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Evaluation of model-based systems engineering in the traction battery product development process

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There’s no such thing as knowledge management;
there are only knowledgeable people. Information only becomes knowledge
in the hand of someone who knows what to do with it.

Peter Drucker, 1909-2005

AFFIDAVIT

I declare that I have authored this thesis independently, that I have not used any other than the declared sources/resources, and that I have explicitly indicated all material that has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master‘s thesis dissertation.

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Date Signature

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Paul Schiffbänker, Graz, Nov. 2016

KURZFASSUNG

Wissen im Kontext der Produktentwicklung kann als einer der entscheidenden Faktoren der modernen Volkswirtschaft unserer Zeit betrachtet werden. [1] Je nachdem wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann, ist es im Stande in immer kürzer werdenden Zyklen innovative Produkte auf den Markt zu bringen. Ein Beispiel für ein komplexes Produkt, das einen hohen Grad von Fachwissen und Informationsaustausch erfordert, ist das Batteriesystem im Technologieumfeld elektrifizierter Fahrzeuge. Als Entwicklungsdienstleister steht die betrachtete Organisation AVL List GmbH vor der ständigen Herausforderung, Wissen im Zuge der Entwicklung und Beherrschung komplexer Systeme aufzunehmen, zu verarbeiten und dieses Kunden sowie Mitarbeitern bestmöglich zur Verfügung zu stellen.

Eine Möglichkeit für die Beherrschung von Wissen bei der multidisziplinären Entwicklung komplexer Systeme ist *Model-based Systems Engineering* (MBSE). Diese Methode wird von der weltweiten Systems-Engineering-Dachorganisation INCOSE in der Vision 2020 [2] als einer der Eckpfeiler für die zukünftige Produktentwicklung gesehen. MBSE beruht auf dem Prinzip der formalisierten Anwendung von Modellierung zur Unterstützung der Spezifikation, Design, Analyse, Verifikation und Validierung über den gesamten Produktlebenszyklus. [3] Der Nutzen dieser Anwendung im Entwicklungsprozess wird in unterschiedlichen Pilot- und Forschungsprojekten ermittelt. Die ersten Ergebnisse zeigen sehr unterschiedliche Resultate und empfehlen zum Beispiel einen Einsatz im Management von Anforderungen, bis hin zum Einsatz als integrative Methode um alle verschiedenen Engineering-Disziplinen zu verbinden. [4] Zur vollen Ausnützung der Potentiale von MBSE in der industrialisierten Anwendung bedarf es eines geeigneten IT-Werkzeuges, welches den Produktentstehungsprozess, die Unternehmensorganisation und das Datenmodell einbindet. Um eine Implementierung eines solchen Werkzeuges zu rechtfertigen, ist eine genaue Evaluierung des zukünftigen wirtschaftlichen Nutzens der Methode MBSE erforderlich. Diese wirtschaftliche Evaluierung wird anhand der Anwendung der Batterieentwicklung für die automobile Anwendung in der AVL List GmbH durchgeführt.

[1] BURSAC, p. 6
[2] INCOSE, 2007
[3] INCOSE, 2007, p. 15
[4] EIGNER, 2012, p. 1

Es werden zuerst die relevanten Themenfelder, MBSE, Produktentwicklung der Begriff Nutzwert in der Produktentwicklung sowie das Anwendungsgebiet, das System Batterie für elektrifizierte Fahrzeuge im Detail beschrieben. In einer qualitativen Studie wird evaluiert, wie sich die steigende Komplexität negativ auf den aktuellen Prozess der Batterieentwicklung auswirkt. Es zeigt sich, dass im sehr schnell wachsenden Umfeld sehr alltägliche Probleme, wie das Auffinden von Informationen oder die Möglichkeit bereits erarbeitetes Wissen nicht nutzen zu können, großen unnötigen Mehraufwand hervorrufen. Darauf folgend werden für diese erfassten Potentiale, Lösungen unter Einbeziehung der beteiligten Entwickler ausgearbeitet. Eine Lösung umfasst die Definition, welche Informationen im Modell enthalten sein müssen und in welcher Form diese Informationen abgebildet werden sollen. Als Modell im Zuge dieser Arbeit werden sowohl ein Produktmodell als auch ein Prozessmodell, sowie deren Verknüpfung betrachtet. In einer zweiten qualitativen Studie werden diese Lösungen, evaluiert und diskutiert. Dies ermöglicht eine Bewertung ob und zu welchem Grad der unnötige Mehraufwand durch den Einsatz von MBSE abgestellt wird.

Abschließend wird in einem Ausblick aufgezeigt, wie die Forschung bezüglich der Evaluierung von Model-based Systems Engineering weitergeführt werden kann, und wie die erarbeiteten Vorteile in die Entwicklungsumgebung der AVL List GmbH aufgenommen werden können.

Abstract

In the context of product development, knowledge is the most crucial factor for success in the modern economy. [5] Whether a company can launch new innovative products in decreasing cycle times, will depend on how fast an organization can acquire, spread and apply new knowledge. An example of an innovative and complex product that requires fast and broad specialized knowledge is the traction battery system of electrified vehicles. The focus of this thesis lies on the company and service provider AVL List GmbH, that has to phase the constant challenge to optimally acquire, process and provide knowledge in the field of development and control of complex mechatronic systems to both customer and employees.

A possibility to apply knowledge in the multidisciplinary development of complex systems is model-based systems engineering (MBSE). The worldwide systems-engineering head organization INCOSE describes MBSE in Vision 2020 [6] as the main method for future product development. MBSE is based on the formalized application of modelling to support system requirements, analysis, design, verification and validation activities starting in the conceptual design phase and continuing throughout the whole development process. [7] Benefits of this approach in the development process are identified in various different pilot- and research- projects. First results draw very different conclusions and recommend, for instance, an application of MBSE in requirements management, up to a form of application as integrative method to connect different engineering disciplines. [8] To utilize the full potential of MBSE in an industrialized application a suitable IT-tool, which includes the product development process, the company organization and the data model, is necessary. Due to the fact that the implementation of such tool needs to be justified, an accurate evaluation of the economic value of the method MBSE is necessary. This economic evaluation is realized during the process of traction battery development for automotive application at AVL List GmbH.

[5] Bursac, p. 6
[6] INCOSE, 2007
[7] INCOSE, 2007, p. 15
[8] Eigner, 2012, p. 1

The thesis is introduced by an introduction of all relevant topics such as MBSE, product development, value in product development as well as the system traction battery for electrified vehicles. Secondly, a qualitative study evaluates, how increasing complexity has a negative impact on the current process of battery development. The study demonstrates, that in a rapidly growing environment, everyday problems such as not having access to information or not using already gained knowledge, results in a high amount of unnecessary effort. In the following part, solutions to solve those documented problems are developed taking into account the involved stakeholder. In a next step, the information that needs to be included in such a model and the form in which it has to be portrayed will be determined. The work presented will introduce a product and a process model, showing the individual models as well as the interaction and link between them. Moreover, a second qualtitative study evaluates and discusses different solutions in order to evaluate to what extend unnecessary effort can be reduced due to the application of MBSE.

Considering everything, the thesis concludes with an outlook, reflecting on the continuation of model-based systems engineering and on how the developed solutions can be included in the development environment of AVL List GmbH.

Table of Contents

1. TOPIC AND KEY ISSUES

This first chapter introduces the topic by giving a short description of the initial situation and by explaining general objectives and the overall structure of this thesis. This introduction illustrates the personal motivation towards the topic and formulates in a second step the scientific question that will pave the way to proposed solutions and answers in the following chapters.

1.1. INITIAL SITUATION

Modern development faces many rising challenges: Scattered engineers working around the world need to exchange up-to-date information to develop products for a global market. Haberfellner (2012) states that one of the biggest challenges is the rising complexity. This complexity shall be controlled by the approach of systems thinking (see chapter 3.1.1). [9] On the one hand products and processes are more individualized, while on the other hand they have shorter development times and more restricted financial limits. In the automotive sector, this can be seen by the increasing number of model choices OEMs are offering paired with a decreasing timeframe for new vehicle launches. [10]

Traction batteries

An example for such a complex product in an uncertain market is the traction battery in pure electric and hybrid driven vehicles within the vehicle powertrain. The requirements for this battery system increase significantly and challenge engineers to develop within time, cost and quality. The market for electrified vehicles has changed significantly over the last decade (see chapter 2.1). The increasing demand for electrified vehicles on the market, induces OEMs to change their product portfolio within the upcoming few years. [11] Consequently the market for traction batteries changes and introduces new highly technological and complex problems within product development.

Product development in the automotive industry

For instance, such as the battery development, product development in the automotive industry has to deal with a very short time-to market, a very sophisticated competition and a highly increasing number of subsystems. Today's approaches for knowledge management quickly reach the limits. One reason are document-based systems, which cannot adapt in time to the constantly changing requirements. This often results in necessary iterative steps and increasingly difficult warehousing, adjustment and transfer of information such as stages of development. [12] Nevertheless, the exchange of information and documentation in various different stages of development is essential for modern product development. Different disciplines, departments, companies and cultures are communicating

[9] HABERFELLNER, 2012
[10] pwc, 2014
[11] FREIMANN, 2015, p. 23
[12] GERICKE/GRIES, 2009, p. 291

with mostly defined processes and digital tools. Although, as stated by Lünemann (2016) a big number of data is still exchanged by the comparably unsecure way of communication such as emails.[13]

Model-based systems engineering

Since human play a central role in product development, it is essential to develop methods and processes, which support product developers in their activities and work. [14] One of these methods could be *systems engineering* (SE) as described by Eigner (2012): It helps engineers in complex systems in cases where it is not humanly possible to overview and understand the whole system in detail. [15] The derived *model-based systems engineering* (MBSE) extends the approach by the use of a consistent and connected product model instead of a document based development.

The underlying basis of MBSE is the common and consistent truth about the progress of development. By the use of MBSE, complex interactions, for instance between requirements, functions and components can be displayed. The method enables development engineers to have a better understanding of non-trivial interactions in product development. According to Züst (2004), the advantage of using models is the reproducibility and the possibility of reusing information for future products. Cost and time factors are reduced in the process of change, as well as an improvement of the product quality throughout continuous repetition. [16]

Evaluation of the application of MBSE

An identified problem is the evaluation of the anticipated value of a concrete implementation of MBSE in the product development process. [17] One approach is described in this thesis. To quantify the potential added-value, the process of battery development is evaluated at the beginning and compared to a process with an integrated approach of MBSE in the end. Due to the new and rapidly changing market and therefore comparably new product development methodology, the development of traction batteries at AVL List GmbH is used for the evaluation in this thesis.

1.2. COMPANY PROFILE - AVL LIST GMBH

AVL List GmbH (Anstalt für Verbrennungskraftmaschinen List) is an independent company for the development, simulation and testing technology of powertrain systems such as passenger cars, trucks and large engines. Its scope of business is divided into three main business fields: Development of powertrain systems, engine instrumentation and test systems and advanced simulation technologies.

