verification and validation models. The system (SYS) discipline provides functional system descriptions like the systems architecture and the requirements. (Kürten et al., 2021)

5.3.2 Architecture of the Digital Model Master

General requirements for a design support method are the ease of application and usability. Consequently, the reuse of already known structures for the DMM is appropriate. Architecture models (see Figure 2.10) of the SiD are designed in the initial development phases and are accessible for all members of the team (ISO/IEC/IEEE 15288, 2015). Modular validation approaches like the IPEK-X-in-the-Loop approach strive for seamless exchangeability of the subsystems. Consequently, initially built-up virtual models are replaced by physical prototypes/models during the development process.

Based on the four levels of system architecture abstraction according to Pearce and Hause (2012), the physical architecture (see Figure 2.10) defines a specific design implementation. Thus, the physical architecture is a model of the SiD detailed in real-world components like the physical prototype of the system. Therefore, the physical architecture defines the structure of the DMM. As a result, the access to the modeling and parameter data is identical for the setup of first simulations as well as for the physical prototypes.

In Figure 5.13 an extract of the physical architecture of an ETDS at MAHLE is illustrated. Additionally, the discipline-specific model containers of the DMM with examples of exchanged data are displayed.

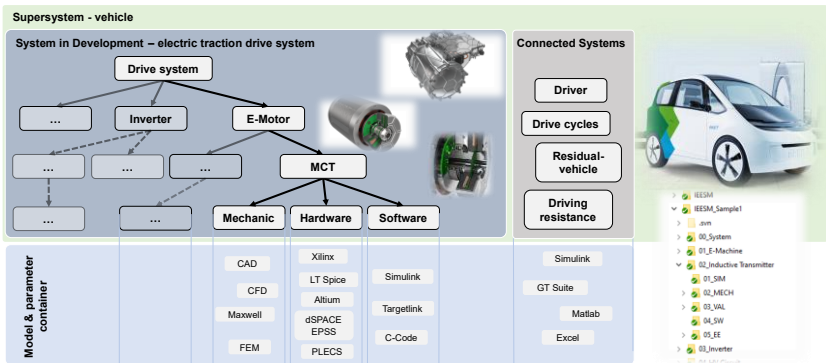


Figure 5.13: Linking of the Physical System Architecture and the System's Models in the Digital Model Master for the Example System in Development – Electric Traction Drive System

The presented structure specifically addresses the need for traceability of modeling and parameter data. The DMM serves as the only source of modeling related system data. From working surface pair to system level, the physical architecture provides intuitive and comprehensive access based on the real-life components. The DMM creates a direct connection between the descriptive system model and the simulation models of the subsystems (e.g., MATLAB/Simulink). The models affected by changes within the solution space are directly traceable by the DMM structure. Vice versa the effect of adaptations to the simulation model on the solution space is intuitively traceable as well.

The discipline specific containers define the responsibility of all provided and accessed data. Multiple representations of the subsystems are thus collected centrally and made available for use in independent evaluations (e.g., different types/variants of stators within the solution space). An independent server solution allows the access of the data from all modeling and simulation tools. Moreover, an automatic versioning tool enables full traceability of responsibilities and changes to all data provided.

The DMM structure allows selective reusability of subsystems beyond the boundaries of one project. Since the DMM links the used models to the architectural elements of the solution space like requirements and Test Cases, reference system elements for the planned reuse/carry-over variation of the subsystem are identified.

5.3.3 Development of Test Configurations with the Digital Model Master

To address validation needs, the team defines specific validation objectives. Validation objectives can be achieved by testing activities. In accordance with the validation objective, Test Cases are created. For the identification of suiting TCs to meet the validation objective, both available and desired models and parametrizations must be surveyed. Especially before the availability of physical prototypes, the task of finding satisfying configurations is accompanied by the challenge of maintaining an up-to-date overview of available model data as well as their suitability.

The DMM serves as the exclusive platform to provide modeling and parameter data for the development of TCs. Using the system's physical architecture as the structural architecture of the DMM allows for easy visualization of the required modeling and parameter data to setup the TC. The consequent usage of the DMM is ensured through continuous validation activities. Non-availability leads to a request by validation activities and thus triggers either the provision or creation of the necessary modeling and parameter data.¹⁰ However, the retrieval of the necessary data for the development of the TCs via the DMM must be monitored by a third party. Only by the access of modeling and parameter data from the DMM the traceability of the applied configurations is assured. In Figure 5.14 an excerpt of the data flow through the DMM for the setup of a TC is displayed.

¹⁰ According to the basic idea of the pull principle of validation (see Chapter 2.4.2)

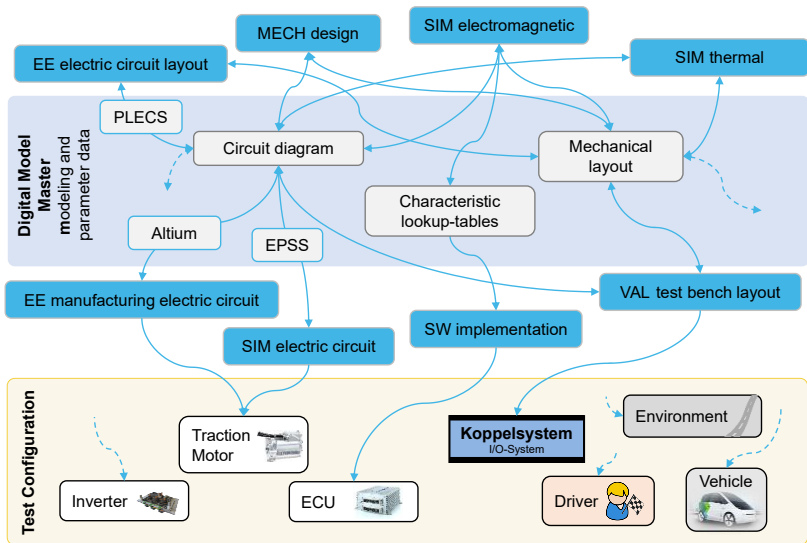


Figure 5.14: Excerpt of Modeling and Parameter Data Flow between Models / Systems for the Development of a Test Configuration at the Advance Development Department of MAHLE

The excerpt illustrates the complexity and interconnectedness behind the development of mixed virtual-physical TCs. The relevant modeling and parameter data for subsystems can be a result of multiple design and validation iterations of several disciplines. Often discipline specific tools are used. Changes to one representation of a subsystem invoke changes to other representations or even other subsystems (Dürr, 1999). Within the displayed excerpt a change of the electric circuit layout can be traced. A change of a diode's resistance value within the PLECS model has direct effects on multiple other models. As displayed, the PLECS model is connected to the real-time electric circuit simulation of the traction motor (EPSS) as part of the TC. When testing within the TC is initiated, the most recent modeling and parameter data such as the resistances of the diodes are directly accessible via the DMM. As indicated within Figure 5.14 further models, as for example the thermal simulation model, are affected and potentially need to be reevaluated.

5.3.4 Initial Evaluation of the Digital Model Master

The initial evaluation of the DMM was conducted within the AD department at MAHLE, focusing on its usability and the effects on the consistency of test results derived from various TCs. For this case study, the DMM was introduced to enhance the management of modeling and parameter data at three development projects. The infrastructure for the data exchange was structured according to the physical architecture and provided by the responsible system engineer. The usage of the DMM was enforced by the project managers. The introduction of the DMM at the MAHLE AD department was supported by a handling guideline on the utilization of the tool and a briefing of the engineers of all disciplines on how to use the DMM. Consequently, between 20 and 30 engineers from various disciplines were involved over the course of the nine-month evaluation period. Feedback was collected through direct observations, unstructured interviews, and document analysis of the relevant project documents. The analysis concentrated on two primary aspects: usability of the DMM and consistency of modeling and parameter data.

Usability of the DMM was evaluated by categorizing feedback from engineers into themes related to ease of use, accessibility, and clarity of the handling guidelines. The analysis also focused on the challenges faced by users, particularly those new to the versioning tool, and how these challenges were addressed in the developed guidelines.

The consistency of modeling and parameter data was assessed by comparing test results conducted in the TCs displayed in Figure 5.15 before and after the DMM's implementation. Instances of inconsistencies in modeling and parameter data were documented and analyzed to determine the DMM's impact on data integrity. The evaluation criteria employed included consistency of data and traceability.

After the introduction of the DMM, the supply of modeling and parameter data of the mixed virtual-physical TCs was updated to the DMM. The considered TCs represent the traction drive system of a vehicle (see Figure 5.15). The SiD is a 48 V ETDS which consists of the ECU, inverter and traction motor. The driver, vehicle and its environment are considered as the CSs.

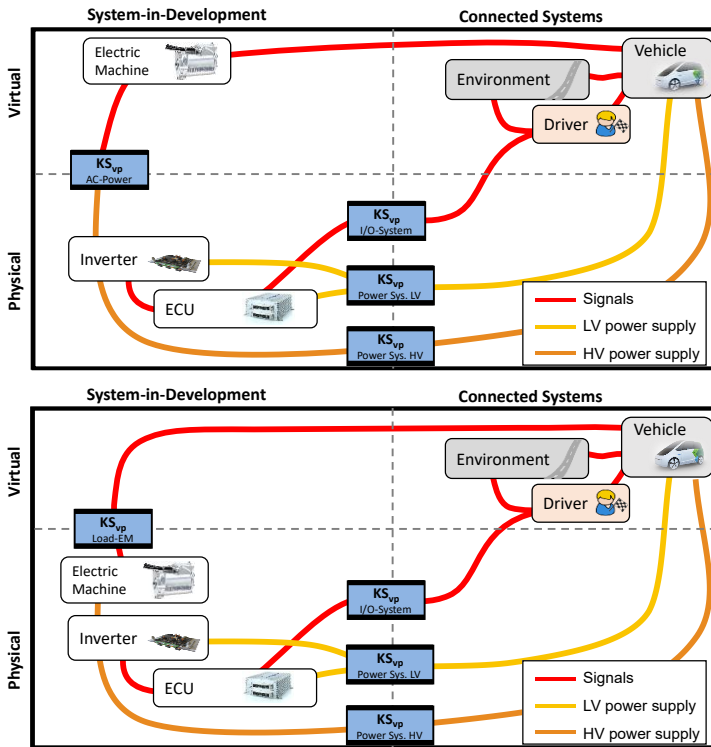


Figure 5.15: Schematic Architecture of Analyzed Test Configurations at the Advance Development Department of MAHLE,
 Top: Inverter Power Level Setup (P-HiL),
 Bottom: System Setup at Electric Motor Dyno Test Bench (EMT)

The main difference between the two setups is the form of the electric traction motor model. However, the shift from a virtual to a physical model is accompanied by major changes to the implementations at the test benches. The necessary Koppelsysteme to include a virtual traction motor into a physical inverter setup are described in detail by Boog et al. (2019). Essential for these inverter setups are the electrical loads which imitate the electric behavior of the electric traction motor. In the present research environment, two different test benches are utilized to implement the displayed configurations. As a result, both the test bench operating and control tools as well as the test bench operators differ.

In order to focus on the effect of inconsistencies in modeling and parameter data, the system under investigation for the evaluation of the DMM is the virtual vehicle model. The model represents the longitudinal dynamics of a smart fortwo eq¹¹ A-segment vehicle. For an overview of the behavior in different configurations, the energy demand of the vehicle during the worldwide harmonized light vehicle test cycle (WLTC – class 3¹²) is analyzed. The cumulated energy demand of the vehicle during the initial 450 seconds of the WLTC is displayed in Figure 5.16. On the left side the measurement of the cumulated energy demand at both TCs is displayed before the introduction of the DMM. On the right side the results of the repeated measurements after the introduction of the DMM are displayed.

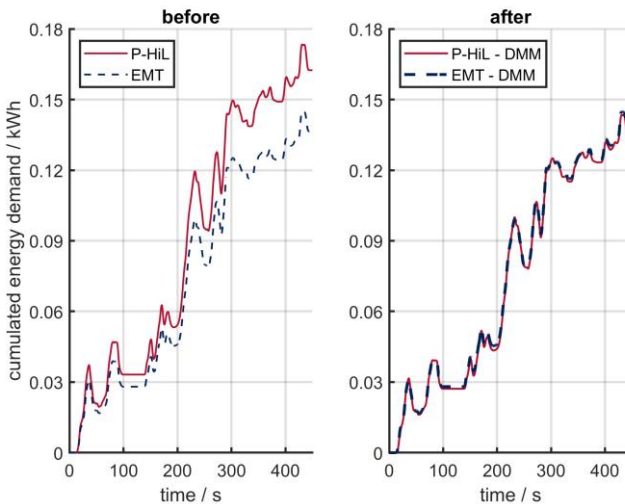


Figure 5.16: Impact of the Digital Model Master on Consistency in Model Behavior - Cumulated Vehicle Energy Demand at the WLTC at two Different Test Configuration at the Advance Development Department of MAHLE, Before and After the Introduction of the Digital Model Master

¹¹ <https://www.smart.mercedes-benz.com/de/de/modelle/smart-eq-fortwo-coupe#technische-daten-smart-eq-fortwo-coupe>

¹² Cycle definition according to Commission Regulation (EU) 2017/1151, 2017

Significant differences in the energy demand between the inverter (P-HiL, red) and motor (EMT, blue) TC are apparent on the left side of Figure 5.16. Due to the interdependencies within closed-loop setups the retrospective identification and allocation of differences is complex. In particular, the lack of traceability of the used modeling and parameter data prior the introduction of the DMM prevents a reliable resolution of the observed deviations. By interviewing the test bench operators and a systematic parameter variation, certain deviations due to different parameter sets could be assigned (Polaczek, 2021)¹³. The presented example, underlines that multiple small deviations in modeling and parameter data can result in accumulated high deviations (Kürten et al., 2021). In the given example the homogenization of modeling and parameter data leads to a substantial reduction of the differences between the two configurations (see Figure 5.16, right). Especially in AD, remaining differences between virtual system representations and physical systems can be caused by the given models' limitations. These limitations include among other things the utilization of models beyond its intended application purpose, the lack of detailed system understanding to accurately replicate the systems behavior and insufficient resources to sufficiently model the systems' complexity.