AVL was founded by Prof. Dr. Dr. h.c. Hans List in 1948. Today, the company has 3,450 employees in its headquarters in Graz and employs more than 8,050 people worldwide. The company has 45

[13] LÜNNEMANN/MÜLLER/NEUMEYER *et al.*, 2016, p. 14
[14] BURSAC, p. 2
[15] EIGNER/GILZ/ZAFIROV, 2012, p. 1667
[16] ZÜST, 2004, p. 30
[17] TSCHIRNER/ACKVA, 2016, p. 34

affiliates worldwide and had an export quota of 96% and a turnover of 1,27 billion euro in 2015. The company uses 10% of its turnovers for research purposes. [18]

One subsector of the business field of powertrain system development is the development of traction batteries for automotive applications. The goal of AVL is to develop tailored battery systems for the increasing number of producers of electrified vehicles. To fulfil costumer requirements regarding quality, time and cost, a combination of new and already established technologies has to be used. Parallel to the constant market growth, the number of competitors is growing. [19] The increasing competition asks for quicker and more innovative developments. This conflict of interests between more complex technologies and shorter development time at AVL List GmbH, makes it necessary to analyse and improve the development processes.

1.3. OBJECTIVES OF THE THESIS

The major goal of this thesis is to evaluate the potential benefit when applying model-based systems engineering (MBSE) in the traction battery development process. This added-value is defined as being a time advantage on the one hand and a cost advantage on the other hand.

The aim of AVL List GmbH is to improve the process of traction battery development and to plan further investments in product development. MBSE shall give a better understanding on the system *battery* with all its associated subsystems. Customer objectives should be grasped quicker and with better quality, to be implemented in a best possible way. Knowledge and systems shall be re-used across projects. Overall, MBSE shall improve the traction battery development by making it more effective and efficient.

The main **research question that is answered in this thesis is:**

> In what form is model-based systems engineering in today's product development applicable and what economic influence does this method have on the overall value chain?

In this thesis, the distance between today's real project world and theoretical methods is evaluated with scientific methods and further synergies and improvements are elaborated.

1.4. STRUCTURE OF THE THESIS

The thesis is divided into a theoretical and a practical part: First, the fundamentals of the subject are explained. Further, according to the design research methodology (DRM) two descriptive and a prescriptive study are established. The thesis is structured in nine chapters.

[18] AVL Facts, 2016
[19] LUGGER, 2016, p. 1

1.4.1. FUNDAMENTALS OF THE SUBJECT

In the second chapter the technology and environment of the use case, the technological basics of battery systems, electrical vehicles and its markets are introduced. Chapter 3 introduces the fundamentals of systems engineering with its two variations, document-based and model-based systems engineering. Lastly, the foundations of product and process development and the term value in product development are being described in chapter 4. To examine and evaluate these fundamentals and the theoretical background, numerous different primary sources were used. The theoretical side has been accompanied by my practical experience and insight during the work as a student assistant in the Global Battery Competence Team at AVL List GmbH. Additional skills and necessary insights were gained, all indispensable for a full understanding of the principles of development in general and in particular the demands for battery development.

1.4.2. ANALYSIS OF POTENTIALS IN THE BATTERY DEVELOPMENT PROCESS

To analyse the actual state of battery development, the method of guided interviews and a self-administrated questionnaire are selected. First, in interviews possible unnecessary efforts are highlighted by the interview partners. The quantitative approach to validate and economically assess a selected number of scenarios is fulfilled in a survey. The detailed description of this procedure regarding the methodology and the result of the interviews and surveys is listed in chapter 6. This first step highlights the need for improvements in product development and emerges in a basis for an economic evaluation of MBSE in the process of battery development at AVL List GmbH.

1.4.3. ELABORATION OF MBSE IN THE BATTERY DEVELOPMENT PROCESS

Based on the evaluated scenarios, different stakeholder-specific requirements set up along the use case of battery development, are prepared. These requirements are used to find possible measures based on MBSE, in problem centred workshops. To subsequently evaluate the solutions and picture the value added, a so called Mock-Up is built (see chapter 7). It shall provide a foundation to assess solutions and consult valid feedback of the stakeholder involved in the development process.

1.4.4. ANALYSIS OF MBSE IN THE BATTERY DEVELOPMENT PROCESS

To analyse the impact and its ability to realize the desired situation, the solutions are investigated. This final study is realized with a final presentation and a succeeding self-administrated questionnaire. The result is the possible improvement by the implementation of the elaborated solutions. This enables an evaluation to what extend the unnecessary effort can be reduced due to the application of MBSE (see chapter 8).

An outlook in the last chapter discusses how research regarding the evaluation of model-based systems engineering can be continued and how presented solutions can be implemented in the development environment of AVL List GmbH.

2. THE TRACTION BATTERY SYSTEM

In this chapter the use case of this thesis is explained in detail: The traction battery system in electrified vehicles. Therefore, electrified vehicles in general, the current market situation and the subsystems of the traction battery are described.

2.1. ELECTRIFIED VEHICLES

Electrified vehicles (EVs) can be found on land, water and in the air. On land, one has to distinguish between electrified on- and off- road vehicles and electrified rail vehicles. Within the development of batteries at AVL List GmbH, the focus can clearly be set on electrified on-road vehicles. First, EVs have to be classified into distinct categories: **Hybrid (HEV)** and **battery electric vehicles (BEV).**

HEV are characterised by **two independent drive systems**, namely a combustion and an electric engine. The size of the battery differs and depends on the degree of hybridization (DoH), which is the amount of electrical power, relative to the total amount of power that is used to propel the vehicle. It ranges from a small 12V system with a battery size of up to 1 kWh for so called micro hybrid vehicles (DoH ~ 0,03), to up to 300-400V systems with 5-15 kWh plug-in-hybrid vehicles (DoH > 0,5). [20] Micro and mild electric vehicles (MHEV) do not have any possible connection to the electric grid. [21] Although MHEV do not have a possibility for charging and can therefore not be named electric cars, these vehicles are nevertheless relevant for the development of battery systems at AVL List GmbH.

Due to the **nonexistence of a combustion engine**, a **BEV** is characterized by a one to one ratio of electrical to total amount of power (DoH = 1). One of the main objectives of electrified vehicles is to recuperate kinetic energy and reuse it to accelerate the vehicle. Electrified vehicles have certain advantages compared to vehicles powered by combustion engines (comparing the same vehicle type with the same weight): Lower CO_2 emissions, reduced exhaust emissions and noise level and increased torque. Disadvantages are the limit of driving range for BEVs and the additional weight for HEVs. [22]

The **market of electrified vehicles** is facing a major increase today: The number of global sales figures of **electric cars (BEVs and PHEVs)** has been growing rapidly. As illustrated by the international energy agency in Figure 1, the number of electric cars in stock has increased to 1.26 million from 2010 to 2015. [23] Although these numbers show rapid growth, the market share as a percentage of the overall market in 2014 was only 0.3 percent. [24] This indicates high potential of electric cars to enter a large market, on the one hand, but still only a very low market share of EVs on the other hand.

[20] VARESI/RADAN/HOSSEINI *et al.*, 2015, p. 33–34
[21] BERTRAM/BONGARD, 2014, p. 10
[22] Libralato Holdings Ltd, 2008, p. 3–10
[23] IEA - International Energy Agency, 2016, p. 4-6
[24] Accenture, 2015, p. 2

The uptake of electric cars varies greatly across domestic markets. In 2014 China, for instance, (world's largest automotive market with 19.8 million passenger vehicles sold in 2014) had accounted for 45,000 sales, which equals to a market share of 0.2 percent. Norway in contrast (144,000 passenger vehicles, 18,000 electric cars sold in 2014) has a market share of 13 percent. [25] The reason for such a strong growth in Norway are monetary and nonmonetary government subsidies, such as nationwide access to bus lanes or free parking. [26]

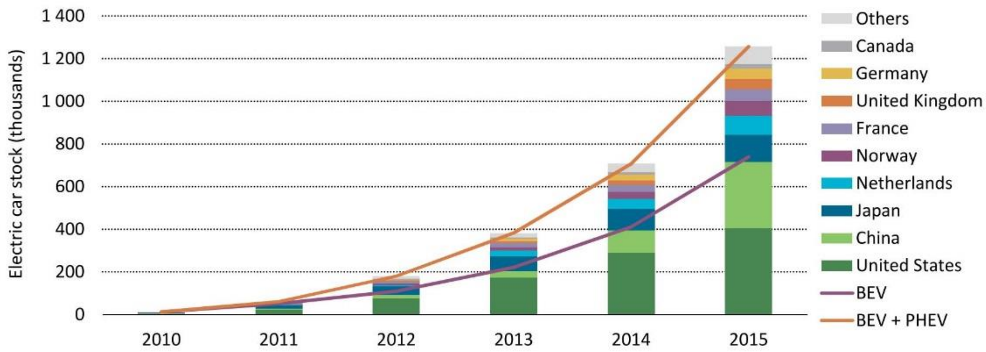

Figure 1: Historical Data of the stock of electric cars (BEV + PHEV) [27]

Future numbers can be expected to increase even at an even higher rate. The rising number of strict legislations on reduction of emissions raise the necessity of vehicles that have no local emissions. The development of scenarios of different representatives predict different numbers for the stock of electrical cars. Nevertheless, all share a high growth within the market (see Figure 2). [28]

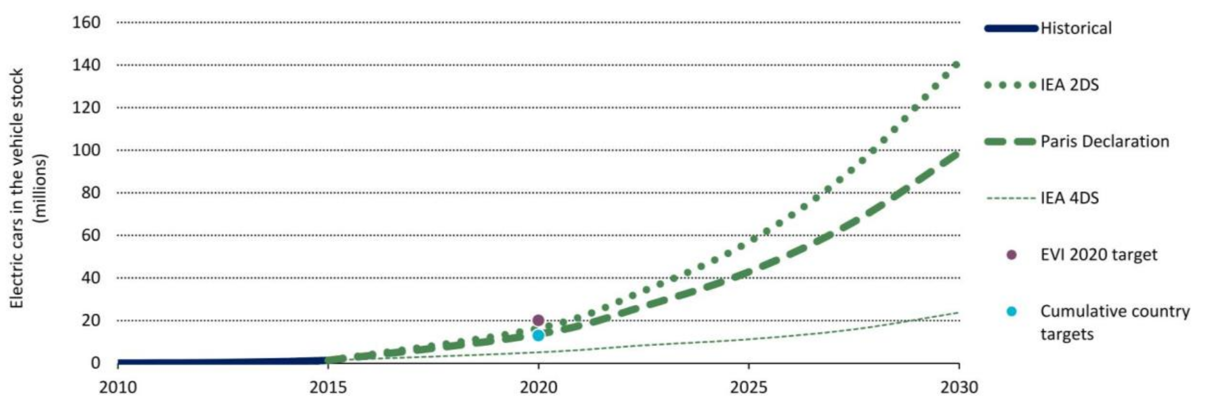

Figure 2: Scenarios for electric cars in the vehicle stock until 2030 [29]