The results of the initial evaluation of the usability of the DMM indicate notable improvements in the availability and accessibility of exchanged modeling and parameter data. The handling guidelines provided a clear framework for usage, although some team members expressed a need for supervision to ensure consistent application across all disciplines. Minor difficulties encountered by new users of the versioning tool were effectively addressed in the guidelines, demonstrating a successful integration of user feedback into the support materials.

Furthermore, the analysis revealed a significant increase in the consistency of modeling and parameter data following the DMM's introduction. The DMM served as a single access point for data, reducing instances of inconsistencies. The automatic data versioning feature facilitated the tracing of discrepancies, thereby enhancing the reliability of testing outcomes. This improvement in data consistency allowed teams to focus on the suitability of models concerning the validation objectives, rather than on revising data inconsistencies.

The DMM established a dynamic connection between the MBSE system architecture model and the simulation models across disciplines. This linkage enabled teams to trace the effects of changes across all models, ensuring that

¹³ Co-supervised thesis (unpublished)

necessary adjustments or re-evaluations are initiated promptly. Furthermore, equal modeling and parameter data are used across all disciplines as the DMM serves as the single access point. Consequently, data inconsistencies are avoided in the first place or if present, are traceable with the automatic data versioning. Additionally, the traceability of testing activities is enhanced as the development of TC is supported and the up-to-date status of data used is ensured.

To achieve a comprehensive evaluation of the developed method, future research should focus on several key areas. First, a long-term study to assess sustainability of the impact of the DMM on data consistency and usability in the development projects needs to be conducted. Second, a larger sample size involving a broader range of engineering disciplines from different departments would enhance the generalizability of the findings. Third, incorporating quantitative metrics alongside qualitative feedback would provide a more robust evaluation framework. Finally, exploring the integration of advanced notification systems within the DMM could address user concerns and further improve collaboration among team members. By addressing these areas, the evaluation of the DMM can be significantly enhanced beyond the central findings of the conducted evaluation: Especially in system test, consistency of all modeling and parameter data is of high significance. Even small inconsistencies on component level can propagate significant changes to the system behavior.

5.4 Analysis of Test Cases and Classification of Test Configurations

The analysis of test results is subject to the validation need and the validation objective. Thus, each analysis is different and requires interpretation of the recorded data. The (non-)fulfillment of a requirement or an evaluation criterion is always related to the selected TC and must therefore be assessed by the engineer. In this chapter, a structured guidance to support the engineer with the analysis and comparison of test results is presented. Thereby, comparability is ensured and inconsistencies due to different validation engineers can be reduced. Furthermore, the guideline allows to shift the focus on the investigation of the unexpected deviations with regard to the models' reduction and pragmatic features. With the evaluation of the models' credibility, target-oriented activities can be derived to increase the maturity of the models and thereby strengthen and expand the use of virtual or mixed virtual-physical TCs. Due to the interdependencies between the subsystems, the isolated analysis and evaluation of a single subsystem's model poses several challenges. It is therefore proposed to extend the analysis and assessment of suitability with regard to the validation objective to the entire TC.

5.4.1 Standardized Data Postprocessing Guideline

The basis for comparability of various TCs is the ability to collect and process test results homogenously. However, due to the characteristic of the AD the used testing tools and equipment is inhomogeneous. Frequently changing setups define the heterogenous validation environments. As a result, often multiple tools are used for measuring and analyzing the systems' behavior.

In the following a standardized data postprocessing guideline is presented which serves as the basis for the analysis of test results and classification of the entire validation environment. To address different validation needs and allow extensibility the guideline is structured modular (Figure 5.17).

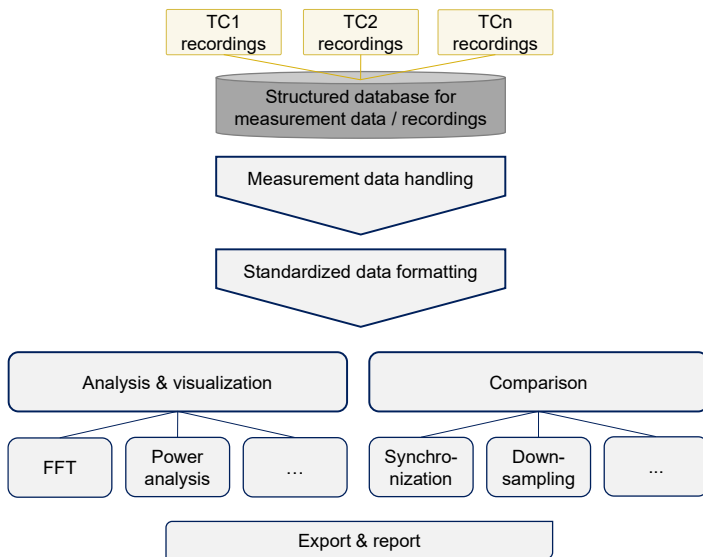


Figure 5.17: Overview of Features and Workflow of the Modular and Standardized Data Postprocessing Tool

In a first step, the relevant measurements and recordings of testing activities in any TC are stored in a central database. The database is structured based on the SiD, Test Cases and the time of execution. The approach to process the recorded data is guided by an implemented postprocessing tool whose main functionalities are displayed in Figure 5.17 (light gray). The tool is able to process all common formats

of recording files. With the standardized processing of the recordings, measurement data are formatted and made available in a consistent form. This provides a uniform platform for the analysis and comparison of the test results.

Besides arbitrary mathematical operations, data visualization and standardized exporting as well as reporting of test results, the comparison of measurement data from different Test Run executions is supported by the tool. Therefore, time synchronization and resampling of the signals is supported if necessary. Even when conducting Test Runs on the basis of the generic Test Run structure, signal synchronization might be necessary due to signal propagation delay on different systems. Identification of signal delays is done by the time-of-arrival metric (Schwer, 2007). The time at which a reference signal reaches a certain percentage of the maximum or a defined threshold value is determined. Due to the heterogeneity of TCs within one validation environment, various limitations for signal acquisition may exist. As a result, measurements with different sampling rates are common. For this case, two down-sampling algorithms are provided. In the case of integer multiples between the sampling rates as well as linear or low frequency signals, a reduction of the higher sampled signal by an integer factor is possible. As an alternative the utilization of the largest-triangle-three-buckets algorithm is supported (Abdelhalim, 2020)¹⁴. (Boog et al., 2021)

For repeating measurements, the processing procedure can be stored in templates. Thus, test results are processed identically and enable immediate comparisons by the testing engineer.

5.4.2 Method for Consistent Analysis and Classification of Test Configurations

A popular approach for the analysis of test results is the visualization of the time course of signals describing the behavior of the system. For the identification and evaluation of differences between the resulting measurements in different TCs, a joint illustration on a common axis is necessary. The approaches and tools developed within this thesis enable the direct comparison of different data qualities. The diagram in Figure 5.18 shows the comparison of a Test Run called “Torque Step”, where the time-based behavior of the EM torque in four different TCs is analyzed.

¹⁴ Co-supervised thesis (unpublished)

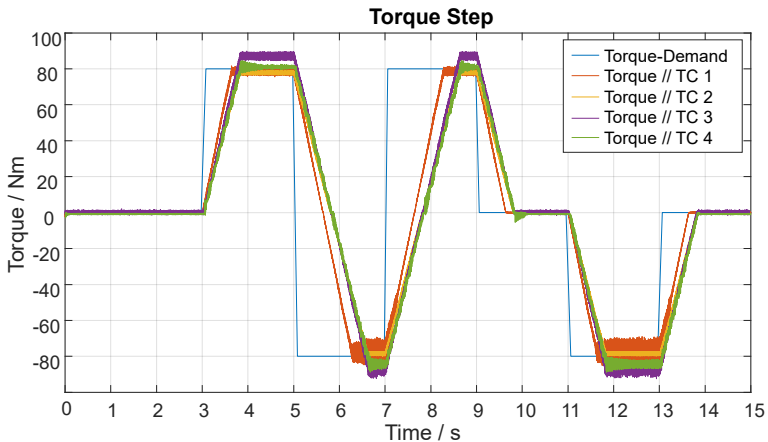


Figure 5.18: Exemplary Visualization and Comparison of Measurements from Test Configurations 1 to 4 for the Test Run “Torque Step” at the Advance Development Department of MAHLE

The displayed Test Run stimulates high load alternations on the system, which represent high stresses to the control algorithm and the utilized hardware. The visualization of the test results allows the immediate identification of deviations between measurements. For the displayed example of measurements in four different TCs, different gradients, amplitudes and oscillations of the EM are visible.

These visual evaluations are well suited for the initial analysis of the systems' behavior, especially when measurements of different system representations exist and can be compared to. Thus, the immediate feedback speeds up testing activities. Visualized deviations can be indicators for measurement or model uncertainties and therefore, they are initiators for subsequent in-detail analysis. The information value of diagrams like the one displayed above is always subject to the knowledge and experience of the analyzing engineer. Moreover, relying on the visual presentation only results in the risk that the engineers bias affects the analysis or that unwanted behavior can even be missed completely.

For the evaluation of models, objective validation metrics are needed. The usage of such metrics addresses the beforementioned weaknesses of graphical visualizations. Moreover, validation metrics provide objective indicators and thus, are essential to communicate the models' credibility towards customers (Oberkamp et al., 2004, p. 353). However, the effort involved in the model evaluation process

poses additional challenges for the development teams. Especially virtual systems tend to be developed in smaller but more frequent increments, than their physical pendants. According to the IPEK-X-in-the-Loop approach, the combination of virtual and physical subsystems can be accompanied by the usage of Koppelsystems. When changing a subsystem's domain, from physical to virtual or vice versa, the interdependencies between the systems can be affected by the utilized Koppelsystems, as well. Consequently, the isolated examination of a virtual system poses several challenges.

One of the central perspectives in the process of choosing suiting TCs to the present validation objectives is the technological perspective (Yan et al., 2018). Instead of looking at models individually, the following method is designed to consider the entire TC for the evaluation. To minimize the additional effort, the method is based on the usage of the methodical support for consistent testing and the DMM to enable consequent reuse and automation of Test Runs as well as consistent usage of the modeling data. Thus, all test results serve as a basis for the evaluation of the TCs. The sum of all individual evaluations of the TCs results in a classification of the entire validation environment.

With the classification, the approach addresses the question: "Which TC is suited to meet the validation objective?" (see also Chapter 2.4.7). In AD, when TCs are initially planned and built up, objective evaluation of the technical uncertainty is necessary to gain the stakeholders' confidence and for the utilization in the validation process (Kaizer et al., 2015). Objective evaluations are especially important for the utilization of virtual systems. The approach is designed to reduce the uncertainty regarding the technological suitability of virtual systems in validation and thereby aiming to increase the utilization of these. In Figure 5.19 the four steps of the approach for consistent analysis and classification of TCs in AD are illustrated.

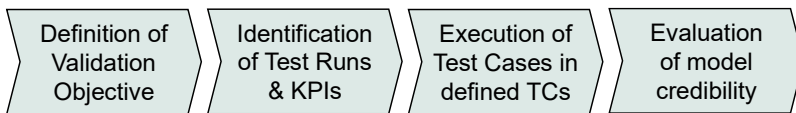


Figure 5.19: Method for Consistent Analysis and Classification of Test Configurations in Advance Development

In a first step, an aspired system property, function or behavior must be identified for the analysis. The corresponding validation objective must be defined or identified. Based on the validation objective and the corresponding system

properties (for example defined in requirements) Test Runs can be derived. The Test Run includes the relevant signals which are observed to analyze the system. Thus, Key Performance Indicators (KPIs), which provide a certain system feedback, can be identified for an objective evaluation. The technical implementation and measurement of these KPIs might differ between TCs. As an example, the current measurement can be executed by hall sensors in physical setups while the current is calculated analytical in a virtual setup.

With the validation objective, the required maturity/credibility in regard to the stage in the development process is defined. After the initial development of any model, the evaluation of its suitability must be conducted. The same applies to the use of TCs that have been set up in this way for the first time. Only the later product can serve as a reference to validate the model. However, during the development, TCs with a higher share of physical models must serve as the reference for the evaluation as products are not yet available. Also, physical models such as physical prototypes of the product are still a model of the later application. Consequently, model validation is never completed. For the classification of TCs, the reference TC as well as at least one TC which is to be evaluated must be defined for the investigation.

The central step for the classification is the execution of consistent and traceable Test Cases in the defined TCs of the validation environment. Only by a consequent reuse of Test Runs across all considered TCs¹⁵ and homogenous modeling data¹⁶, the subsequent comparison and classification is possible. Based on the validation need, suiting statistical measures must be defined for the analysis and evaluation of the measured data. Accordingly, these measures differ for needs in the AD like the knowledge generation or initial error detection and to the needs close to the start of production. The scope and depth of the KPIs and their analysis must match the stakeholders' expectations for the model credibility.

Alike validation, the classification of the TCs can be seen as a continuous and iterative activity. Each loop, through the four-step approach provides a snapshot, and the sum of many snapshots contributes to the credibility of the classification. The consideration and documentation of several peculiarities support the built up of credibility. For example, before the comparison of different TCs, the Test Runs should be repeated within one TC several times to evaluate the repeatability and measurement uncertainties. Additionally, measurement data from physical setups

¹⁵ See Chapter 5.2

¹⁶ See Chapter 5.3

are often used to calibrate and parametrize the models. The comparison of these calibrated models can lead to overfitted models to specific applications. Therefore, large datasets, where both measurements used for parametrization and divergent measurements, are aspired to be used for the classification.