A very similar market structure can be seen in the market of **electric 2-wheelers**. A strong uptake was particularly noticeable in China, where policies banned the use of conventional motorcycles either completely or partially in 29 cities. [30] For this reason, China is by far the major market for electric 2-

[25] Accenture, 2015, p. 2
[26] MALVIK/HANNISDAHL/WENSAAS, 2013, p. 996–998
[27] IEA - International Energy Agency, 2016, p. 4
[28] IEA - International Energy Agency, 2016, p. 7
[29] IEA - International Energy Agency, 2016, p. 5
[30] Asian Development Bank, 2009, p. 37

wheelers today with, according to China Reports, 35.5 million new registered and a stock of 198 million electric 2-wheelers in 2015. [31]

Overall, the **change in environmental legislations**, such as strengthened CO_2 regulations and governmental incentives as well as **new technologies** and materials for batteries are **reasons for the rising numbers of sold EVs**. Nevertheless, the market of EVs still has to overcome some **difficulties**: The **price** of EVs, due to the high battery costs, and **missing charging solutions** are often a negative side effect for potential users. [32]

2.2. THE TRACTION BATTERY SYSTEM IN ELECTRIFIED VEHICLES

The energy used in the described EVs is mostly provided by so called traction batteries. These batteries cannot be compared to batteries of conventional vehicles. As stated by Cao (2011) mechatronic systems – such as the traction battery – “require a complex combination of multiple disciplines such as mechanical, electrical, hydraulic and control to accomplish the entire requisite functionality”. [33]

For a better understanding of the battery the basic principles and functions are explained. Furthermore, the system structure of a battery system is described to get a more detailed understanding of the integration of batteries as a part of this greater system. Besides the functions and the systemic integration of a lithium ion battery, main components are presented as they can be seen as an element of a holistic system.

2.2.1. PRINCIPLES AND FUNCTIONS OF A BATTERY CELL

Technically spoken, a battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction.[34] In other words, a battery is not a storage device for electrical energy, rather it is a converter for chemical energy stored. Firstly, one has to distinguish between the term battery and cell: A **cell** is the basic electrochemical unit providing a source of chemical energy. A **battery** consists of one or more electrochemical cells. [35]

All **electrochemical cells** in principle have the same structure: The **anode** gives up electrons to the external circuit and is oxidized during the electrochemical reaction. The **cathode** accepts electrons from the external circuit and is reduced during the electrochemical reaction. The **electrolyte** is providing the medium for transfer of charge. The **conductive current collectors** are important passive system elements of the battery, since they are needed for the construction. [36] The two electrodes are

[31] China Reports, 2016
[32] APEC, p. 7
[33] CAO/LIU/PAREDIS, 2011, p. 1063
[34] LINDEN, 2011, p. 1.3
[35] LINDEN, 2011, p. 1.3
[36] LINDEN, 2011, p. 1.3-1.4

made of different materials, with unequal potentials. They are separated by a separator, that prevents any contact between these two electrodes. The electrolyte, in which the electrodes are swimming, is located in a housing, which encloses the entire assembly of one cell. [37]

Besides the storage of electrochemical energy, the **functions** a cell has to comply with are charge and discharge (see Figure 3): [38]

- While **discharging**, the cell is connected to an external load. Electrons flow from the oxidized anode through the external load to the cathode. The electric circle is completed with the electrolyte by the flow of anions and cations.
- While **charging**, the current flow is reversed and oxidation takes place at the positive electrode and reduction at the negative electrode (anode). Since the oxidation occurs at the anode, the positive electrode is the anode and the negative the cathode.

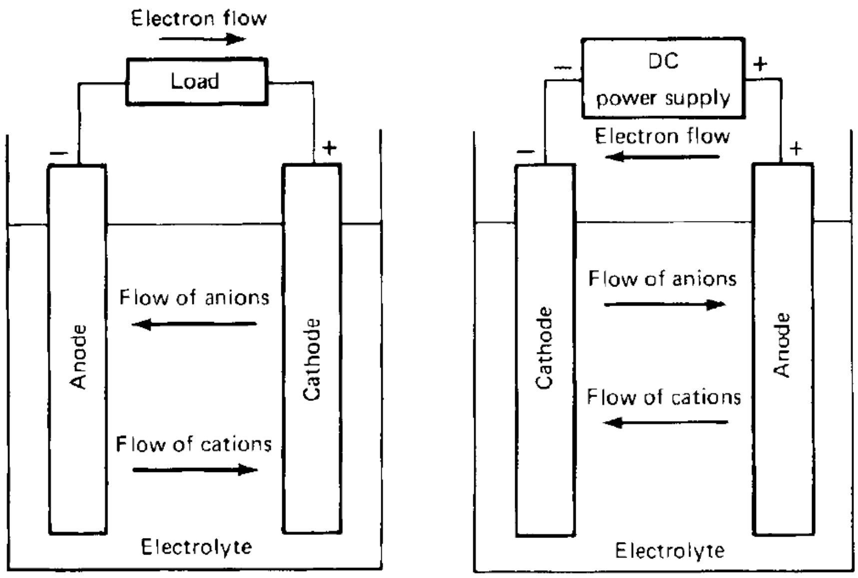

Figure 3: Electrochemical operation of a cell during discharge (left) and charge (right) [39]

Considering the technology, not all batteries are able to provide both these functions: They can therefore be divided into primary and secondary cells. Primary cells can only be discharged, not charged. **Secondary cells can be charged** and are then **dischargeable for many times**. [40] Due to the necessity of recharging, batteries utilized for EVs are always housing secondary cells. Such batteries, that are also called accumulators, are the main focus of in this thesis.

[37] TSCHÖKE, 2015, p. 52–53
[38] LINDEN, 2011, 1.7-1.8
[39] LINDEN, 2011, 1.7-1.8
[40] MINKE, 2015, p. 4

The main difference in battery cells are its materials. Each material has its own advantages and drawbacks. The first primary battery cell technology was the lead-acid battery, which is comparably heavy and has a very low capacity, but is still in use today within many different technologies. Alternatives are nickel-cadmium batteries, nickel metal hydride or the lithium ion batteries. [41] A very important parameter to compare different technologies is the energy density: With greater **energy density**, the cell can ‘hold’ more energy to, for instance achieve longer journeys with an electrified vehicle (measured in Wh / kg & Wh / l). Another factor would be the **power density**: With greater power density the cell can deliver higher power for the acceleration and hill climbing / towing loads etc. of a vehicle (measured in Wh / l & W / kg). [42] Some common secondary cell chemistries are compared in Figure 4.

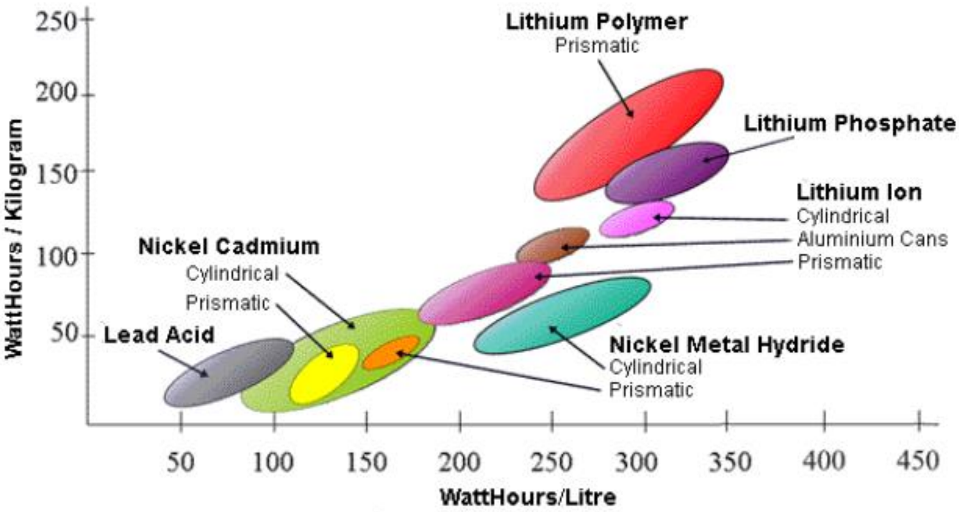

Figure 4: Relative energy density of common secondary cell chemistries [43]

Tschöke (2015) believes that lithium ion batteries are most promising for modern hybrid and electrical vehicles. He states the very high energy density and the high cell voltage as main advantages. However, the technology (compared e.g. to lead acid batteries) is more expensive in production. [44]

Cells for lithium ion batteries for powertrain development are commercially available in different designs: cylindrical, pouch-bag-cells and prismatic cells (see Figure 5).

According to different uses, the voltage of the battery system varies between 12 V for micro hybrid vehicles and a few hundred volt for EVs. This is reached by switching several cells in series. These **string of cells** are collected in so called **modules**. [45]

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[41] TSCHÖKE, 2015, p. 52
[42] Libralato Holdings Ltd, 2008, p. 12
[43] Woodbank Communications Ltd, 17.05.2015
[44] TSCHÖKE, 2015, p. 60
[45] TSCHÖKE, 2015, p. 85

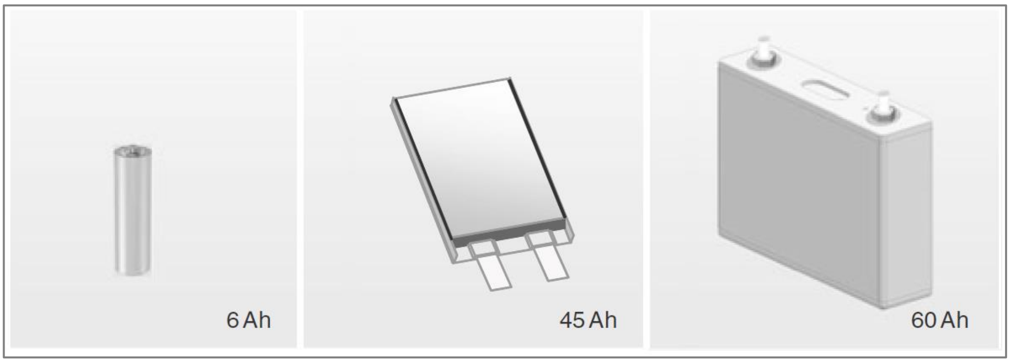

Figure 5: Different possible state of the art cell designs: Cylindrical, pouch-bag and prismatic [46]