5.5 Summary of the Developed Methodology

In order to increase development efficiency, the usage of virtual and mixed virtual-physical TCs is inevitable. However, the stakeholders' doubts regarding the credibility of models are ubiquitous (Gausemeier et al., 2013, 39). Nevertheless, the trustworthiness of modeling and simulation is essential to the acceptance of model-based development and validation approaches (Kalawsky, 2010, p. 44). In spite of the fact that the usage of models is established in the industry, no theory has been established on how to verify and validate TCs (Durst et al., 2017). Model credibility can be increased by demonstrating that the models result to various stimulations do not exceed certain deviations from the values in the field (Klingler, 2017, p. 33). In practice, these investigations are always associated with additional financial and human resources (Kutluay & Winner, 2014, p. 187). However, the flexibility of simulation models promotes frequent changes of the models and thus requires continuous validation with full traceability. The methodology presented in this thesis addresses these contradictions with the methods shown schematically in Figure 5.20.

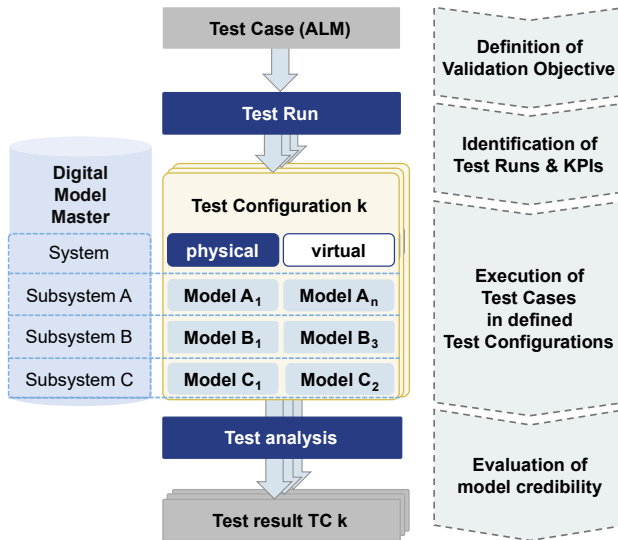


Figure 5.20: Methodology to Support Consistent and Flexible Validation in Advance Development of Mechatronic Systems

On the left side of Figure 5.20, a schematic excerpt of a modular validation environment consisting among other things of Test Case definitions, Test Run implementations, the DMM, TCs, Test Analysis and test results is displayed. To the right, the method for the analysis and classification of TCs is illustrated.

The validation environment includes the methods introduced within this thesis to answer the second research question. Based on functional Test Case descriptions, the generic Test Run implementation is supported by the presented method (Chapter 5.2.1). Moreover, the methodical support for consistent testing includes a guideline (Chapter 5.2.3) to derive Test Cases based on Use Cases and the developed method for communication of the superordinate test automation tool and the TC specific operation tools (Chapter 5.2.2). This ensures consistent and automated stimulation of the SiD as well as its CS independent of the TC. The utilized test automation tool is constituted in such a way that documentation of testing activities is structured and partly automated. Thus, traceability of performed activities is increased and consequent reuse of Test Runs facilitated.

As indicated in Figure 5.20 the modular validation environment comprises of multiple virtual, mixed virtual-physical and physical TCs. The DMM ensures that all models within the validation environment are based on identical modeling and parameter data (Chapter 5.3.3). The exchange of modeling and parameter data in interdisciplinary teams is funneled by the DMM and the consistent propagation of changes to models is assisted (Chapter 5.3.1). Additionally, the DMM interlinks the physical architecture of the system model¹⁷ with the discipline-specific simulation models (Chapter 5.3.2). Thus, the developed methodical support aspires to enable consistent and traceable validation from idea generation to functional prototypes in AD.

In order to increase flexibility of validation, credibility of virtual and mixed virtual-physical TCs must be enhanced. With the utilization of the method and tool for consistent testing and the DMM comparability of test results is improved. The standardized data postprocessing guideline (Chapter 5.4.1) supports a uniform test analysis and enables visual comparability of measurement data. The proposed method for consistent analysis of TCs (Chapter 5.4.2) supports the objectivation of strengths and misconceptions of the model-based approaches and thereby provides an answer to the third research question. With the proposed methods and tools to seamlessly repeat and compare Test Runs executed within different TCs, the additional efforts for the evaluation of the utilized models are attempted to be kept as low as possible.

¹⁷ Descriptive model as the basic element of MBSE

6 Initial Evaluation of the Proposed Methodology

In this chapter the application and evaluation of the methodology, its methods and tools developed in Chapter 5 are elaborated. The evaluation of the proposed methodology took place in the AD department of MAHLE. To allow both the direct support of the engineers by the author and direct feedback regarding the proposed methodology, the case studies took place within running development projects. Integration of the evaluation into ongoing development processes without special training ensures high validity. Furthermore, the applicants and the author are able to directly identify potential for improvement of the methodology. It should be noted that the reproducibility of case studies in the industry is lower compared to Live-Labs or laboratory studies. In Figure 6.1 an overview of conducted case studies and the therein addressed elements of the proposed methodology is given.





DS II: Initial Evaluation of proposed Methodology								
Case study:	Rotor current control 		Vehicle model 		EM current control 		Operation strategy 	
Element:	Usability	Impact	Usability	Impact	Usability	Impact	Usability	Impact
Test Run	✓	✓			✓	✓	✓	✓
DMM			✓	✓	✓	✓	✓	✓
Test Analysis					✓	✓	✓	✓
Classification					✓	✓	✓	✓

Figure 6.1: Overview of Case Studies and Addressed Elements of the Initial Evaluation of the Proposed Methodology (Descriptive Study II)

As displayed in the Figure above, four case studies were conducted. In the first case study (Chapter 5.2.4) the method for consistent testing was applied on the verification of the rotor current control and evaluated both the usability and the technical impact of the proposed method. The applicability and the technical impact of the DMM is evaluated in the case study regarding the vehicle models at different TCs (Chapter 5.3.4). The results from two comprehensive case studies at the AD department of MAHLE are presented in Chapter 6. Both examples are part of the

development of an inductive externally excited synchronous machine (IEESM), which is presented in Chapter 6.1. The described examples (Chapters 6.2 & 6.3) target the initial evaluation of the usability and technical impact of the developed methodology. The two following examples incorporate the application of the methodical support for consistent testing, the DMM and the method for consistent analysis of TCs. The exemplified classification of the used TCs and the technical impacts on system development are presented in Chapter 6.5. As it is not the focus of this thesis the observed technological phenomena are not explained in detail.

In accordance with the Action Research approach¹, the author was part of the validation team of the two regarded case studies. Accordingly, he coordinated and supported the usage of the developed methodology over the course of several EGs. The engineers from all disciplines contributed to the usage of the DMM and thereby served the validation team for setting up the described TCs. The generic test run implementation and execution was conducted by two software and three validation team members under the supervision of the author. The applicants were chosen based on their expertise and experience with the development processes and the SiD. The test case analysis, interpretation and evaluation of the regarded TCs were coordinated by the author and supported by seven engineers from different disciplines. All results were discussed among the project team members and stakeholders. For the evaluation of the applicability and understandability of the proposed methodology (Chapter 6.4), both unstructured face-to-face interviews as well as plenary sessions where all participating engineers and stakeholders discussed different viewpoints, were conducted. The impact on the validation outcome, mainly consistency and flexibility of the validation environment is assessed based on the relevant documents which were created, used and analyzed during the testing activities (Chapter 6.5).

6.1 Development Project – Inductive Externally Excited Synchronous Machine

Permanent-magnet synchronous machines (PMSM) are predominant in the automotive market due to their high-power density and durability. However, the ecological impact and economic uncertainties regarding the rare earth magnet materials lead to a strategic search for alternative machines (Bailey et al., 2017).

¹ See Chapter 3.2

EESM use excitation coils instead of magnets to generate the magnetic field of the rotor. Furthermore, EESMs are well suited for the application in electrified passenger cars due to their efficiency characteristics. The efficiency of EESMs at partial load, which is the most frequent operation area at the application in passenger cars, is higher than the efficiency of PMSMs. In addition, EESMs typically display higher efficiency than PMSMs in the high speed area. (Finken, 2011; Müller et al., 2023)

State of the art for the connection of the rotor coils within EESMs are carbon brushes and slip rings. However, the downsides of this connection type are the electrically conductive abrasion due to sliding friction between the carbon brushes and the slip rings and the high variation of the contact resistance due to aging and manufacturing tolerances. Furthermore, these contacts have to be replaced when their wear limit is reached. The mentioned development project at the AD of MAHLE addresses these issues by replacing the conductive system with an inductive power transfer system called the MAHLE Magnet-free Contactless Transmitter (MCT). (Grelle et al., 2021)

The MCT can be divided into three subsystems: the electronics on the primary side, the rotating transformer and the electronics on the secondary side (see Figure 6.5). The electronics on the primary side are used to control the excitation current of the rotor. With the inductive system, these electronics act as a single-phase current inverter to provide the AC² voltage for the rotating transformer. The transformer enables the contactless energy transmission from the stationary (primary) winding to the rotor (secondary) winding. The electronics on the secondary side act as a rectifier of the AC voltage into a pulsating DC voltage which is needed for the rotor excitation. The high inductance of the rotor coils smooths the excitation current within the rotor.

6.2 Case Study – Current Control of the MAHLE Magnet-free Contactless Transmitter

At the time of the case study, a central challenge regarding the development of the MCT was the rotor current control. The rotor current is directly linked to the EM torque and thereby to the vehicle acceleration and deceleration. Consequently, stable and accurate rotor current control is necessary to ensure the drivers safety and comfort. With the introduction of the rotating transformer a direct measurement

² AC: alternating current

of the DC rotor current at the stationary side becomes physically impossible. Placing a current transducer on the rotating side and transmitting the measured data back to the stationary side is not wanted due to its disadvantages as for example the necessary additional wireless signal transfer system or the needed power supply in the high temperature rotor environment (Illiano, 2014, p. 23). In this case study, the uncertainty regarding the accuracy and stability of the rotor current control of the IEESM including the newly developed MCT is perceived as the validation need.

The development of the IEESM can be described as the development of a system with a high share of new development since a wireless power transfer system has not yet been developed within the entity up to the start of this project. Consequently, during the time of the case study, the main focus is laid on knowledge generation regarding the new system. Based on the validation need, multiple validation objectives regarding the rotor current control are derived. Validation objectives vary from the identification of system requirements as for example in the maximum tolerable overshoot of the rotor current due to stator current changes, to the evaluation of the design and parametrization of the current control algorithm. To enhance the system understanding, the magnetic coupling between rotor and stator was investigated in further detail. A benefit of EESMs is the fast rotor demagnetization to quickly remove the machine torque for safety reasons. The effect of the MCT on the rotor demagnetization must be investigated and for the design of the rotor current control algorithm, the electromagnetic coupling between rotor and stator must be considered to ensure stable and accurate current control. Accordingly, the validation objective within this case study targets the investigation of the rotor current behavior in response to stator current changes.

6.2.1 Electromagnetic Coupling Between Stator and Rotor

The electromagnetic field of the rotor and the stator overlap inside the EM. For the consideration of this validation objective, the calculation of the rotor voltage is described in detail. Based on Equation 6.1 the rotor voltage U_r is dependent on the rotor resistance R_r and rotor current I_r as well as the change in magnetic flux linkage of the rotor Ψ_r .

$$U_r = R_r \cdot I_r + \frac{d\Psi_r}{dt} \tag{6.1}$$

The magnetic flux linkage of the rotor can be calculated according to Equation 6.2, where L_{rr} is the main inductance and L_{rd}, L_{rq} are the mutual inductances between the rotor and the direct/quadrature axis of the stator.

$$\Psi_r = \frac{3}{2} \cdot (L_{rd} \cdot I_d + L_{rq} \cdot I_q) + L_{rr} \cdot I_r \quad 6.2$$

Thus, the magnetic flux linkage of the rotor is also dependent on the stator currents in the direct axis I_d and in the quadrature axis I_q . The voltage equation for the rotor can be rearranged accordingly (Equation 6.3):

$$U_r = R_r \cdot I_r + L_{rr} \cdot \frac{dI_r}{dt} + I_r \cdot \frac{dL_{rr}}{dt} + \frac{3}{2} \cdot \left(L_{rd} \cdot \frac{dI_d}{dt} + I_d \cdot \frac{dL_{rd}}{dt} + L_{rq} \cdot \frac{dI_q}{dt} + I_q \cdot \frac{dL_{rq}}{dt} \right) \quad 6.3$$

Consequently, for stationary operation points U_r is dependent on R_r and I_r only. The inductances are dependent on the currents flowing in the stator and in the rotor $L = f(I_d, I_q, I_r)$. Therefore, changes to the currents affect the rotor voltage by both the derivative of the current as well as the changing inductances. (Schröder, 2015, 986 ff.)

6.2.2 Test Case Planning – Current Changes

Based on Equation 6.3 the magnetic coupling between the stator and rotor can be assessed with quick changes to the rotor current I_r as well as stator currents I_d and I_q . Accordingly, a Test Run has been defined as displayed in Figure 6.2.

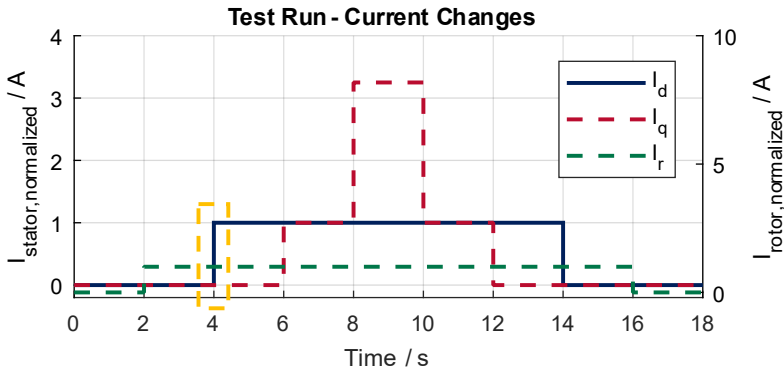


Figure 6.2: Schematic Overview of the Rotor and Stator Current Setpoints for the Test Run – I_r, I_d, I_q -Current Changes

In the Figure above, the schematic sequence of the current changes is illustrated. On the left y-axis, the stator currents I_d (blue) and I_q (red) are plotted, while the rotor current I_r (green) is displayed on the right y-axis. Every two seconds a change in the displayed currents is visible. With the present time constants of the stator and rotor winding and the requirements on the control system, the system stabilizes within milli-seconds after the changes. First, a rotor field is established, then the stator field in the direct axis (d-axis) is built up before the stator field in the quadrature axis (q-axis) is sequentially increased. Subsequently, the reduction of the currents is implemented in a similar manner to the increasing steps. The preconditions regarding the SiD for the execution of the Test Run include constant machine speed, constant temperatures of the SiD and all machine currents set to zero.

Based on the validation objective, the relevant elements for the TC can be identified. The SiD consisting of the ECU, inverter, MCT and EM as well as the CSs vehicle, driver and environment need to be implemented within the TC. For the investigations of the electromagnetic coupling behavior, the elements of the TC should be as close to the later application as possible. Furthermore, a highly virtual TC is aspired to be able to quickly adapt SiD designs and thus, evaluate the effects on the rotor current control design and parametrization.

For the following analysis the excerpt (yellow) of the displayed Test Run where the stator current I_d is increased is consulted in detail. The stator current control of I_d and I_q is in closed loop control. The Test Run can be executed for both the open loop and closed loop control of the rotor current control. In open loop mode, the

effect of the stator currents on the rotor current can be investigated, while in closed loop mode, the response of the rotor current controller is inspected. As the validation objective is targeting knowledge generation regarding the system behavior in respect to the electromagnetic coupling, the expectations regarding the test results up to the considered point in the development process are limited to the theoretical relations.³ Thus, for the considered sequence, the rotor current is expected to increase during the change in the stator current.

Further, subsequent validation objectives address the requirements regarding the maximum permissible change in the rotor current based on the needed torque stability of the motor. Thereby, the design of the transformer as well as the design of the control algorithm are affected. A suiting TC is being sought to evaluate these changes.

The functional description of the Test Case is stored in the ALM tool and thus serves as the basis for the implementation within the test automation tool. The generic implementation of the Test Run in the test automation tool is successfully supported by the presented method.⁴

6.2.3 Test Configuration TC 4 – EMT

During the period of the development project in which the case study took place, the first prototype of the MCT is designed. Consequently, for the first system of this kind, a physical setup to prove the technological functionality is needed. To reduce uncertainty regarding the new system, multiple TCs are realized for the investigation of different validation objectives. For example, a dedicated TC is used to evaluate the mechanical stability of the rotating electronics on the secondary side.

For this case study, the rotation of the SiD was neglected by adding a brush system to the TC. In this way, the focus is placed on the electro-magnetic behavior of the system while mechanical uncertainties are neglected. Thus, the design of the first Engineering Generation is simplified and thereby the development time is reduced. A schematic of the referred TC is displayed in Figure 6.3.

³ See Chapter 6.2.1

⁴ Similar to the implementation presented in Chapter 5.2.4

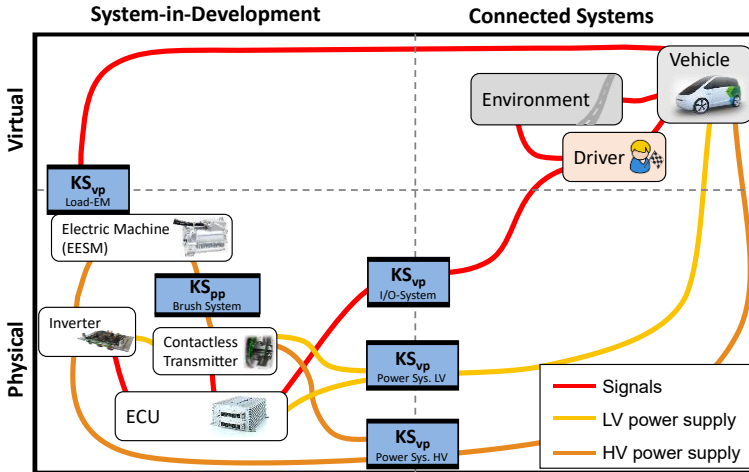


Figure 6.3: Schematic Architecture of the Test Configuration 4 – EMT at the Advance Development Department of MAHLE

The displayed schematic is structured according to the IPEK-X-in-the-Loop approach as described in Chapter 2.4.4. All subsystems of the SiD are realized in a physical form. The CSs, vehicle, driver and the environment are represented virtually. The connecting lines represent the signal and power connections of the subsystems. Additionally, the TC consists of five Koppelsysteme:

- KS-Load-EM: mechanical connection of the traction motor, the load machines behavior is supposed to represent the driving resistances within the vehicle application
- KS-I/O-System: signal connection to transform the drivers command into readable commands for the drive systems ECU (in this case implemented as a CAN-BUS-System)
- KS-Power sys. LV: low voltage power supply for the power electronics
- KS-Power sys. HV: high voltage power supply for the inverter and the MCT
- KS-Brush System: carry-over of the brushed slip-ring power conduction to the rotor winding

The KS between the MCT and the electric motor, the brush-based rotor conduction system is used to reduce the uncertainties of the new system. Based on the model

of SGE – System Generation Engineering by Albers the development risk increases with the share of new development. Here, this principle is transferred to the development of TCs. The more unknown systems are introduced into a set-up the more uncertainty regarding the observed effects emerges. Additionally, to introduce the MCT into the traction drive system, mechanical rework of the EM is necessary. By utilizing the existing brush-based motor setup, early testing of the MCT in the system context is enabled. Based on the electromagnetic description, the introduction of the considered KS should not significantly affect the electromagnetic coupling between the rotor and stator of the EM. The electric connections of the KS are kept short to minimize the changes of the rotor resistance and inductance. In Figure 6.4 a picture from TC 4 within the electro-mobility test field at the AD department of MAHLE is displayed.

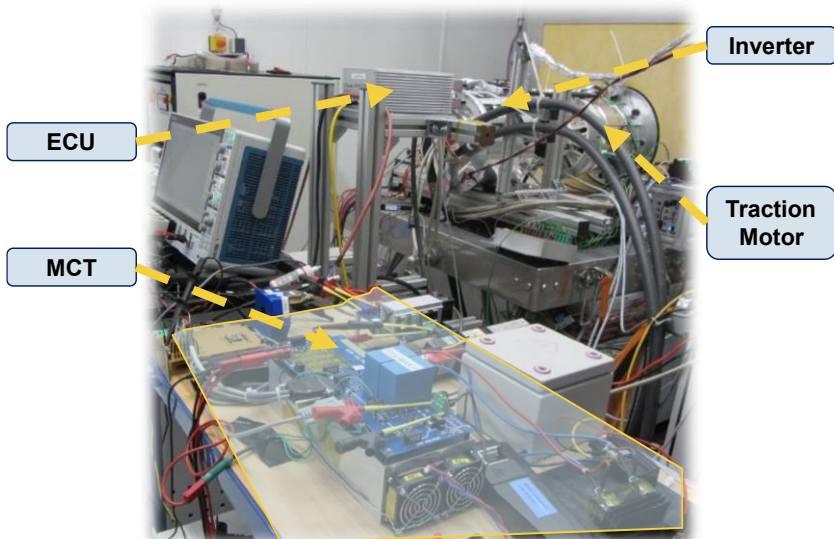


Figure 6.4: Test Configuration 4 – EMT at the Advance Development Department of MAHLE with ECU, MCT, Inverter and EESM

6.2.4 Test Configuration TC 2 – S-HiL

In the role of the automotive supplier the ability to quickly respond to customer requests and to adapt the developed design to create new system variants is

essential for success. The profitability of the supplier often depends on supplying several customers with the same or only a slightly adapted product. Based on the vehicle design, the supersystem of the IEESM, customers raise different requests regarding the design of the MCT. At this early stage of the development process, implementability of customer requirements is not investigated in detail. However, basic functionality of different designs and the limitations of design variations are systematically analyzed. These investigations are closely linked to the maturity level of the SiD.

For the design and parametrization of the rotor current controller a highly virtual TC is developed in addition to TC 4. A convenient time to answer customer requests in a highly competitive industry falls short of the design and development of a physical prototype. Thus, new designs must be validated in virtual TCs. With the use of simulation models of the EM and MCT, the effects of (electric) design changes, due to changing customer requirements such as changes of the rotor or mutual inductances, on the parametrization of the control algorithm can be quickly evaluated. However, in terms of the general model properties (reduction/pragmatic/cost-effective feature), many assumptions and simplifications must be made when developing and implementing such virtual TCs. A suitable trade-off between the representations accuracy and the time needed to present first results must be found. An existing TC which was initially built up for the control development and testing of a brush-based EESM is modified. The model of the brush-based EESM is extended by a real-time model of the MCT and the rotor-stator coupling behavior according to Equation 6.3. All relevant modeling and parameter data of the newly developed model are stored and connected in the DMM. Furthermore, the utilization of identical modeling and parameter data within the different TCs is ensured by the DMM. The wiring schematic of the real-time MCT model is illustrated in Figure 6.5.

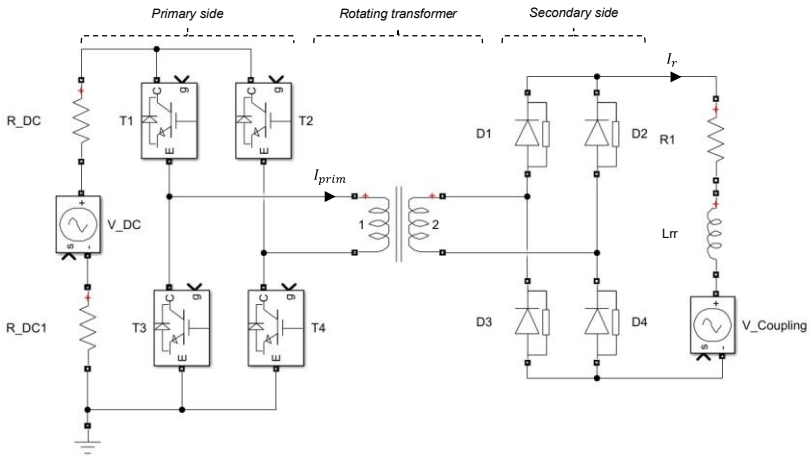


Figure 6.5: Wiring Schematic – DC Source, MCT and Rotor with Consideration of Rotor-Stator-Coupling (EPSS)

As displayed, the model is implemented in MATLAB Simulink and the usage of the Simscape Electrical⁵ libraries. The configuration and execution of the FPGA-based real-time model is supported by the dSPACE Electrical Power Systems Simulation (EPSS)⁶ package. This approach allows the flexible and quick adaptation of the key design parameters of the MCT such as the inductances and resistances of the transformer. On the primary side the full bridge converter, consisting of the four controlled transistors (T1-T4), is supplied by the DC voltage “V_DC”. Transformer excitation is realized by the phase shift of the PWM-signals of the two half-bridges. The rectifier on the secondary side consists of four diodes (D1-D4). The substitute voltage source “V_Coupling” is used to represent the coupling effects of the stator field on the rotor voltage according to the second row of Equation 6.3. The calculation of the voltage source value is implemented within the simulation model of the stator. The modeling and parameter data as for example the rotor inductance “L_{rr}”, are supplied by the DMM. Furthermore, the compiled model of the MCT is provided in the DMM itself. Thus, for the development and implementation of the TC all modeling and parameter data alike the MCT model can be accessed in the DMM.

⁵ <https://www.mathworks.com/products/simscape-electrical.html>

⁶ <https://www.dspace.com/en/ltd/home/products/sw/impsw/epc-sim-pack.cfm>

The displayed model replaces the model of the brush-based conduction system. The resulting, highly virtual, TC is displayed in Figure 2.15. A picture from TC 2 within the electro-mobility test field of MAHLE AD department is displayed in Figure 6.6.

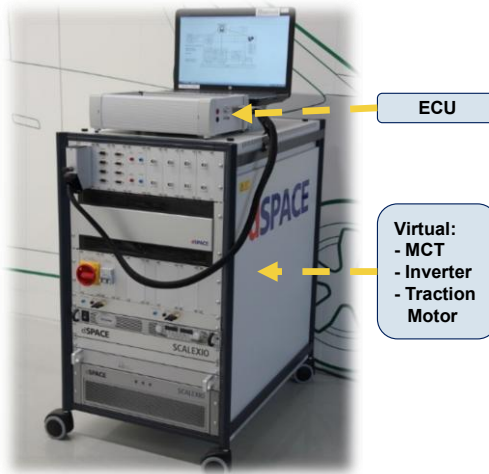


Figure 6.6: Test Configuration 2 – S-HiL at the Advance Development department of MAHLE with ECU and Simulation Platform of MCT, Inverter, EESM and Connected Systems

The development and extension of this TC serves as an example for the simultaneous development of the SiD and its validation environment in AD projects. The highly virtual TC offers great flexibility regarding the testing of different designs. However, for the validation of the used models, the comparison with physical implementation is necessary and thus, the validation of the models itself requires many resources. For the usage of such virtual TC in product validation, a continuous evaluation and classification of the TC is needed. Consequently, the performed investigations regarding the electromagnetic coupling between rotor and stator within TC 4 are repeated in TC 2.

6.2.5 Test Case Analysis and Interpretation – Current Changes

To increase flexibility in validation, the proposed approach is focused on the analysis and classification of TCs. The evaluation of the TCs suitability regarding the validation objective increases flexibility regarding the usage of the considered TCs

for future validation activities. The present validation need regarding the rotor current control is extended by the investigation of the highly virtual TC 2 regarding its strengths and limitations. With the given example the following question is investigated: “Is the developed Test Configuration (TC 2) suited to meet the validation objective?”.