Cells, used within the automotive industry, are in most cases ordered from a cell supplier, due to mostly expensive in-house production. [47] Most of the cells are produced in Asia, whereas more than 50% are produced in Japan. Figure 6 shows the worldwide market share of the most important lithium-ion producers in 2010. The mostly used cell type worldwide is the 18650 (18 equals the diameter, 65 equals the length; both in mm) cylindrical cell. It was first introduced by Sony in 1991 and aimed at consumer goods. [48] This standardized type of cell built by Panasonic is for instance currently used for the Tesla Model S. [49]

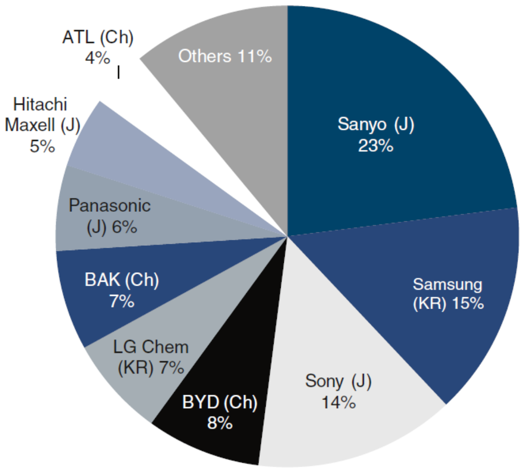

Figure 6: Market share of secondary lithium-ion cells in 2010 [50]

2.2.2. STRUCTURAL INTEGRATION OF THE BATTERY SYSTEM AND ITS COMPONENTS

For an allocation and the better understanding of the structural integration of every component, it is necessary to apply the structure tree of a generic vehicle, as being understood as **level structure at AVL List GmbH**. In this level structure, the whole vehicle is divided into several subsystems. The advantage is that every system can be, according to its level, very well described and aligned. On each

[46] KORTHAUER, 2013, p. 112
[47] MINKE, 2015, p. 5
[48] KORTHAUER, 2013, p. 112
[49] Tesla motors (company), 11.10.2016
[50] KORTHAUER, 2013, p. 112

level, every system with its function and attributes can be seen as a black-box with connections to systems on the same level and levels below or above. The level structure is displayed in Figure 7.

In this defined structure the battery system is being allocated on level 2. The battery is a subsystem of the powertrain (level 1) which again is a subsystem of the whole vehicle (level 0). On the same level as the battery other main systems of the powertrain such as the electric or combustion engine, or the transmission are allocated. [51] Considering this level structure, and the integration of a battery system and its components, the cell, as a subsystem of the HV-system, would be located on level 4, and the elements of the cell on level 5.

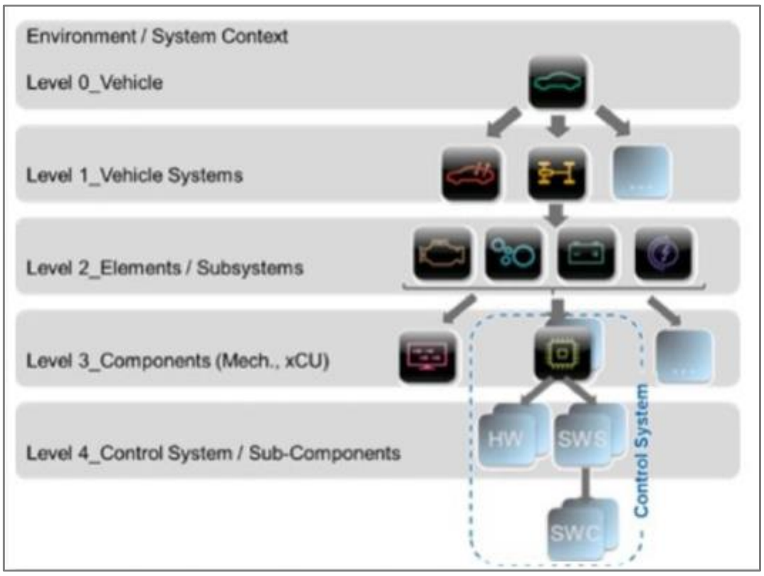

Figure 7: Level structure of a vehicle [52]

To satisfy the requirement of higher electrical capacity and the necessary performance, it is not only sufficient to come up with an appropriate number of cells, but there has to be an **implementation of further different systems**, whose functions must be closely coordinated in order to guarantee overall functionality. This includes mechanical and thermal requirements, electrical interaction with the powertrain, communication concepts and ensuring correct functioning. [53]

Lugger (2016) worked out an overview of all necessary systems on level 3: [54]

- **Thermal system:** All components/functions that are responsible for the heat exchange of a battery (E.g.: Heat exchanger).
- **Venting system:** All components/functions that are responsible for safe degassing of the cell in case of damage (E.g.: Venting valve).

[51] LUGGER, 2016, p. 12
[52] MINKE, 2015, p. 5–6
[53] TSCHÖKE, 2015, p. 85
[54] LUGGER, 2016, p. 11

- **Breathing system:** All components/functions that are responsible for the pressure compensation between battery and environment (E.g.: Pressure compensation valve).
- **Condensation handling system:** All components/functions that are responsible for the removal of possible accruing condensate (E.g.: Condensation pump).
- **Control system:** All components/functions that are responsible for measurement and control (E.g.: Sensors, signal lines, control devices).
- **HV system:** All components/functions that are responsible for energy transportation of the charge carriers for energy supply and storage (E.g.: Relais, Cells).
- **Mechanic System:** All components/functions that are responsible for the structure of the battery (E.g.: Housing, struts).
- **Module:** Special system consisting of cells and potentially all other named systems.

As stated before, a module is defined by a stack of cells and potential other systems, such as a control or HV system. Those modules together form one **battery pack**. The implementation of the system battery pack within the powertrain on level 2, faces equal challenges as the system integration on level 3.

A very important requirement for this implementation, as stated by Tschöke (2015) is the available **installation space** in the vehicle, which varies significantly between different types of vehicles. The most favourite **packaging design** is a battery located in the **middle underbody** outside of the crash zone, such as in the Mitsubishi iMiEV. Other possible packaging designs are within the **centre tunnel** underneath the rear seats (Opel Ampera), or **in the rear** of the vehicle (Tesla Roadstar). [55] Those three different concepts can be seen in Figure 8. Another very popular concept, increasing especially the mechanical requirements, is the new form of a **full integration** as a load bearing component (usually in the vehicle floor) such as implemented in the Tesla Model S. [56]

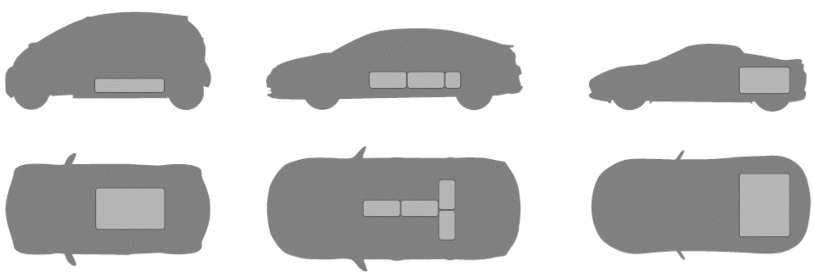

Figure 8: Different packaging concepts within vehicles [57]

[55] TSCHÖKE, 2015, p. 86
[56] Tesla motors (company), 11.10.2016
[57] TSCHÖKE, 2015, p. 86

Different to the cell production, battery systems are **offered by various organizations**. Both OEMs and suppliers, usually collaborating with a cell producer, are very committed. Nevertheless, standardization to make exchanges of cells or packs possible is only being strived by, for instance, the VDA (Verband der Automobilindustrie). [58] Despite this lack of standardization, the cost of battery packs have dropped significantly in the last few years. According to the International Energy Agency (IEA, 2016) especially technology learning, R&D and mass production lead to these rapid cost declines, and the increase of energy density, which is mostly influenced by the battery cells (see Figure 9).

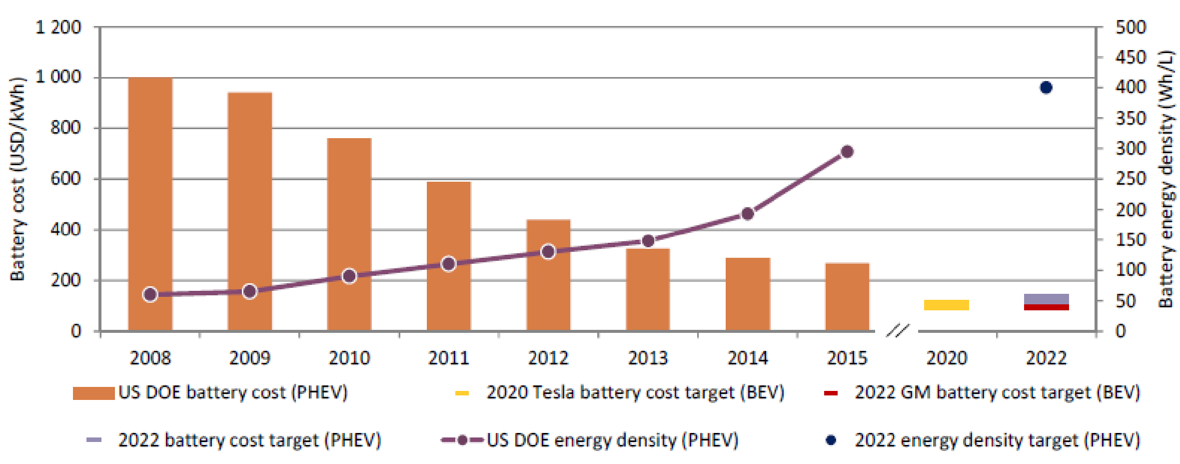

Figure 9: Evolution of battery energy density and cost (DOE – Department of Energy) [59]

2.2.3. BATTERY DEVELOPMENT

Originating from the demanded functions, components are being developed, which can implement the required functions. The criteria is the satisfying implementation of those functions considering the customer objectives and all boundaries such as legal constraints.

The favoured functional level of a battery system always refers to the requirements of the customer. If a battery system is used for a conventional car with an average lifetime of 14 years and a mileage of around 200.000 km, a complete different orientation is needed as, for example, a racing car whose battery should only last for 100 rounds in a racing ring. [60] Additionally, requirements such as flexibility, reliability, standardization and serviceability are mainly optimized by the design of the battery pack. In today's industry mostly single battery packs, fitted into a predetermined installation space are being developed. For the efficient use of a big number of common parts and therefore reduction of prize most battery packs are designed in standardized modules. [61]

During the development of a battery system, different concepts to favour a functional adjustment or orientation of the system are to be followed. According to Minke (2015) the main concepts during

[58] TSCHÖKE, 2015, p. 85
[59] IEA - International Energy Agency, 2016, p. 12
[60] MINKE, 2015, p. 10
[61] TSCHÖKE, 2015, p. 88

battery development are as follows. The focus during the concepts is mainly to capture relevant topical interfaces, including mechanical, electrical, and thermal development and those who focus on guaranteeing requested aspects by norms & standards such as recycling and safety: [62]

- Thermal concept
- Service concept
- Pressure handling and condensation concept
- Safety concept
- Recycling concept

The interaction of many different parts shows the necessity of an interdisciplinary cooperation of many competence areas such as electrical and mechanical engineering, chemistry, physics, procurement and project management. Only the combination of all fields of expertise provides the full view on the complete system. Within a very short time a tremendous amount of data is being generated, which can be seen as a big challenge for the organization (project management). It is a difficult and complex procedure to collect, handle, store and distribute all information and data. [63]

The battery is seen as one of the more challenging development tasks in powertrain element development, due to the complexity resulting from all the dependencies of different key parameters within the battery and all stakeholder involved. As a, comparably very young member, development methods are still being worked out and implemented. Therefore, this use case was picked for a possible implementation of model-based systems engineering, as being described in the following chapters.