For the evaluation of TC 2 a detailed comparison with the reference (in this case TC 4) is conducted. The basis for the comparison is a modification of the Test Case described in Chapter 6.2.2. The TC is adapted accordingly, while the Test Run and preconditions are kept constant. The subsequent Test Case analysis focusses on the impact of the stator current change I_a on the rotor current I_r (yellow circled sequence in Figure 6.2). For the objective evaluation of the rotor current behavior the following three KPIs are identified:

1. Maximum amplitude of the rotor current deviation
2. Rise time – defined as the duration of the rising signal from the reference value up to 90 % of the maximum amplitude
3. Fall time – defined as the duration from maximum amplitude to the point where 101 % of the initial value is reached

For the analysis and comparison, the identical generic Test Runs created according to the generic implementation method, can be reused and executed in both TC 2 and TC 4. The modeling and parameter data used in both TCs are provided by the DMM. The used tool for the execution in both TCs automatically tracks the used modeling and parameter data and thus ensures consistency between the models. The recorded measurement files are processed by the developed tool. Accordingly, the measured and normalized stator and rotor current for both Test Cases are jointly illustrated in Figure 6.7. The rotor current control is in open-loop mode, thus a constant phase shift is applied within the displayed time frame.

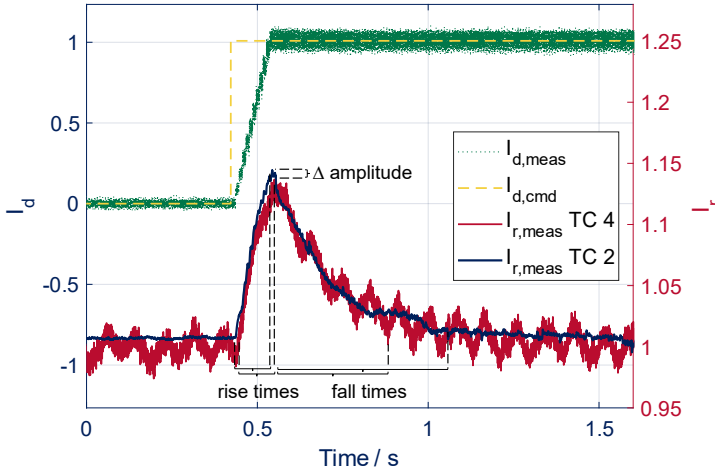


Figure 6.7: Comparison of Rotor Current Response Measurements from TC 2 and TC 4 – Excerpt of Test Run Current Changes

The figure above shows the stator current on the left y-axis and the rotor current on the right y-axis over time. Based on the consistent test automation, the stimulation of the system, in this case, the stator current change $I_{d,cmd}$, is identical for the execution in both TCs. The resulting measured stator current increase is limited by the identical stator current control parametrization (ensured by the DMM). Due to the identical behavior of the stator currents in both TCs and for the purpose of simplicity, the stator current command $I_{d,cmd}$ and measurement $I_{d,meas}$ is displayed only once. The system responses in form of the rotor current are displayed for the execution in both TCs – $I_{r,meas} TC 4$ (red) and $I_{r,meas} TC 2$ (blue).

With the positive step in stator current I_d , the magnetic flux in the direction of the rotor flux (d-axis) increases. As expected, in open-loop control mode the rotor current I_r reacts with a significant overshoot, which can result in a significant torque spike at the mechanical output of the EM. When the stationary operation point of the stator current I_d is reached, the rotor current decreases to its initial value based on the time constant of the rotor inductance. One requirement for the rotor current controller design is to minimize the overshoot in closed-loop control mode. The KPIs, amplitudes, rise- and fall times of the rotor current response are indicated for both measurements. The visualization and analysis of the KPIs is performed with the support of the standardized data postprocessing approach. Table 6.1 summarizes

the KPIs of the rotor current responses in the considered excerpt of the Test Run for both TCs as well as the difference Δ between the two. The displayed KPI-values are average values of three Test Run executions in each TC.

Table 6.1: KPI-Analysis of Rotor Current Response to Stator Current Change

<i>TC / KPI</i>	<i>Amplitude (%)</i>	<i>Rise time (ms)</i>	<i>Fall time (ms)</i>
TC 2	114,4	89,3	466,3
TC 4	113,7	90,2	324,9
Δ	0,7	0,9	141,4

The objective analysis of the KPIs indicate high similarities in the amplitude as well as the rise time. However, according to the data in Table 6.1, a significant difference of the automatically identified fall times is indicated. Based on the observation of the two signals in Figure 6.7 the difference is a result to the noise on the rotor current signal recorded in TC 4. The visualization indicates similar time constants for the decrease of the rotor current. The usage of filtered signals or the fundamental wave for the analysis can be considered with respect to the validation objective. With the focus on knowledge generation, detailed objectification using extended or advanced methods is dispensed with in this case study. However, when the TCs are intended to be used for product qualification or certification tasks, these methods might be necessary to meet credibility demands (Dona et al., 2022).

With the analysis and comparison of the current responses at all eight current changes within the Test Run (Figure 6.2), a conclusion regarding the suitability of TC 2 for the design and parametrization of the rotor current control algorithm can be drawn. Alike the sample presented in this chapter, no significant deviations between the measured current values within TC 4 and TC 2 were observed. Thus, TC 2 is likely to be well-suited for the development and parametrization of the rotor current control in regard to the electromagnetic coupling between the stator and rotor. However, to avoid an overfit of the designed models with the investigated physical prototype the comparison must be repeated for different designs of the MCT.

6.3 Case Study – Operation Strategies of IEESM

A key driver for the development of new systems in battery electric vehicles is the technical objective to improve the overall system efficiency. With the ability to control the rotor excitation, EESMs provide the capability to actively control the power factor $\cos \varphi$. Thus, additional losses due to excitation can be canceled out by a higher efficiency on the stator side. However, the additional degree of freedom and the resulting higher control complexity must be handled by the ECU. Usually, Look-up-Tables are created based on simulations and parameter identification Test Cases and thus, provide desired current setpoints (I_d, I_q, I_r) for the driver's torque demand (Tq_{set}). Detailed Look-up-Tables place a high load on the ECUs memory while simplified Look-up-Tables require computationally intensive interpolations and might lead to unwanted discontinuities of the current setpoints (Green et al., 2019). Possible alternatives to the Look-up-Table based control algorithms (LUTA) are analytical approaches. These online calculations are usually less memory intense but place higher loads on the processor. However, the different operating ranges require different overlapping analytical approaches.⁷ Thus, analytical torque control algorithms (ATA) are always faced with the challenge to meet the reached efficiency of LUTAs in all operation points.

Typically, system efficiency maps are used for the evaluation of the system's efficiency. In order to simplify the correlations in this case study, the system efficiency is analyzed for constant battery voltages and constant system temperatures. As both determinants affect the system's efficiency, it is necessary to consistently expand the presented efficiency maps across the entire operating range. Additionally, the behavior of the system's efficiency during transient operations is not considered.

In this case study, a newly developed ATA is assessed. As with the development of any new system within AD, the central validation need of the newly developed torque control algorithm is the proof of its feasibility. Thereby, several system requirements are addressed. For example, the ATA needs to be able to achieve stable torque control over the entire operation range of the EM. Moreover, the new developed algorithm needs to match or exceed the system efficiency achieved by the previously developed LUTA, which is optimized regarding the system efficiency of the

⁷ See Chapter 6.3.1

considered EESM. The considered validation objective therefore targets the efficient operation of the system when controlled by the newly developed ATA.

6.3.1 Control Theory of Externally Excited Synchronous Machines

Equivalent to the rotor voltage (Equation 6.1), the stator voltages can be calculated as shown in Equations 6.4 and 6.5:

$$U_d = R_s \cdot I_d + \frac{d\Psi_d}{dt} - \omega \cdot \Psi_q \quad 6.4$$

$$U_q = R_s \cdot I_q + \frac{d\Psi_q}{dt} + \omega \cdot \Psi_d \quad 6.5$$

Where R_s is the stator resistance, ω represents the electric angular velocity and Ψ_d, Ψ_q the magnetic flux linkage of the stator in dq-coordinates. The magnetic flux linkages of the stator can be calculated according to Equation 6.6, where L_{dd}, L_{qq} are the main inductances of the stator in the direct and quadrature axis and $L_{dq}, L_{qd}, L_{dr}, L_{qr}$ are the mutual inductances between the direct and quadrature axis of the stator and between the stator and rotor respectively.

$$\begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} = \begin{bmatrix} L_{dd} & L_{dq} & L_{dr} \\ L_{qd} & L_{qq} & L_{qr} \end{bmatrix} \cdot \begin{bmatrix} I_d \\ I_q \\ I_r \end{bmatrix} \quad 6.6$$

Furthermore, for externally excited synchronous machines, the air gap torque can be calculated according to Equation 6.7 with p as the number of pole pairs:

$$Tq = \frac{3}{2} p \cdot (\Psi_d \cdot I_q - \Psi_q \cdot I_d) \quad 6.7$$

For the control of torque and speed of EMs, operation ranges can be divided into the base speed range and the field weakening range. In the base speed range, the maximum torque can be achieved for all speeds. In order to increase the speed, the

magnetic flux must be reduced. Thus, in the field weakening range, the maximum torque decreases with increasing speed. (Schröder, 2013, 365 ff.)

To enable the most efficient operation possible, control strategies for EMs in electric vehicles are designed to minimize losses. Within the regarded ETDS, the following losses are predominant (Fischer, 2013; Müller & Ponick, 2006; Pyrhonen et al., 2008; Schröder, 2012, 2013; Yamazaki & Seto, 2006):

- Copper losses of the electric machine
- Iron losses of the electric machine
- Mechanical friction losses of the electric machine
- Conduction losses of the inverter
- Switching losses of the inverter

In addition to the system losses, the thermal behavior of the machine directly impacts the control strategy (Schutzhold & Hofmann, 2013; Wang et al., 2023). The schematic of the field-oriented control (FOC) strategy, which is commonly used for the control of ETDSs is displayed in Figure 6.8 (Bayer et al., 1972).

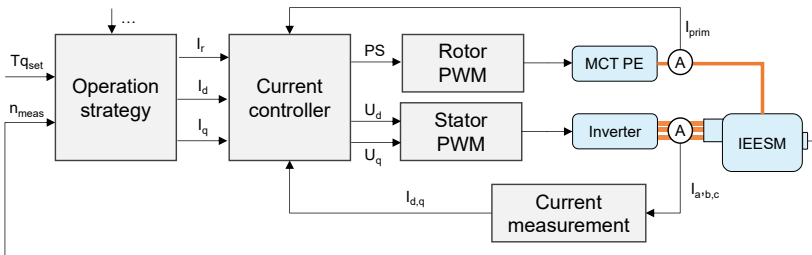


Figure 6.8: Schematic of Investigated Field Oriented Control Strategy for Inductive Externally Excited Synchronous Machine

The aim of the FOC is to enable dynamic and efficient control of the EM over the entire operation range, while considering the given current and voltage limits at all times. The operation strategy defines the required current commands (I_r, I_d, I_q) for the requested drivers torque demand ($T_{q_{set}}$) at the given speed (n_{meas}) and under consideration of all other boundary conditions such as the given machine temperatures and the battery voltage. The current controllers typically include decoupling and pilot control strategies and are implemented as PI-controllers with anti-windup functionalities. While the stator currents can be measured (I_a, I_b, I_c), transformed

(I_d, I_q) and fed back to the current controller, a rotor current measurement is not available. Thus, a more complex current control strategy based on the measured primary side current (I_{prim}) is implemented. The output of the rotor current controller is the phase shift (PS), while the output of the stator current controllers are the desired machine voltages (U_d, U_q). Subsequently, these outputs are transformed into the required pulse width modulation (PWM) signals for hardware control.

Under consideration of all limitations and losses, there is an optimal combination of the three currents I_d , I_q and I_r for each operation point. As the observation and consideration of all influences is both hardware and calculation intensive, often simplifications are made. A common approach is to define an operation strategy based on simulations and system characterizations on testbenches (offline) and store the desired operation points in Look-up Tables, which are accessed during operation (online). As an alternative approach, simplified analytical equations are solved during the operation and thus, the desired currents are derived. Detailed descriptions regarding typical operation strategies are for example presented by: Bao et al., 2019; Oliver Haala et al., 2013; Schröder, 2015, 1050 ff.; Tang & Liu, 2017.

6.3.2 Test Case Planning – Efficiency Map

For the evaluation of the system's efficiency, characteristic maps are commonly used. Consequently, the designed Test Run spans a map of operation points at different machine speed and different machine torque setpoints as displayed in Figure 6.9.

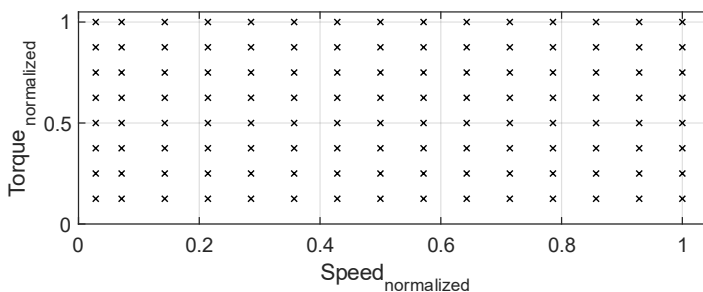


Figure 6.9: Test Run – Efficiency Map: Operation Points of Electric Machine in the Torque and Speed Range

For the initial evaluation of the torque control algorithm, only a section of the entire operation area of the EM, which is most representative for the vehicle application, is considered. The operation points are distributed within the first quadrant of the EM map. Thus, the EM is operating as a motor to imitate the most common application mode in the vehicle.

A key prerequisite for the comparison of the system efficiency are comparable system temperatures. Thus, the precondition includes a procedure regarding the thermal conditioning of the system to reach and maintain a reference temperature during the execution of the entire characteristics map. Accordingly, the Test Run procedure is structured as illustrated in Figure 6.10.