[62] MINKE, 2015, p. 9
[63] LUGGER, 2016, p. 12

3. THEORETICAL BACKGROUND OF MODEL-BASED SYSTEMS ENGINEERING

The fundamentals of systems engineering and model-based systems engineering such as definitions, methods and concepts known in literature are introduced in this chapter. On the one hand, this shall be the initial introduction, on the other hand define boundaries for the considered topic within the extended context.

3.1. FUNDAMENTAL TERMS

An important distinction in this thesis has to be made between processes, methods, tools and environment. Sendler et al. (2013) define those to be: [64]

- **Process:** Defines ***what*** is to do. The logical sequence of activities to reach a goal.
- **Method:** Defines ***how*** something is done. Techniques to implement those activities.
- **Tools:** ***Enhances*** **what** is to do and how it is done. Usually a software solution to higher the efficiency of a method.
- **Environment:** ***Enables*** **or** ***disables*** **what and how**. It is defined by external objects, individuals or groups and conditions such as social, organizational, functional or cultural.

Therefore, the process of battery development is this logical sequence of activities to develop a battery considering requirements and the boundary conditions. Model-based systems engineering is the method for implementing the development activities.

3.1.1. THE TERM SYSTEM

A **system** is the totality of elements, which are in relation to each other as described by Haberfellner (2012). The set of **elements** (or objects) is described to be a major product, service, or facility of the system. Each element can be a subsystem to a hierarchical higher system. Each system, its elements and its relations own a set of **properties (characteristics)**. These properties can be used to describe and classify the specific system or subsystem. [65]

According to INCOSE (2004) a **subsystem** is "an integrated set of assemblies, components, and parts which performs a cleanly and clearly separated function, involving similar technical skills, or a separate supplier." Such as described, concerning the use case of powertrain engineering a subsystem can be split up into assemblies, subassemblies, components and parts (see Figure 10). [66]

[64] SENDLER, 2013, p. 99–100
[65] HABERFELLNER, 2012, p. 31–39
[66] INCOSE, 2004, p. 10

Those components include attributes and are connected by relations. These can be described as followed: **Attributes** are the properties (characteristics, configuration, qualities, powers, constraints and state) of the components of the system as a whole. **Relationships** between pairs of linked components are the result of engineering the attributes of both components so that the pair operates together effectively in contributing to the system's purpose(s). [67]

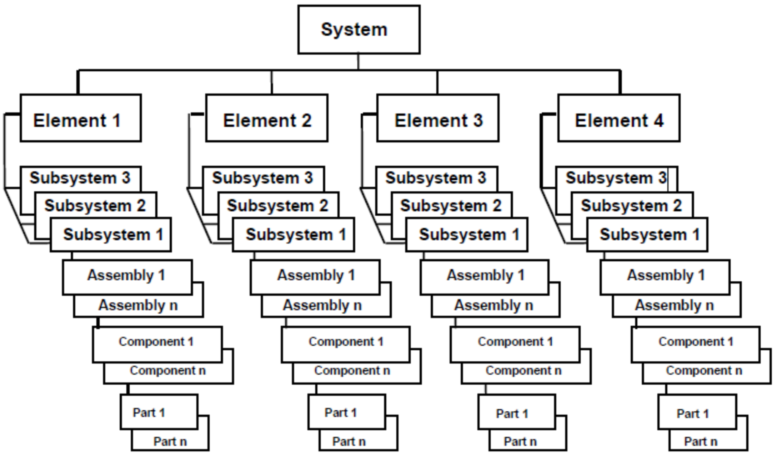

Figure 10: Hierarchy within a system [68]

Furthermore, a system is described by a **systems boundary** to the surrounding area. This is the, mostly arbitrary, delimitation between a system and its boundaries. It can be both physical and/or theoretical. Systems within the environment outside the boundaries can still be in a relation to the system. [69]

The system **interacts** with the system boundary through **input and output variables** (open system). Also, it is possible to separate between static and dynamic systems by their behaviour. [70]

Further, every system is described its perspective: A **function-oriented perspective** which is described by the difference of attributes such as the purpose of in- and output variables. A **structure-oriented perspective** which has the focus on the elements and their relationships in a system. In this structure, patterns of arrangement can be recognized. The aim is to explaining the behaviour of the dynamic interaction of its elements. Finally, within an **environment-oriented perspective**, a system is seen as a black box and the effects of and on the environment are on focus. In this perspective a hierarchical thinking is used for gradual concretization of a system, which improves the system awareness and understanding, especially for complex systems. [71] In this **black box** only the function of the subsystem, inputs and outputs are being described. The inner assembly is temporary without any importance (see Figure 11). [72]

[67] BLANCHARD/FABRYCKY, 2014, p. 3
[68] INCOSE, 2004, p. 13
[69] HABERFELLNER, 2012, p. 33
[70] EHRLENSPIEL, 2009, p. 41
[71] BRAUN, 2014, p. 31
[72] HABERFELLNER, 2012, p. 36

Nevertheless, as it is stated by INCOSE (2014), people from different (engineering) disciplines have different perspectives of what a *system* is. As a consequence a mechanical engineer has a different understanding of a *system* compared to a software engineer. Hence, the term *system* depends on one's perspective. [73] This perspective can be used to make a system visible in different views. Single elements, attributes or relationships can be emphasized or neglected to reduce complexity. [74]

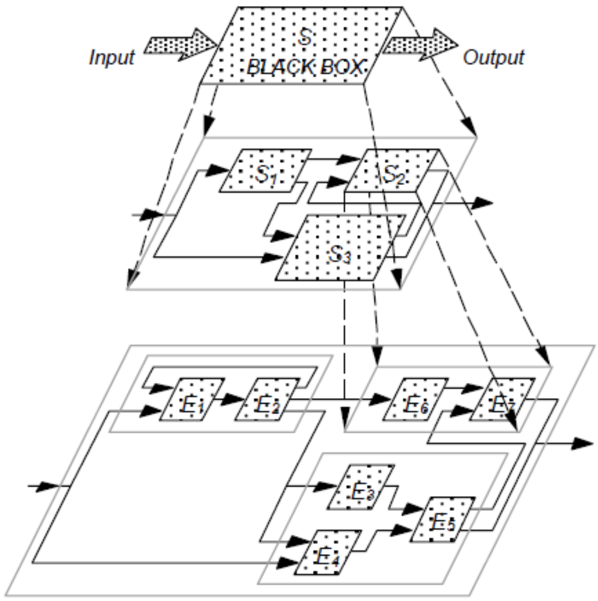

Figure 11: The structure of a system with different, hierarchical details and Input-Output relations [75]

3.1.2. COMPLEXITY

Systems can be distinguished into three types: Simple, complicated and complex. A **simple** system is characterized by a low number of influencing elements, which are in a weak correlation to each other. The system can be perceived quickly and is behaving simply. [76]

Different to a simple system, with a higher number of influencing elements in a system and a strong relationship, but a static behaviour, it develops to be **complicated**. [77] The behaviour of such a system is not obvious anymore and the effect of a change within a complicated system cannot be assessed easily. However the behaviour of a complicated system, which is defined to be static, is reproducible by the help of algorithms.

If both factors appear, namely a great number of influencing elements and a dynamic behaviour, a system appears to be **complex**. Relationships change as a function over time. [78]

[73] INCOSE, 2004, p. 10
[74] HABERFELLNER, 2012
[75] EHRLENSPIEL, 2009, p. 21
[76] VRIES, 2006, p. 33
[77] WEILKIENS, 2008, p. 9-11
[78] VRIES, 2006, p. 34

3.1.3. THE MODEL

According to the model theory of Stachowiak (1973), every model is characterized as followed: [79]

- Every model is an image or a pattern
- Every model abbreviates
- Every model is created to a designated use

Overall, a **model** in a product development project is described to be **an abstraction of a system of interest constructed from one or more representations.** [80] Therefore, models are not representing the original to the full extend, they **present**, according to the purpose, a **subset of attributes of the original**. This purpose is given by the involved person, the time interval and the necessary operations.

Models are differentiated into various kinds. A model can be mental, verbal (colloquial description), graphical (e.g. picture, diagram), material (e.g. prototypes) or formal (e.g. mathematical model). In this thesis it is focused on formal and graphical models. Those can be divided into several different kinds:

Descriptive models describe the domain it represents in a manner that can be interpreted by humans as well as computers. This model can include behavioural, structural and other descriptions that establish logical relationships about the system, such as its whole-part relationship, the interconnection between its parts, and the allocation of its behavioural elements to structural elements. Descriptive models are generally not built in a manner that directly supports simulation, animation or execution, but they can be checked for consistency. [81]

Functional models are a special form of descriptive models and provide an abstract method for understanding and representing the overall product. The primary task of this model is to support finding suitable solutions in design by creating discipline-independent functional models of a product. [82] Functions itself are elements, which specify the target behaviour or the task of a system. In software engineering these are the activities which the targeted system shall be capable of realizing. In mechanical engineering these elements, which are independent of the technology, are realized in a later phase by specific physical effects. [83]

Analytical Models are used to answer a specific question or make a specific design decision. This model is quantitative in nature. Analytical models must be expressed with sufficient precision that they can be formally analysed, which is typically by a computer. This model can be further classified in static

[79] STACHOWIAK, 1973, p. 131–134
[80] INCOSE UK Ltd, 2015, p. 1–6
[81] FRIEDENTHAL/MOORE/STEINER, 2012, p. 524–525
[82] EIGNER/GILZ/ZAFIROV, 2012, p. 1668
[83] EIGNER, 2014, p. 85

(models representing properties which are independent of time) and dynamic models (representing the time-varying state of a system). [84]

Product models are formal images of real or planed product attributes. Those can be texts, sketches, calculations, physical or virtual models that picture structure of functions or concepts of solutions. [85]

Process models are describing a pragmatic abbreviation of real or planned situations. More specifically, those models are representing the logical and/or chronological approach within product development. Those shall support by subdividing the complex emergence of products into controllable work packages. This facilitates a step by step concretisation of the product. [86]

3.2. SYSTEMS ENGINEERING

Every discipline in every trade has developed its own methods. This distinctness has proven to work out well, as long as those divided disciplines within a project are strictly delimited. The development of discipline specific subsystems can be governed well by today's industry. Nevertheless, those disciplines are not delimited to specific disciplines anymore. Therefore, interfaces between them have to be accomplished and aligned. According to Weilkiens (2008) the technical progress is mostly named as the main reason for a system to be complex. [87] Similarly also Haberfellner (2012) and Gausemeier (2012) name the rising complexity as one of the biggest challenge in today's product development projects, which implicates that targets concerning time, cost and quality are often not achieved. [88] [89]

Systems engineering was presented the first time by Hall (1966), as possible solution for this increasing complexity arising in product development. The goal is to successfully solve the increasingly complex and interdisciplinary tasks. [90] Following this method many exemplary developments took place, such as the Space-Shuttle or the rocket family Ariane by NASA. Further, also during the military and the civil arms race during the cold war between 1950 and 1980, systems engineering had been used to solve differ issues of technology- and science disciplines but also not-technical disciplines for problem-solving processes. [91] Anyway, according to Honour (2004) "we understand less about systems engineering than about nearly any other engineering discipline" [92].