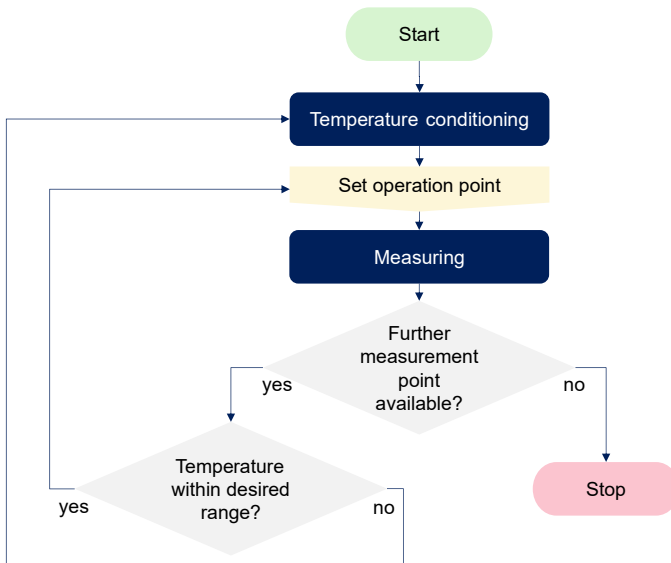


Figure 6.10: Abstract Test Run Procedure – Efficiency Map Including Thermal Conditioning

To begin with, a temperature conditioning operation point is initiated to establish constant temperatures within the system. Subsequent to the conditioning, the desired operation points (see Figure 6.9) are given as setpoints. Firstly, the desired speed is given to the control of the load machine to accelerate the SiD. Secondly, the desired torque is given as an input for the ECU. After a short stabilization phase of two seconds, capturing of the signals by the power analyzer, as displayed

schematically in Figure 6.11 is initiated. The measured power values are averaged over five seconds before the next operation point is approached. When the system temperature is within the desired range the next operation point is examined. If the system temperature exceeds the given limits, the system will re-enter the conditioning stage. The procedure is repeated until all desired operation points have been measured. The expected behavior, or in this case the expected system's efficiency is based on the results from the previously conducted simulations.

The functional Test Case description which is given in this chapter and is stored within the ALM tool serves as the basis for the implementation of the generic Test Run in the test automation tool. Besides the execution of the Test Run, the automation tool is also used to automatically execute the predefined postprocessing procedure to create a visualization of the efficiency maps. Thus, visualization of the measured results (see Figure 6.12) is provided within a few seconds after the execution of the Test Run.

6.3.3 Test Configurations to Evaluate Operation Strategies

Based on the given validation objective all relevant system elements are identified. The system's efficiency is mainly affected by the mechanical losses of the EM and both the electrical losses of the inverter and the EM. Furthermore, within the case study, the losses of the developed MCT are analyzed separately.

With the relevant systems and the defined Test Run a schematic overview can be derived. Figure 6.11 illustrates this schematic, including the wiring for the needed measurement points. The form of the displayed subsystems as in virtual or physical is not defined at this point in time.

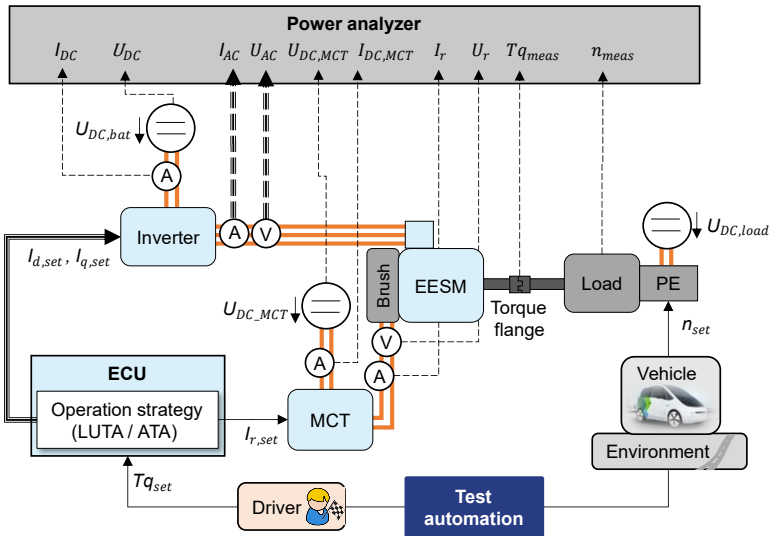


Figure 6.11: Schematic Wiring and Measurement Setup of the Electric Traction Drive System (blue) and its Connected Systems for the Test Case – Efficiency Map

According to Equation 2.1 the total input power of the system and the total output power of the system need to be measured. With the depicted configuration, the input power is calculated as the sum of the inverter input power as well as the input power of the rotor excitation system (MCT)⁸. The output power is the mechanical power of the EM and is calculated based on the measured speed and torque at the shaft between the EESM and the load machine. In order to split the system losses into inverter, MCT and machine losses, the AC voltage and currents in the stator and the DC voltage and current at the MCT output are measured as well. For the power

⁸ The separation of the inverter and the MCT electronics is a result to the development approach of the study at hand. In series application, the electronics for the stator and rotor excitation are combined within the inverter-housing and will be supplied by the identical power source (vehicle battery). In series application the MCT replaces the brush excitation system.

calculation a high accuracy and a suitable bandwidth of the measurement equipment must be chosen.

The initial development and verification of control algorithms usually takes place in a MiL environment. However, the evaluation of the performance and resource consumption of the newly developed control algorithm (ATA) must take place on the target controller. Consequently, for the proof of feasibility, a physical ECU is needed. A high development flexibility could be achieved when the remaining systems displayed in Figure 6.11 are represented in a virtual form. However, the ability of the simulation models to accurately represent the physical systems regarding the considered validation objectives must be demonstrated.

As a reference for the evaluation of highly virtual TCs, TC 4, where all systems of the SiD are physically represented (see Figure 6.3) is selected. However, testing on system test beds like TC 4 depends on the availability of the latest physical design of all subsystems and thus are costly, time-consuming and only available in a later development stage.

The conducted analysis in this case study is designed to evaluate the suitability of TC 2 regarding the system's efficiency. In TC 2, the physical ECU is surrounded by simulation models of the remaining systems (see Figure 2.15). In regard to the power calculations, the current and voltage measurements bandwidth within the remaining system model is limited to its sample time of eight nanoseconds. Furthermore, the FPGA-model is optimized for real time performance and thus does not take any transient temperature dependencies of the components into account. Hence, for the thermal conditioning of the system, the models are parametrized according to the desired temperature which remains constant during the execution of the Test Run.

6.3.4 Test Case Analysis and Interpretation – Efficiency Map

In this case study, the developed approach for the classification of TCs is applied to investigate the suitability of the highly virtual TC 2 for the development of torque control algorithms. Therefore, the system's efficiency is analyzed. In regard to the validation objective, the total system losses are defined as the KPI for the objective analysis. A generic Test Run according to its description is implemented according to the developed method. Thus, identical Test Runs for both operation strategies are executed within both TCs by the test automation. The DMM ensures the consistency and traceability of the modeling and parameter data within the TCs. In total, four Test Cases are analyzed:

- 1) LUTA in TC 2
- 2) LUTA in TC 4
- 3) ATA in TC 2
- 4) ATA in TC 4

Based on the presented standardized postprocessing approach, a template for the measurement data processing is utilized. Thus, efficiency maps are automatically generated. The comparison of the four Test Cases is displayed in Figure 6.12.

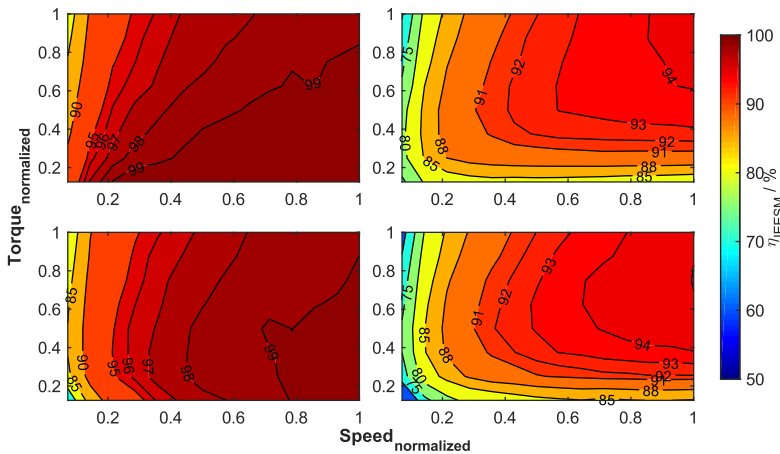


Figure 6.12: Measured Efficiency Maps of the IEESM at the Advance Development Department of MAHLE – upper LUTA, lower ATA, left TC 2, right TC 4

The first column displays the efficiency maps based on the measurements in TC 2, the second column, the results from TC 4. The measurement results in the upper row are based on the conventional torque control algorithm (LUTA) and serve as a reference for the newly developed ATA (second row). On the x-axis the normalized machine speed and on the y-axis the normalized machine torque is displayed. The system’s efficiency is illustrated by the isolines on the z-axis.

The characteristics maps of the system’s efficiency measured in TC 4 match the expectations based on the carried out simulations. A slight increase in the efficiency within the upper right machine range for the ATA compared to the LUTA is

noticeable. Thereby, the ATA matches or exceeds the systems efficiency compared to the LUTA.

The results based on the measurements performed in TC 2 differ from the expected behavior. Moreover, implausible system efficiency of up to 99 % is displayed. The preparation of the KPI is performed automatically by the used test automation (see Appendix C). For the description of the observed behavior, a summarized analysis of the system losses (KPI) is illustrated in Figure 6.13.

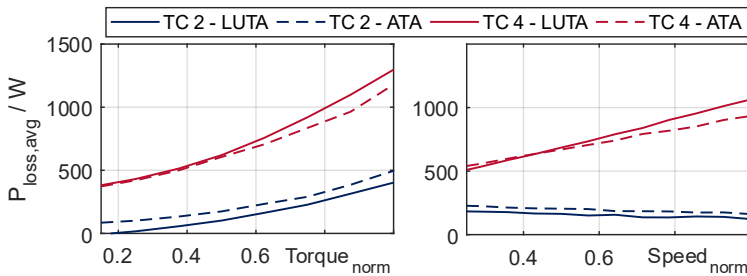


Figure 6.13: KPI Analysis of Measurement Results: Comparison of System Losses in TC 2 & 4 for both Control Algorithms; Left: System Losses over Torque, Right: System Losses over Machine Speed

On the left, the system losses are displayed over the machines torque. For each measured torque setpoint, the system losses at different speed setpoints are averaged. On the right, the system losses are displayed over the machine speeds. Equivalent to the left, the system losses are averaged over the different torque setpoints for each speed setpoint to simplify the visualization.

The analysis of the average system losses over torque (left graph of Figure 6.13) indicates a deficit of the modeled losses in TC 2. Detailed investigations regarding the models' behavior were initialized. As an explanation for part of the displayed deviations, the inverter model lacks accuracy regarding the on-state losses of the inverter. Additionally, the copper losses of the EM model do not sufficiently represent the measured losses within TC 4. Nevertheless, the general quadratic relation between the applied torque and the system losses is apparent.

Yet, the depiction of the measured system losses over speed (right graph of Figure 6.13) indicates major differences between the physical (TC 4) and the mainly virtual representation of the traction drive system (TC 2). A negative correlation between speed and system losses is shown by the results from TC 2 (blue). However, due to

friction, switching and iron losses, system losses increase with rising speeds. The described physical phenomena are apparent at the analysis of the measured system losses in TC 4 (red). (Kürten et al., 2022)

6.4 Initial Evaluation of the Usability and Applicability

Based on the application of the methodology, unstructured feedback regarding the usability of the methodology from the engineers was gathered. The generic implementation of Test Cases, the automation of the Test Case execution as well as the automatic postprocessing of the measurement data was described as beneficial, especially in regard to the comparability of measurement data and the general efficiency of testing activities. The provided support for the definition and implementation of generic Test Cases was described as extensive and comprehensive. The extend of the additional effort to implement or make use of APIs in order to execute the generic implementation of Test Cases at specific Test Configurations was mentioned several times. As many testing activities are defined as commissioning activities, automation and structured documentation of these activities is avoided. A lack of clear definitions regarding the systems requirements and the Test Runs needed to verify these requirements was described as one cause. Apart from that, the reusability of generic Test Runs has been highly appreciated by the development teams, also in the subsequent predevelopment department.

The facilitates access to exchangeable model and parameter data through the DMM is seen as a major improvement. However, consequent usage of the DMM was demanded as existing structures other than the DMM were repeatedly used by some participants. A detailed evaluation of the applicability and usability of the DMM is presented in Chapter 5.3.4.

The method for consistent analysis and classification of the TCs in AD is seen as mandatory for a more successful transfer of knowledge from AD to product (pre-) development. The structured analysis and documentation regarding both the SiD and the TCs are aspired. The initial group of users was extended as both applicability is seen as beneficial and the integration of all test analysis activities requires significant resources. However, a common medium for storage, access and transfer of the gathered knowledge by the comprehensive test analyses and classifications of the TCs is sought after. It has to be noted that the utilized ALM tools within the company were changed during the research period. Consequently, methods, procedures, and tools for the traceable storage of this knowledge with regard to the system and the validation environment should be investigated.

The introduction and dissemination of the new methodology in AD has been associated with several hurdles both technical and interpersonal. While most of the technical hurdles were iteratively addressed, consistency and further measures to convince and ensure usage of the deployed methods and tools are needed to meet for example the challenge of the human resistance to change.

6.5 Classification of Test Configurations – Technical Impact of the Applied Methodology

Validation needs describe identified gaps of knowledge and thus initiate validation activities. Each need is divided into multiple validation objectives and thus activities are planned, prioritized and executed. Testing activities are commonly documented with Test Cases. Based on the investigation and understanding of the system's use cases and functionalities, Test Runs can be defined. For the descriptive Test Run description as well as the generic implementation proposed in this thesis, the relevant elements of the system need to be identified. However, the form as in virtual or physical of any subsystem does not affect the Test Run. The case studies demonstrated the reusability of the generic implementations of the Test Runs. Furthermore, the developed method and tools support the TC specific mapping of the generic implementations and considered the necessary modification of preconditions to ensure comparability of the Test Runs.

The validation environment evolves gradually at the AD, where new technologies are investigated in order to develop new systems. Testing activities usually start with the availability of first simulation models. Subsequently, physical models are partially integrated to create new TCs. The development and set-up of any TC is supported by the DMM. Especially for the set-up of virtual or mixed virtual physical TCs the DMM serves as a unique source for the modeling and parameter data (both the most recent as well as older versions). In practice, the DMM was used to funnel the exchange of the necessary data and thus to ensure the data's actuality. With the availability of physical prototypes, the ability to execute the predefined Test Runs is investigated for knowledge generation. Thereby, the defined Test Runs are repeated regularly in different TCs to continuously validate the SiD. In addition to the added value for the validation of the SiD, the repetition of Test Runs enables an evaluation of the TCs and thus contributes significantly to the continuous improvement of the entire validation environment. The proposed methods and tools reduce the hurdles that exist in practice for continuous comparison between the TCs. In particular, the methodology contributes to consistent reuse and automation of procedures as well as their documentation.

Through a consequent definition and implementation of KPIs, the objective assessment of test results regarding both the SiD and the TCs promotes credibility. Furthermore, each testing activity which is conducted according to the proposed methodology can serve as a basis for the evaluation of the technical suitability of TCs. In order to increase the flexibility of validation, the additional activities for the continuous comparison and evaluation of test results from different TCs must be demanded and realized by the project teams. The sum of the individual evaluations of the various validation objectives and test runs results in a classification of the entire validation environment. The classification of the validation environment addresses the question which TC is best suited to address the present validation objective from a technological perspective and thereby serves as the basis for the subsequent product validation in series development.

The examples presented in Chapters 6.2 and 6.3 are part of the AD project regarding the development of the IEESM. All testing activities which were conducted in accordance with the proposed methodology contribute to the classification of the validation environment. Thereby, strengths and weaknesses of the different TCs in regard to multiple validation objectives are evaluated and documented. Excerpts of the classification of TC 2 in the context of the given project are presented in the following.

Based on the test results of the case study – operation strategies of IEESM – (Chapter 6.3) strengths and weaknesses of the simulation models are identified and the technical suitability of the highly virtual TC can be classified accordingly. Regarding the examination of the system's efficiency several deficits within the simulation models are identified. The following necessary measures for modification of TC 2 are derived to enable utilization for predictions regarding the system's efficiency. Minor adoptions of the modeled resistances can improve the accuracy of the loss behavior in regard to the applied machine torque. However, to overcome the negative correlation between system losses and machine speed significant changes and thus extensions of the existing simulation models are necessary. In this case study, the needed modifications increase the model's complexity in such a way that the available hardware resources of the FPGA are exceeded. Consequently, for a detailed evaluation of the systems efficiency, either a new TC must be developed to meet the demand regarding the model's complexity or a highly physical setup such as TC 4 must be used only. (Kürten et al., 2022)

To summarize, TC 2 is well suited for the development of new control concepts and algorithms as well as for its proof of feasibility on the target hardware. For example, the real-time capability and resource consumption of the controller can be reliably evaluated within TC 2. Furthermore, TC 2 is suitable for the verification of the control

algorithms stability, especially for the transition between base speed and field weakening range. The performed comparisons demonstrated the accuracy of the simulation models to represent the physical systems behavior (observed in TC 4). Within the projects scope, TC 2 significantly contributed to the development of a new control strategy for EESM (Buchali et al., 2023). The identification of weaknesses regarding the efficiency evaluation triggered the development and construction of several dedicated TCs within the series development department.

With the successful application and initial evaluation of the proposed methodology, the research questions two and three can be answered. The presented case studies demonstrate how testing can be conducted consistently and traceable from idea generation to functional prototypes in AD based on the presented methodology. Furthermore, the application of the method to support the systematical analysis and classification of the TC is successfully demonstrated in Chapters 6.2 and 6.3. The continuous evaluation and systematic documentation of strengths and limitations of the used TCs in the context of the IPEK-X-in-the-Loop Framework is supported by the developed approach. Thus, the credibility of the used TCs in validation is enhanced. The gained knowledge regarding the TCs increases the flexibility of early system validation and provides references for the further extension and development of TCs.

7 Summary and Outlook

7.1 Summary

In this thesis, the characteristics and specific challenges of the development and validation of mechatronic systems in AD are presented. Therefore, the validation activities at the AD department of the automotive supplier MAHLE were examined in detail. In order to enable the transferability of existing and newly developed methods from and to the considered research environment, the interdependencies between development paths like AD and product engineering were further investigated. Based on the fractal character of the model of SGE – System Generation Engineering according to Albers, the characteristics as well as the contribution of AD to product engineering were successfully described and illustrated. A core objective of AD is to build knowledge regarding new technologies for the entity and thus reduce uncertainties in product development. Activities of AD provide entity internal references in regard to the product to be developed and the therefore required validation environment.

Especially for automotive suppliers, the ability to quickly adapt the system's design to meet different customer requirements is essential for their success. In addition, the validation of the supplier's subsystem can only be achieved by integrating the subsystem into the overall system, its environment and other interacting systems. This demand for a flexible and holistic validation is addressed by the IPEK-X-in-the-Loop-approach. The usage of simulation models in virtual or mixed virtual-physical TCs provides flexibility. However, the credibility of simulations compared to physical systems is often questioned by stakeholders. Continuous, objective and transparent assessments of the models' technical suitability are necessary to answer the question: "Which Test Configuration is suitable to meet the present validation objective?". The utilization of virtual or mixed virtual-physical TCs can increase the efficiency of validation.

Based on a literature review, participating observations and an interview study carried out in the AD department of MAHLE, challenges of system validation and the usage of virtual or mixed virtual-physical TCs were identified. Subsequently, corresponding requirements for methods to support validation activities were derived. Based on these requirements a methodology to support consistent and flexible validation was iteratively developed and evaluated. The methodology is focused on testing activities in AD and the evaluation of the technical suitability of

TCs in regard to the validation objective. The methodology contains two methods to increase consistency of system stimulation as well as modeling and parameter data in any TC. Furthermore, these methods are designed to enhance the traceability of testing activities. On the basis of consistent and traceable testing, a method to support the analysis and classification of TCs is presented. Thereby, the methodology aims to increase the flexibility and efficiency of system validation by increasing utilization and credibility of virtual or mixed virtual-physical TCs.

The developed methodical support for consistent testing assists the definition and implementation of generic Test Runs. By utilizing the configured APIs between the test automation tool and the TCs, reuse of identical Test Runs in different TCs is enabled. Furthermore, the execution of the Test Runs is automated by the superordinate tool, ensuring comparability of measurement data from different TCs. For the comparisons, standardized postprocessing of measurement data is supported by a developed tool. Furthermore, the postprocessing procedure can be integrated into the automation tool to support immediate and traceable Test Case analysis.

The DMM provides a central platform for the exchange of modeling and parameter data. Linking the model data with the MBSE system description enables direct traceability of changes of the SiD and their effects on the system's requirements and vice-versa. Furthermore, the development of new or adaptation of existing TCs is supported by the DMM. With the DMM, up-to-date and consistent usage of modeling and parameter data in different TCs is ensured. The combined application of the methodical support for consistent testing and the DMM enables full traceability of the entire Test Case data. Furthermore, the automation of Test Case execution and analysis facilitates the documentation of the testing activities.

Traceability and consistency are key to the comparability of TCs. Based on the methodical support for consistent testing and the DMM, a method to support the analysis and classification of TCs regarding their technical suitability considering the validation objective was developed. The method for consistent analysis and classification of TCs is designed to continuously provide feedback on the technical suitability of the utilized TCs. Moreover, the identification of strengths and weaknesses of virtual or mixed virtual-physical TCs in regard to their physical references is systematically supported. Thereby, the TCs credibility is enhanced and necessary measures to improve existing TCs or requirements on new TCs can be derived.

The approach was evaluated within several case studies at the AD department of MAHLE. The method and tool to support the usage of generic Test Runs improved

comparability of the system's stimulation in different TCs. Furthermore, the reuse of Test Runs is facilitated and automation of Test Case execution increases testing efficiency. The DMM ensured the comparability of the utilized model and parameter data in different TCs. The automation of the Test Case execution enables traceability of the Test Case data. With the analysis and classification of the utilized TCs, essential information regarding their subsequent reuse in pre- and series development are presented. According to the pull-principle of validation, this information initiates the further development of both the SiD as well as the validation environment. The gathered knowledge regarding the TCs allows the efficient allocation of validation resources in the subsequent product development, by using the most suiting TCs and prioritizing the modification or development of new TCs in accordance with the identified strengths and weaknesses.

7.2 Outlook

The general applicability of the developed methodology must be investigated in other environments and under other boundary conditions. In particular, the application in regard to mechatronic systems that differ from ETDSs must be investigated further. The presented methodology focuses on the testing activity. Accordingly, the transferability to further validation activities should be evaluated. Thus, further prerequisites and limitations of the transferability of the developed approach must be derived.

Based on the functional Test Case descriptions, generic Test Runs are implemented by the engineers. With the extension of the presented Test Run templates (see Table 5.1) to the functional level, the automation of the generic Test Run implementation based on the functional Test Case description is conceivable (Kessel & Atkinson, 2024; Utting et al., 2012). The further integration of the DMM concept into a virtual single underlying model (Klare et al., 2021) to improve consistency are subject to further research projects (Reussner et al., 2023).

The proposed approach is designed to support continuous data collection. The documentation of each conducted testing activity and the testing result can be used as a source for the classification of TCs. A structured testing database serves as the basis for the usage of advanced data analytics. In a first step, the classification of TCs could be extended by using extensive data metrics to enhance the objective evaluation of the chosen KPIs (Dona & Ciuffo, 2022). The effect of the usage of extended metrics on the stakeholders' perception regarding the models' credibility must be evaluated. In a second step, the support of TC analysis and classification by the use of artificial intelligence is subject to further research. Algorithms to support

the identification of KPIs or the search for correlations, similarities and differences between the TCs are investigated.

The presented case studies demonstrate that detailed knowledge regarding the developed TCs is gathered when TCs are classified systematically. In order to successfully spread and transfer the knowledge, appropriate documentation must be provided to guarantee traceability. Existing obstacles for the consistent use of MBSE in AD need to be further investigated (Mandel et al., 2023). The applicability of appropriate methods (Mandel et al., 2020; Wiecher et al., 2024) for the documentation of the results in regard to the SiD as well as the validation environment must be examined in this context. Especially in the context of the automotive supplier, frequent change requests to the initially developed systems at AD are expected. An investigation to which degree the provided methodology serves as a basis for model-based engineering change management (Martin et al., 2022) should be conducted.

Identifying the strengths and weaknesses of the TCs provides further starting points for research. On the one hand, these findings must be systematically broken down into the individual models of the subsystems and interactions in order to derive possible model adjustments. On the other hand, the effort required for model optimization must be compared to the long-term benefits. To decrease development times, a high degree of virtualization of the validation activities is aspired. Investigations to what extent virtual or mixed virtual-physical TCs can support the systems validations are subject to further research (Düser et al., 2023; Freyer & Düser, 2023; Schmidt et al., 2023). In addition, the usage of the developed models beyond the scope of product development towards product production needs to be investigated. The DMM is designed to serve as the foundation for setting up digital twins (Stark et al., 2020). However, especially for new systems, the knowledge about model limitations is essential and must be pointed out in order to focus on the system's validation.

In addition, the consequent application of the proposed methods in pre- and series development projects should be evaluated. Reusability of Test Runs beyond the scope of one product line could decrease testing overhead resources. Furthermore, using the results from Test Case executions of systems with a high TRL to reflect the performance and maturity of simulation models can further improve their credibility.

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Publications Co-Authored by the Author of this Dissertation

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Appendix A – Literature Review

verwendete Datenbanken		KIT-Katalog Classic, KIT-Katalog Plus, Google Scholar		
Suchbegriffe				
Kernbegriffe	Oberbegriffe	Unterbegriffe	Verwandte Begriffe	Übersetzungen
<i>Herausforderungen</i>	Transformation, Umbruch, Wandel	Anforderungen	Schwierigkeiten, Probleme, Problemstellungen	challenges, complexities
<i>Automobilindustrie</i>	Wirtschaftsbranchen	OEM, Zulieferer, Wertschöpfung, Absatzmarkt, Beschaffungsmarkt, (globale) Produktion, digitale Produktion (Industrie 4.0)	Automobilbranche	automotive
<i>Zulieferer</i>	Zulieferindustrie, Beziehungsstruktur	Automobilzulieferer, Zuliefererpyramide	Lieferanten	supplier, Tier(-n)
<i>Vorentwicklung</i>	Innovationsprozess/-management, Entwicklung	Ideenfindung, Prototyp	Vorausentwicklung, Technologieentwicklung, Serienentwicklung	predevelopment
<i>E-Mobilität</i>	Mobile Antriebssysteme	Batterieelektrische Fahrzeuge, BEV, Hybrid, HEV	Elektrifizierung des Antriebsstrangs, elektrische Antriebssysteme	e-mobility
<i>Digitalisierung im Fahrzeug</i>	Digitalisierung, veränderte Mobilitätskonzepte	Autonomes Fahren, Car-Sharing	Konnektivität	digitalization, connectivity

Figure A.1: Literature Review: Used Databases and Search Terms (Renner, 2022)¹

¹ Co-supervised thesis (unpublished)

Appendix B – Interview Study

Interview Guideline for Experts in Advance Development (German)

Einstiegsfrage
„Welche Erfahrungen hatten Sie vor diesem Projekt bereits in Vorausentwicklungsprojekten sammeln können? / In welchen Vorausentwicklungsprojekten haben Sie vor diesem Projekt bereits in dieser Rolle (Projektleiter, Stakeholder, etc.) gearbeitet?“
„Waren diese Projekte ebenfalls interdisziplinär (Mech.+Elek.+Softw.)? Falls ja, welchen Anteil hatten neben der Mechanik- die Elektronik- und Softwareentwicklung?“
Themenblock 1: Allgemeine Schwierigkeiten und Herausforderungen
1-1 „Wenn Sie an das Projekt ... (zurück) denken, wo lagen/ liegen aus Ihrer Sicht die größten Herausforderungen (technisch, organisatorisch, strategisch) ?“
Themenblock 2: Unbekanntes Supersystem/ Anwendungsfall / Produktprofil (initial)
2-1 „Zu Beginn der Entwicklung von unseren Systemen ist das Fahrzeug und z. T. sogar die Fahrzeugklasse, in die das System später eingebaut wird, noch nicht bekannt. Wie wird das bei der Entwicklung berücksichtigt? Sollten beispielhafte Fahrzeuge/ -klassen ausgewählt worden sein, warum wurden genau diese gewählt?“
2-2 „Ich kann mir vorstellen, dass die Schnittstellen des entwickelten Systems zum Fahrzeug mit besonderer Vorsicht behandelt werden. Wie wurde denn bei der Definition/ Spezifizierung von unbekanntem Schnittstellen vorgegangen?“
2-3 „Inwiefern hat sich das von der Vorausentwicklung angenommene Fahrzeug/ Fahrzeugklasse im Verlauf des Entwicklungsprozesses geändert? Gab es dabei einschneidende Momente, an denen sich dies besonders deutlich geändert hat?“
Themenblock 3: Änderungen im Zielsystem
3-1 „Aufgrund der speziellen Eigenschaften von Vorausentwicklungsprojekten kommt es in diesen zu regelmäßigen Änderungen des Zielsystems . Was waren in diesem Projekt die Hauptursachen dafür?“ (interne/ externe)

3-2 „Gibt es **Zielsystemelemente, die auf keinen Fall verändert werden können**, wenn ja warum sollten diese nicht geändert werden?“

3-3 „Wie wird allgemein in der Vorausentwicklung bzw. speziell in diesem Projekt bei **Änderungen des Zielsystems vorgegangen?**“ (Änderungsprozess)

3-4 „Wie werden **Änderungen dokumentiert und kommuniziert?** Wie gut hat die Kommunikation aus Ihrer Sicht in diesem Projekt funktioniert und wo gab es Schwierigkeiten?“

3-10 "Erwarten Sie **Änderungen am Produkt bis SOP?** Wenn ja, welche **Ursachen** könnte es dafür geben?"