This subchapter defines the discipline of SE. Further, due to the importance for the later study, the stakeholder role SE and the approach of document based SE are described.

[84] FRIEDENTHAL/MOORE/STEINER, 2012, p. 525
[85] BRAUN, 2014, p. 27
[86] BRAUN, 2014, p. 28
[87] WEILKIENS, 2008, p. 9-11
[88] HABERFELLNER, 2012, p. 1–8
[89] GAUSEMEIER/GAUKSTERN/TSCHIRNER, 2013, p. 303
[90] HALL, 1966
[91] MINKE, 2015, p. 18–19
[92] HONOUR, 2004, p. 1207

3.2.1. DEFINITION AND FUNDAMENTALS OF SYSTEMS ENGINEERING

INOCSE (2014) describes Systems Engineering as followed:

> „An interdisciplinary approach and means to enable the realization of successful systems." [93]

Whereas successful systems satisfy the needs of their customers, users and other stakeholder[94]. In other words systems engineering deals with **how a system functions and behaves overall**, how it interfaces with its use*rs* and other systems, how its subsystems interact, and how to unite various engineering disciplines so that they work together. It covers the domains of technical knowledge and engineering management.

Eigner (2012) describes systems engineering to **help engineers with complex systems** in cases where it is not humanly possible to overview and understand the whole system in detail. [95] Therefore, systems engineering starts with the conceptual design phase and continues throughout development and later lifecycle phases. [96] In a nutshell systems engineering can be described to be a **supervisory discipline to combine various different domains of engineering.** As stated by Haberfellner (2012) it is a "hyphen-discipline", which shall always be seen in combination with one or more other disciplines. [97]

The **aim of today's Systems Engineering** is to **control** this described **complexity** and not to reduce or eliminate the very same. Therefore, methods have to meet the, or be adapted to the extensive environment. [98] Systems engineering provides better methods to support **systems thinking**, in product development. This approach makes it possible to understand, improve or create complex systems. **[99]** It makes it possible to recognize interactions between the system and its environment and characterize system elements and its relations. The system boundaries can be defined (mostly by functions) and being increased during the solution search. System thinking is essential for the development of a system image (model). [100]

Other fundamental essentials of systems thinking, and therefore systems engineering are being described by Winzer (2013) and by Ehrlenspiel (2009), as described in the following section: [101] [102] [103]

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[93] INCOSE, 2004, p. 12
[94] A **stakeholder** in this context can be described to be „a group or individuals that is affected by or in some way accountable for the outcome of an undertaking. Stakeholder may include project members, suppliers, customers, end users, and others." (HOOD/FICHTINGER/PAUTZ *et al.*, 2008, p. 4)
[95] EIGNER/GILZ/ZAFIROV, 2012, p. 1667
[96] INCOSE UK Ltd, 2015, p. 1–6
[97] HABERFELLNER, 2012, p. 25
[98] SCHANDERA, 2013
[99] HABERFELLNER, 2012, p. 33
[100] WINZER, 2013, p. 17
[101] WINZER, 2013, p. 17–19
[102] EHRLENSPIEL, 2009, p. 79
[103] Principles of Systems Thinking - SEBoK, 09.08.2016

- ***From rough to detail:*** Enables to display systems hierarchically following the black box-model and minimizing complexity of the system. Very often also being called “top-down-approach”.
- ***Structure:*** A larger problem is more effectively solved when decomposed into a set of smaller problems or concerns. For this purpose it can be grouped, clustered or modularized. The way of structure depends on the object and its approach.
- ***Minimization of models:*** For the accomplishment of complex tasks, it should be concentrated on a few elements of a model only. A model of a system has to be as minimalistic as necessary to be used and understandable by everyone involved.
- ***Minimization of interfaces:*** The formation of systems and subsystems should enable a minimum number of interfaces. This facilitates the shape of system boundaries.
- ***Utilization of several perspective:*** Due to the variety of today’s systems, it is not possible to consider a system with a single perspective only, to create one holistic model. Technical, commercial, legal or organizational aspects demand a different perspective of a single system.
- ***Reusability:*** Complex systems should be structured in groups in a way to make a reuse of one group upon different conditions possible.
- ***Standardization:*** Is the basic for multiple reusability of parts of systems. Besides components and modules of a technical system, standardization refers also to a processes or documents.
- ***Modularity:*** Unrelated parts of the system should be separated, and related parts of the system should be grouped together.

3.2.2. STAKEHOLDER ROLE: SYSTEMS ENGINEER

In today’s product development each product team’s primary objective is the development of its subsystem or component. The aim is mostly described by the achievement of a specified performance on schedule, within the allocated costs. Due to the mostly component or subsystem set objectives, the system responsibilities are often overlooked. [104] To prevent this from happening, the stakeholder-role systems engineer (often: system engineer) is described and assigned to employees in many organisations [also at AVL List GmbH]. Although in detail this role differs strongly within organisations, it can be defined as following:

Simply spoken, a systems engineer is an **engineer trained or experienced in the field of Systems Engineering**. INOCSE (2014) defines systems engineers “to be the *glue* that binds all the sometimes diverse system elements together.” They are intended to be the unbiased arbitrator of those natural internal conflicts and to make the critical trade-offs and decisions between subsystems on a large

[104] INCOSE, 2004, p. 14

system. [105] According to Weilkiens (2008) the systems engineer has got, such as the customer, always a holistic view on a system. [106]

During a project the role of systems engineers are considered to be most important during the development phase, since here overall requirements need to be defined. Systems engineers help to **allocate** and ***balance*** the **requirements** to lower level system elements. [107] Nevertheless, according to Honour (2004) systems engineers today still struggle with the basic mathematical relationships that control the development of systems. [108]

3.2.3. DOCUMENT BASED SYSTEMS ENGINEERING

The traditional approach of systems engineering, is the document based approach. It is followed by the creation of textual specifications and documents along the product development process, which then are exchanged between customers, developers, testers and other stakeholder. Typical documents are requirements specifications, functional specifications or design specifications. [109]

This document centred approach has got advantages and disadvantages:

Advantages are for instance the clearly defined documentation and structure of content, which supports the orientation in a complex project. Standardized and unique conventions for the naming (of documents etc.) bring the advantage of finding information as well as it increases the transparency and comparability of a project. Standardized repository structures enable a centralized storage and therefore a simplified version management. [110]

However, disadvantages of this approach arise due to information being hidden inside texts and therefore cannot be identified in a short time. Further, the information needs to be distributed through various documents, in which explicit cross references are very often neglected. Moreover the maintenance of such references is mostly very work intensive. [111] In terms of complete, consistent information that is available in combination with requirements, design solutions, analytical- and test data, etc. the document centred approach to trace individual aspects of the system, due to the fragmented data storage, is not suitable. The traceability and the comparison/adjustment of systems requirements and from it derived component requirements as well as the impact analysis is made difficult in particular. This problem refers not only to maintenance but also to the reuse of information relating to the, to be developed system or its variant versions. Furthermore, the discrepancy between the quality of documentation and the actual requirements represent a potential hazard: The effects of

[105] INCOSE, 2004, p. 14-15
[106] WEILKIENS, 2008, p. 72
[107] INCOSE, 2004, p. 14
[108] HONOUR, 2004, p. 1207
[109] MINKE, 2015, p. 21
[110] MINKE, 2015, p. 21–22
[111] ALT, 2012, p. 12

it are usually recognized in the later stages of a project, for example on the engine test rig or in the worst case by the customer or the users. [112]

Due to the non-negligible disadvantages of document based systems engineering, the attempt for a consistent, traceable model based reproduction of systems is established. It is called model-based systems engineering. With this approach modern product development could overcome document based product development processes (see chapter 3.3). [113]

3.3. MODEL-BASED SYSTEMS ENGINEERING (MBSE)

Different to the document based approach of systems engineering, model-based systems engineering (hereafter referred to as **MBSE**) **extends systems engineering by a model**, to be used in all development scenarios. The model supports engineers to maintain an overview of complex systems, to understand the correlations and to fulfil all defined requirements. [114] Incose (2007) defines MBSE as follows: [115]

> "[MBSE] is the formalized application of modelling 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."

The collaboration between involved disciplines shall not longer use documents, but a centrally available, mostly graphical and always up to date semantic model. [116] All necessary generated data is stored in this **single point of reference**. Everyone involved in a project (stakeholder) can add or read data, which facilitates the exchange of data. [117] Ideally it will be in one place but in practice may be distributed across multiple tools or repositories. [118] This does not imply, that all up to the point of modelling, compiled and used documents should be neglected, but those are no longer the main source of information. The new documents are more just a perspective on the model automatically generated by a tool for modelling. [119]

Incose (2007) expects MBSE to "replace the document-centric approach that has been practiced by systems engineers in the past and to influence the future practice of systems engineering by being fully integrated into the definition of Systems Engineering processes". [120] Eigner (2012) believes that MBSE

[112] FRIEDENTHAL/MOORE/STEINER, 2012, p. 15–16
[113] BRAUN, 2014, p. 96–97
[114] EIGNER, 2012, p. 1
[115] INCOSE, 2007, p. 15
[116] EIGNER, 2014, p. 80
[117] ALT, 2014, p. 4
[118] INCOSE UK Ltd, 2015, p. 1–6
[119] MINKE, 2015, p. 22
[120] INCOSE, 2007, p. 15

could become the integrative method to combine all different engineering disciplines. [121] Braun (2013) highlights integrative approaches, that consider both the perspectives of development and management and states the necessity of appropriate visualization and handling of information among the whole product development process. [122]

The way to build a model is called modelling. Eigner et al. (2012) define three different views for modelling: [123]

- **Modelling and specification:** In this early specification the system is described by qualitative models, such as requirement, function or system oriented models. The models are descriptive and cannot be simulated. In this view an interdisciplinary language (e.g. SysML – see chapter 3.3.3) can be used to specify the first design. A *computer-stored* common system specification model can be evolved, to support the specification process for all involved disciplines.

- **Modelling and first simulation:** In this view quantitative aspects are integrated in an interdisciplinary view. This can comprise of simulation models (in e.g. Matlab or Modelica) for multidisciplinary simulations.

- **Discipline specific modelling:** In this view the system is modelled more precisely in a discipline-specific way. These are mainly tool dependent CAx models that represent discipline-specific aspects. An example for such models can be a mechanical CAD model, which contains the concrete geometry representation and many other properties, such as mass or length.

3.3.1. SYSTEM MODEL

The outcome of MBSE activities is an **integrated and consistent system model**. As discussed before, the system model is a primary artefact of MBSE, and is an integral part of the technical baseline of the system. This system model is a descriptive model that captures elements as requirements, structure, behaviour, and parametric constraints associated with a system and its environment. Further it captures inter-relationships between those elements. Any changes to the system are made first to the model, and then propagated through views, linkages, and artefacts to various stakeholder affected by the change. [124]

As described in chapter 3.1.3 a model is an abstraction of a system of interest constructed from one or more representations. A system model is generally created using a modelling tool (see chapter 3.3.4). INCOSE explains the system model to be a **mapping of the system of interest onto a simpler system** which approximates the behaviour of interest in selected areas. [125]

[121] EIGNER, 2012, p. 1
[122] BRAUN, 2014, p. 117
[123] EIGNER/GILZ/ZAFIROV, 2012, p. 1670
[124] FRIEDENTHAL/MOORE/STEINER, 2012, p. 523–525
[125] INCOSE, 2004, p. 167

System models offer different views. A view serves to display a specific purpose, which can be formulated as a specific question. [126] According to Friedenthal (2012) the system model includes system specification, design, analysis, and verification information. The system model consists of model elements that represent requirements, design, test cases, design rationale, and their interrelationships. A primary use of the system model is to enable the design of a system that satisfies its requirements and supports the allocation of the requirements to the system's components. The model elements that compose the system model are stored in a **model repository** and are depicted on diagrams by graphical symbols. [127] To sum up, a system model contains of a set of elements and the relationships among those elements.

3.3.2. MBSE PERSPECTIVES

In many development processes, a very intensive model in general will be created. Since this model shall be the communication interface between all different stakeholder, the view on a specific area in a model could be too confusing for a single stakeholder. In order to not excessively fill the viewpoint of one individual stakeholder with system elements, a systematic definition of views and viewpoints is important. As stated by Winzer (2013), the system must be viewed from several perspectives to understand the system/model in its entirety. [128] According to this reason the model should be reduced to a user-oriented view. Only the necessary information is represented. Each model user's perception influences the work with a model. [129]

In this context, three different types of perspectives on a model can be described: [130]

- The **role-specific perspective** is linked to a task in a process or workflow and not a specific person. The tasks which are performed by one role usually change along the process. Due to the growth of available information related to the individual domains in the system model, the level of detail in a model rises.

- The **context-depending perspective** are related to activities, which can be used regardless of the specific role or lifecycle stage. The perspective focusses on general or global deposits, regulatory and administrative structures.

- The **user-specific perspective** are sufficient for the demands of a single person concerning visualisation, data structure and relevant content. This perspective is not suitable for standardization and reuse of views relating to their individual form.

[126] Institute of Electric and Electronic Engineers, 2000, p. 3–4
[127] FRIEDENTHAL/MOORE/STEINER, 2012, p. 17–19
[128] WINZER, 2013, p. 17–19
[129] BRAUN, 2014, p. 27
[130] MINKE, 2015, p. 25

3.3.3. POTENTIAL BENEFITS OF MBSE

As stated above, MBSE provides an opportunity to address many limitations concerning the document-based approach. Friedenthal et a. (2012) provide a list of **potential benefits** that shall arise when utilizing MBSE (see Table 1).

Benefit	**Description**
Enhanced communications	– Shared understanding of the system across the development team and other stakeholder – Ability to integrate views of the system from multiple perspectives
Reduced development risk	– Ongoing requirements validation and design verification – More accurate cost estimation for the system development
Improved quality	– More complete, unambiguous, and verifiable requirements – More rigorous traceability between requirements, design, analysis, and testing – Enhanced design integrity
Increased productivity	– Faster impact analysis of requirements and design changes – More effective exploration of trade-space – Reuse of existing models to support design evolution – Reduced errors and time during integration and testing – Automated document generation
Leveraging the models across life cycle	– Support operator training on the use of the system – Support diagnostics and maintenance of the system
Enhanced knowledge transfer	– Capture of existing and legacy designs – Efficient access and modification of the information

Table 1: Potential benefits of MBSE [131]

In addition to the obvious advantages over document-based systems engineering, there also need to be named some **disadvantages** according the **model-based approach**:

Transitioning to MBSE underscores the need for up-front investment in processes, methods, tools, and training. During the transition phase, MBSE will be performed in combination with document-based approaches. The first creation of a model must be associated with an increased workload, this is owed to the mapping of complex relationships of different elements in the model and the generally larger model architectures. [132]

Nevertheless, as stated by Cao et al. (2011) knowledge can be expressed and shared unambiguously between engineers and different stakeholder with the help of the models. In addition, MBSE facilitates dependency tracing between different models and the reuse of knowledge. [133]

[131] FRIEDENTHAL/MOORE/STEINER, 2012, p. 20
[132] MINKE, 2015, p. 24
[133] CAO/LIU/PAREDIS, 2011, p. 1063

3.3.4. LANGUAGES AND TECHNIQUES FOR MODELLING

The search for ways and possibilities to visualise data of complex systems is the foundation of many research disciplines. The general aim of every form of representation is to provide a global overview of the system and to generate necessary views for each purpose. This shall provide a better understanding of the system for the solution of technical problems. [134] One of the already commonly established visualizing techniques for technical systems and their relationships, for the elements inside and the environment outside, is the methodology for visualizing a system by a **modelling language**. [135]

A modelling language is an artificial set of rules comprising of single elements with fixed prescribed meaning and rules for the interconnection within each other. These languages are used for the description of models. They can be ***text based*** or ***graphically***. In graphical modelling languages, drawings and symbols have concrete meanings. Those are called *graphical notation*. [136]

The origin of modelling languages addresses the connection of system components, the decomposition of system functions, and dynamic behaviour of the system and was created in the early 1950s. It is called the **Unified Modelling Language (UML)**. Today this language is standardised by the Object Management Group (OMG) and the International Organisation for Standardization (ISO). This language dominates software-system-modelling. [137]

Besides UML, the **extensible markup language (XML)** provides the possibility to build up documents out of tags and attributes. This textual based language enables documents to be read-out and interpreted by machines. [138]

Based on those two modelling languages the graphical **Systems Modelling Language (SysML)** is created by OMG and INCOSE. Numerous different modelling languages also based on UML build the foundation for this language. [139] While UML and XML are kept very unspecific on purpose, SysML is developed to specifically model technical problems. Its aim is the formal description of structure, behaviour and requirements of a system. Especially the relations between those aspects are expatiated. [140]

Due to the scope of SE to be cross disciplines, the software oriented UML could lead to irritations and lack of acceptance in non-software disciplines. Further, the UML does not cover requirements engineering, which is included in SysML. [141]

[134] LINDEMANN, 2009, p. 39
[135] MINKE, 2015, p. 45
[136] EIGNER, 2014, p. 88
[137] BUEDE, 2009, p. 23
[138] BRAUN, 2014, p. 95
[139] MINKE, 2015, p. 45
[140] BRAUN, 2014, p. 95–96
[141] WEILKIENS, 2008, p. 23–24

An overview of the available types of diagrams in SysML are displayed in Figure 12.

SysML as language can be used in several different software tools: On today's market tools such as *Magicdraw*, *Enterprise Architect* or *PTC Integrity Modeler* are of relevance. In addition to SysML modelling tools, requirement management tools, such as the *Dynamic Object Oriented Requirements System (DOORS)*, *RequisitePro* or *PTC Integrity Lifecycle Manager* provide a powerful support for modelling requirements. The, mostly textual based requirements can be connected to SysML editors and therefore be updated automatically. [142]

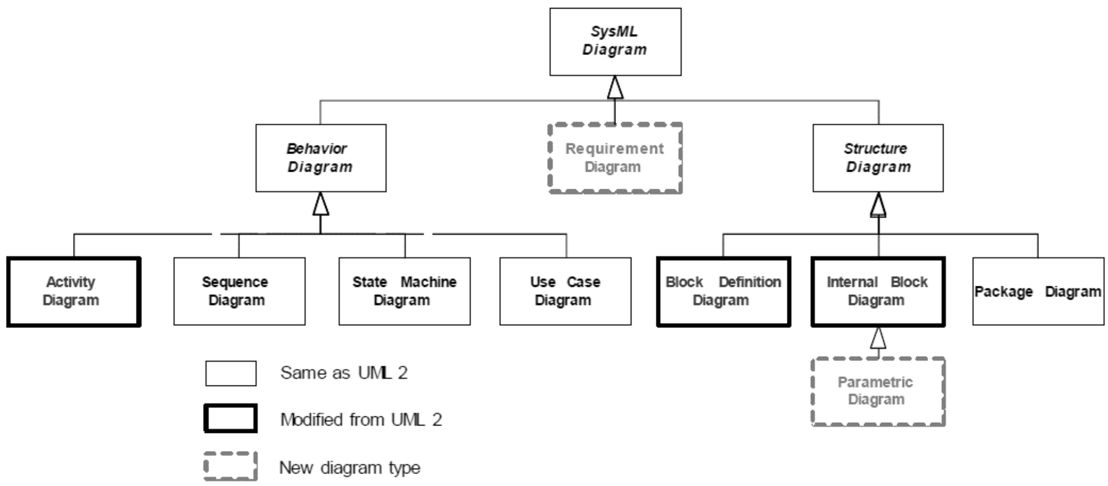

Figure 12: SysML diagram taxonomy [143]

An example of a **functional product description** of a windshield wiper **in SysML** can be seen in Figure 13. Here, requirements (see chapter 4.1.3) are modelled in a hierarchical *requirements diagram*. Functions and system elements are modelled hierarchically in a *block definition diagram*. Connections to internal block diagrams represent a view of the functional and the logical architecture. An allocation relationship is established between two model elements. Those allocations can be of different types, such as a standard allocation in SysML: The requirement *detect raindrops by the window* is satisfied by the function *detect raindrops*. If all cross references are defined, requirements can be related to the functional and logical architecture. In case of the change of a requirement, it can be traced to the affected logical or functional system elements. [144]