3-5 „Abgesehen von den Aspekten der Bewertung, Kommunikation und des Prozesses interessiert uns auch das Vorgehen zur Implementierung einer Änderung im Zielsystem bzw. zur Realisierung dieser Änderung im Prototyp. Inwiefern ist es möglich, das zukünftige Auftreten von Änderungen bereits von Anfang an in der Modell- und Prototypenerstellung zu berücksichtigen, damit die Änderungen leichter integriert werden können?“

Themenblock 4: Aufbau und Entwicklung des Validierungssystem

4-1 „Was war der **initiale Zustand des Validierungssystems (eventuell Unterschiede zwischen Komponenten und System)?** Wo wurde also bei der Planung der Validierungsumgebung und der Validierungsaktivitäten begonnen?“

4-2 "Vorausentwicklungsprojekte sind, wie bereits diskutiert, durch viele technische Änderungen geprägt. Welche **Auswirkungen hat das auf die Planung und Durchführung der Validierung?**"

4-10 "Inwieweit wurde das **Supersystem (Fahrzeug)** bei der **Validierung berücksichtigt?**"

4-11 "Welchen **Nutzen** und welche **Qualität** haben die aufgebauten **Modelle** im Projekt hinsichtlich der Produktentwicklung? Wo liegen die **Unterschiede** zwischen **virtueller und physischer Validierung?**"

4-3 "In welchem **Umfang mussten Anpassungen des Validierungssystems** im Laufe des Projekts vorgenommen werden? Wie würden Sie die **Flexibilität des Validierungssystems** beschreiben?"

4-4 "Der modellbasierte Ansatz liefert mehrere Möglichkeiten (MiL, SiL, HiL,...) zum Testen bestimmter Produkteigenschaften. **Wie wird entschieden auf welcher Systemebene getestet wird?**"

4-5 "Wie würden Sie die Effizienz der Validierungsaktivitäten im Projekt bewerten?"
4-6 „In der modellbasierten Entwicklung kommt den verschiedenen Validierungsumgebungen (S-HIL, P-HIL, EMT) ja eine außerordentliche Rolle zu. Wie wurde die Planung, Beschaffung und Erprobung von neuen Prüfumgebungen parallel zur Systementwicklung in das Projekt integriert und inwiefern hatte dies Auswirkungen auf den Projektverlauf?“

Extraction Results of Interview Study (German) (Renner, 2022)¹

Zentrale Herausforderung	Identifizierte Herausforderung	Kategorie	Quellenangabe	Genannt von
Management von Zielen und Anforderungen bzgl. Anwender-, Anbieter- und Kundennutzen	Projektvorgaben der Geschäftsführung	K3 K4	P1-PL-2/3, P3-Val-18, P3-PL-6, P2-PL-12, P2-PL-7, P1-SH1-8	9 von 9
	Detaillierungsgrad des initialen Produktprofils	K3	P1-SH2-3/6, P1-SH2-23, P1-Val-20, P1-Val-4/12, P2-SH-23, P3-Val-1, P3-Val-15/16	
	Markt- und kundenorientierte Produktentwicklung	K3	P1-SH1-5, P2-PL-12, P2-PL-15, P3-PL-4, P2-Val-9, P3-Val-1/2	

¹ Co-supervised thesis (unpublished)

	Unklare Anforderungen an das System	K4	P2-PL-6, P1-PL-9	
	Festlegung des Supersystems	K3	P1-SH1-4/6	
Identifikation von Referenzsystemelementen	Vorgängergenerationen	K3	P1-SH1-3, P2-Val-4	5 von 9
	Zugänglichkeit zu Spezifikationen (da keine Wettbewerber vorhanden)	K3	P2-PL-13/14, P3-PL-5, P3-Val-3	
Flexibler Systemaufbau	Aufbau eines flexiblen Systems	K3	P2-PL-5, P1-SH1-8, P1-SH2-5, P3-Val-4/5	6 von 9
	Festlegung von Grenzen	K4	P1-SH2-12/15, P1-SH2-15, P2-SH-10/11, P1-Val-9	
	Effiziente Konzepterstellung	K2	P1-PL-7, P1-PL-8, P1-PL-23, P1-SH1-12, P3-Val-20	
	Paralleler Aufbau von Produkt und	K5	P2-SH-26, P3-Val-31	

	Validierungssystem			
Änderungen im iterativen Produktentwicklungsprozess → Entwicklungs-generationen	Änderungen von Kundenanforderungen im Zielsystem	K4	P2-SH-6/7/9, P2-SH-5, P2-Val-7/8/28, P3-Val-8, P3-Val-7, P2-PL-12	8 von 9
	Supersystemänderungen im Produktentwicklungsprozess	K4	P1-PL-9/10, P1-PL-5, P2-SH-3/4, P1-Val-9, P1-Val-8, P3-PL-7, P1-SH1-7	
	Nichterfüllung von Zielsystemelementen (erfordert Überarbeitung)	K4	P1-SH1-11, P3-Val-17	
Systemdenken und methodische Produktentwicklung	Fehlendes Systemdenken (Denken in Teildisziplinen)	K1	P1-PL-3/11, P1-PL-14, P1-SH2-3/7, P1-SH2-22, P2-PL-7, P3-Val-22	6 von 9
	Geringe Akzeptanz für methodengeleitete Produktentwicklung	K1	P1-Val-5/21, P2-Val-34	

	Fehlendes einheitliches Verständnis (Definitionen)	K1	P1-PL-19, P1-Val-16	
Zusammenarbeit im Produktentwicklungsprozess	Zusammenarbeit im Projektteam	K1	P3-Val-9, P1-PL-2/3, P1-PL-4, P1-SH1-3, P2-Val-14, P2-Val-36/37	7 von 9
	Aufwendige Koordination in interdisziplinären Projekten	K2	P1-SH2-11, P1-Val-5, P3-Val-20, P2-Val-15/16	
	Zusammenarbeit über die Grenzen des Projektteams	K1	P2-PL-5, P2-PL-4, P1-SH1-10, P1-SH1-9, P3-Val-6/7	
	Geringer Austausch und fehlende Kommunikation von Aufgaben	K2	P2-Val-14, P1-PL-4, P2-PL-11	
Dokumentation im Projekt	Unbekannte Handhabung mit ALM	K2	P1-Val-14, P2-PL-9, P1-PL-5	8 von 9
	Geringe Zuverlässigkeit der Dokumentation	K2	P2-PL-10, P1-SH1-3/12, P1-Val-18, P1-PL-7/8, P1-PL-3,	

			P2-SH-13/14/15, P2-Val-12, P2-Val-5, P3-Val-31/32, P1-SH2-4	
	Arbeit mit lückenhafter Dokumentation infolge Zeitdrucks	K2	P1-PL-2, P1-SH1-20, P2-Val-16	
Aufbau und Festlegung der Validierungsumgebung	Integration virtueller Modelle	K5	P2-SH-16, P2-SH-16/17, P3-Val-25, P3-Val-21/23, P3-Val-24/27/28, P1-PL-29, P1-SH2-16, P1-SH2-17/18, P1-Val-16	9 von 9
	Ableitung und Erstellung von systemrelevanten Testfällen	K5	P1-Val-13, P1-SH2-21	
	Effektiver Einsatz der Validierungsebenen	K5	P1-PL-20/21, P1-PL-28, P1-SH1-13/14, P1-SH1-21, P1-Val-10, P3-Val-11/12/13,	

			P3-PL-14/19, P2-Val-24/25
	Externe Einflussfaktoren auf notwendige Ressourcen für die Validierung	K5	P2-Val-19, P2-PL-21, P2-PL-23
	Auslagerung von Elementen der Validierungsumgebung	K6	P1-PL-18, P1-PL-24 P2-PL-16
	Flexibilität der Validierungsumgebung	K6	P1-SH2-19, P1-Val-16, P2-PL-18, P2-PL-20 P2-SH-18/19, P2-Val-22/23, P2-Val-17/31, P1-SH1-18/19
	Validierung der Validierungsumgebung	K5 K6	P1-SH2-22, P1-Val-17, P1-Val-19, P2-Val-36, P2-SH-28/29, P3-Val-10/11
	Beschaffung von Elementen der Validierungsumgebung	K6	P2-PL-20, P2-PL-24, P2-PL-19, P1-PL-16/17, P1-PL-18,

			P1-PL-25/26/27, P1-SH1-13, P1-SH2-13, P1-Val-15, P2-Val-21, P2-SH-31	
Validierungsaktivitäten (aus Systemverhalten Rückschlüsse über zuvor definierte Zielsystemelemente ziehen)	Testinterpretation	K5	P2-SH-26/27	8 von 9
	Abgrenzung zwischen Validierung und Verifikation	K5 K6	P1-Val-12, P1-SH1-7, P2-PL-16, P2-Val-17/18, P2-SH-16, P3-PL-16/17, P3-Val-23	
	Festlegung von Grenzen im Validierungsprozess	K5 K6	P1-SH2-20, P3-PL-16, P2-SH-24/25, P1-SH1-15/16,	

Appendix C

KPI Analysis for Torque Control of EESM – TC 2 - LUTA

Table 7.1: Measured System Losses at TC 2 with LUTA in Watt

Speed/ Torque Setpoint	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	20	16	7	2	1	2	2	1	2	3	0	6	1	1
2	53	48	42	34	34	28	18	20	19	1	2	12	4	2
3	96	90	81	74	71	63	53	41	52	24	42	49	40	33
4	144	140	130	121	121	111	100	105	92	61	76	80	71	59
5	200	200	189	193	192	179	164	138	152	153	136	167	131	100
6	272	271	257	265	254	241	266	225	219	214	191	217	195	171
7	356	346	340	339	322	316	313	327	312	292	277	280	321	297
8	451	438	429	421	427	399	402	380	421	390	400	371	403	354

KPI Analysis for Torque Control of EESM – TC 4 - LUTA

Table 7.2: Measured System Losses at TC 4 with LUTA in Watt

Speed/ Torque Setpoint	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	86	117	149	186	224	269	309	352	398	444	494	536	585	634
2	137	171	202	240	283	325	372	420	464	506	559	610	654	704
3	202	241	278	318	363	399	447	489	544	596	646	697	752	794
4	282	328	367	406	470	505	558	596	655	709	759	817	871	921
5	406	445	486	544	582	638	693	741	804	823	906	959	1022	1084
6	535	581	626	669	735	794	846	905	953	1020	1085	1150	1213	1273
7	704	741	792	857	911	960	1020	1089	1155	1238	1288	1330	1390	1435
8	896	949	988	1047	1119	1175	1237	1288	1352	1376	1492	1538	1605	1664

KPI Analysis for Torque Control of EESM – TC 2 - ATA

Table 7.3: Measured System Losses at TC 2 with ATA in Watt

Speed/ Torque Setpoint	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	77	72	64	64	52	47	43	45	43	51	28	12	15	2
2	97	93	85	80	69	70	66	53	61	63	47	26	39	19
3	134	128	123	116	109	104	101	86	86	85	85	72	66	64
4	182	172	170	155	160	145	137	147	127	95	124	105	125	111
5	240	236	227	224	219	202	199	195	184	174	175	175	170	163
6	316	308	299	303	273	277	277	257	246	239	246	288	247	206
7	399	398	387	376	351	359	360	351	322	335	334	311	321	279
8	500	489	479	478	472	450	450	476	410	433	421	401	416	448

KPI Analysis for Torque Control of EESM – TC 4 - ATA

Table 7.4: Measured System Losses at TC 4 with ATA in Watt

Speed/ Torque Setpoint	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	155	172	195	213	249	274	298	324	351	397	419	443	474	513
2	192	215	237	262	282	321	343	376	408	435	473	501	540	576
3	258	277	301	333	366	397	422	451	491	520	554	587	633	661
4	336	369	390	420	453	491	530	572	601	638	668	704	744	783
5	463	484	512	543	593	621	663	700	736	786	801	853	905	937
6	605	626	660	693	736	790	826	877	902	900	990	1030	1094	1118
7	778	804	849	887	941	986	1026	1050	1108	1183	1202	1243	1285	1318
8	986	1025	1049	1107	1159	1200	1250	1299	1331	1477	1440	1452	1544	1562