Overall, it can be stated that the modelling language SysML has the great advantage of on the one hand capturing the reality in a model and on the other hand visualizing the different dependencies to subsystems, functions, component characteristics, technical requirements and their validation & verification method [145]

[142] EIGNER/GILZ/ZAFIROV, 2012, p. 1671
[143] OMG, 2012, p. 167
[144] EIGNER/GILZ/ZAFIROV, 2012, p. 1671
[145] MINKE, 2015, p. 46

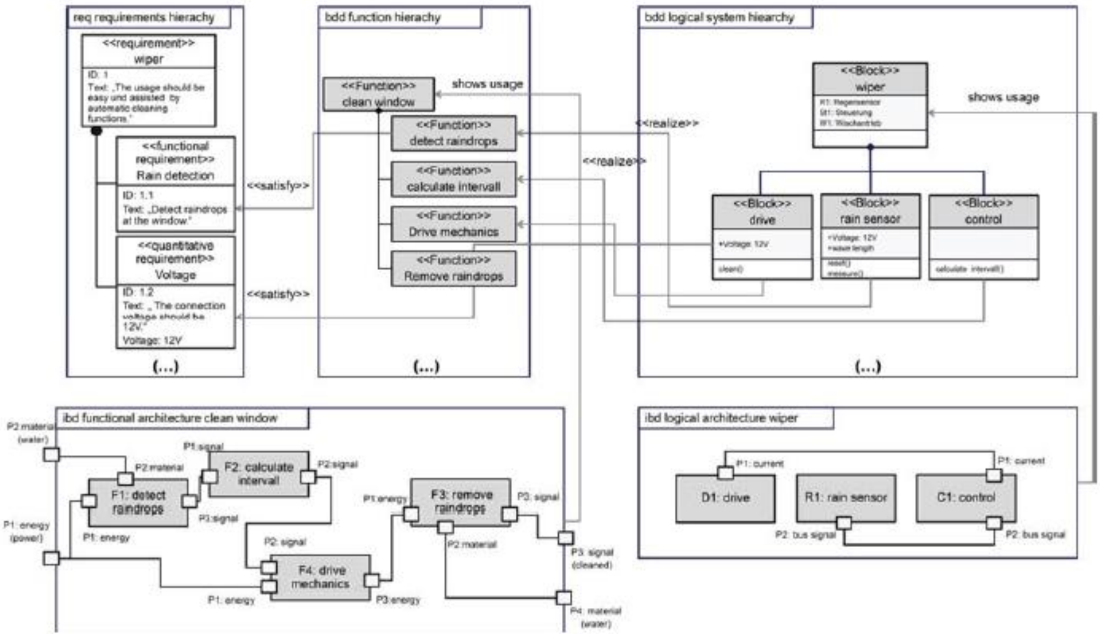

Figure 13: Example for a functional product description in SysML [146]

3.3.5. INTRODUCTION OF MBSE IN AN ORGANIZATION

The introduction of MBSE in an organization requires an initiative for change, which does not only require modelling tools, but also processes relevant for SE, methods and qualification of all involved stakeholder. In this change process clear responsibility for the improvement initiative should be established, and the expected cost and benefits of the change shall be understood and agreed on with all stakeholder. Friedenthal et al. (2012) define a **five-step improvement process**, similar to the PDCA-cycle: [147]

1. **Monitoring and Assessing:** At the beginning the organization should assess how SE/MBSE is currently practiced and identify the issues, improvement goals, and costs expected for later comparison (baseline). This baseline contains aspects of the process, methods, tools and stakeholder. It is the foundation for metrics and objectives for the assessment of the introduction and the level of adoption by projects, and the resulting value provided to the projects.

2. **Planning of the improvement:** In this step it is defined how to accomplish the improvement goals, including the improvement process (see Figure 14). The plan needs to detail the schedule, resources and responsibilities and shall be approved by the management. Stakeholder for MBSE include members of the improvement team responsible for defining the change, as well as project management, systems engineering, development and if necessary customers and subcontractors.

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[146] EIGNER/GILZ/ZAFIROV, 2012, p. 1671
[147] FRIEDENTHAL/MOORE/STEINER, 2012, p. 557–563

3. **Definition of changes to process, method, tools and training:** The introduction demands many changes in the organisation. Those changes are within this step defined, documented, validated and approved by the affected stakeholder, to achieve the desired results.

4. **Piloting the approach:** The choice and the planning for a first pilot project requires willing participants provided with the necessary resources and commitment of the management. During the execution there shall be an ongoing optimization. After the project an extensive evaluation and modifications to the approach shall be conducted.

5. **Incremental deployment of changes:** The pilot results help to determine the requirements and approach for deploying the capability of MBSE onto projects. Examples are the necessary type of training methods or project-selection criteria. Those criteria may include time, size, level of internal and customer support and the expected results when modelling.

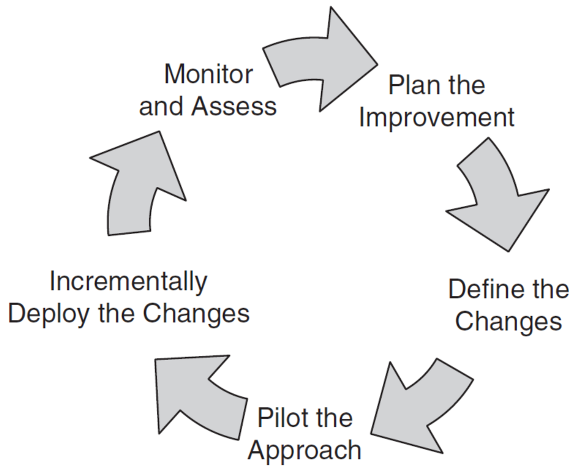

Figure 14: Introduction of MBSE within an organisation [148]

3.3.6. MBSE IN THE INDUSTRY

Today, most organizations of the automotive industry push MBSE in its entity ahead in applied research. Eigner (2012) names the modelling language **SysML** to be the **enabler for MBSE** in today's industry. [149] The biggest dissemination takes place in the function development. Hereby tools and techniques such as Matlab Simulink are used. Further SysML is also utilized, in the early phase of the system development at the customer requirements and an initial system design. This phase takes place in so called requirement management tools. [150]

Although, languages such as **SysML** or **UML** are widely known, they are **only applied isolated in a few divisions** of a few organizations (see 3.3.4). [151]

[148] FRIEDENTHAL/MOORE/STEINER, 2012, p. 557
[149] EIGNER, 2012, p. 1
[150] WEILKIENS, 2008, p. 23–24
[151] FRITZ, 2013, p. 58–59

A possible reason for the rare use is given by Zingel (2013): He names the **generic character of modules** a **hindering factor** for the use in classical mechanical engineering disciplines. Further, the gap between the generic description of systems in SysML and the specialized, already used computer tools (e.g. CAD-tools) is mentioned. Further, SysML-diagrams do not offer the visualization of management relevant information, such as costs, status or resources. As described, this information can be deposit in the model, but not displayed. [152] Furthermore, according to Broy et al. (2010), inadequate language specifications including the interfaces and available software tools hinder the operation in organizations. [153]

MBSE and Industry 4.0

Evidently, MBSE and its enabler SysML are highly discussed and therefore, also play a role for the upcoming fourth industrial revolution to an Internet of Things, Data and Services: Industry 4.0. [154]

Today, consumer products and capital goods are highly differentiated according to the customer's wishes. This is followed by unforeseeable fluctuation of demand. Production, development and logistic processes have to be highly dynamic. According to the German ministry of education and research this can hardly be implemented with centrally controlled processes. This would only be possible by so called cyber physical systems. Humans, in this system, should become flexible and agile problem solvers. [155] This **cyber physical system** (CPS) is described to be a network of interacting elements with physical in- and outputs. In contrast are not interacting standalone-products and networks without physical in- and outputs. [156]

Alt (2014) formulates many communalities in-between the concepts of model-based systems engineering and the ideas of Industry 4.0: [157]

- The basis of Industry 4.0 is the **extensive exchange of information** among all stakeholder involved in the process of development and production (supplier, customer, producer). MBSE solves this problem by the **application of a central model repository**.
- In Industry 4.0 so called **production chains** are in use. To specify those productions chains, the concept of a **functional model** can be utilized. Whereas all in a functional model concerned components (mechanics, electronics and software) are displayed, to highlight which components are involved, and which data or material is exchanged. Compared to a physical architecture representation (such as a bill of materials or a circuit diagram) this allows the specification of a continuous model of all system components including software. Generated

[152] ZINGEL, 2013, p. 66–67
[153] BROY/FEILKAS/HERRMANNSDOERFER *et al.*, 2010, p. 526–532
[154] SENDLER, 2013, p. 30–36
[155] BMBF, 2015, p. 2–5
[156] SENDLER, 2013, p. 8
[157] ALT, 2014, p. 4–9

data can be both code or XML (machine-readable) but also documents or lists (human-readable).

- **Individual customized products**, manufactured in mass-production like environment is a key factor of industry 4.0. To realize these capabilities, the definition of customer projects (**requirements**) can be **implemented with MBSE**, where the handling of requirements and the variants of a product in a model are a key aspect.

- Another important aspect of Industry 4.0 is the **coupling of tools among each other**, and beyond technology borders. Necessary **standards**, such as the requirements interchange format (**ReqIF**) for this data exchange are defined by the Open Management Group (OMG). This format allows to exchange any desired development and production data.

Consequently, with the use of MBSE reaching the aims of Industry 4.0 is attainable. The combination of today's available methods, technologies and tools, such as the OMG standards, or models in SysML to specify production or the value chain is a first step to paving the way of Industry 4.0.

4. THEORETICAL BACKGROUND OF PRODUCT DEVELOPMENT PROCESSES

In the current market the intensification of financial factors, the time frame and decreasing cycle times to develop new innovative products is challenging organizations. The requirements for staff, teams and organizations dealing with the development of powertrain elements are increasing. From a company's perspective, the **aim** of product development is to **create competitive products** in the given cost and time limits. [158]

This product creation takes place in a very **knowledge-intensive environment**. On the one hand organizations need to bring a high degree of individual specialization, on the other hand the competence in dealing with interdisciplinary topics. [159] Browning (2003) describes product development as a **problem solving-process**. It ranges from marketing, design, management and other activities done between defining a market opportunity and starting production. The goal is set to be the creation of a *recipe* for producing a product. [160] Ulrich and Eppinger (2012) exemplarily separate the **steps of a product development process** into five phases: [161]

1. **Concept development:** In this first phase the needs of the target market are identified, alternative product concepts are generated and evaluated, and one or more concepts are selected for further development and testing.
2. **System-level design:** This phase includes the definition of the product architecture, decomposition of the product into subsystems and components, and preliminary design of key components. Further, initial plans for production system and final assembly are defined.
3. **Detail design:** The next phase includes the complete specification of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers.
4. **Testing and refinement:** Construction and evaluation of multiple preproduction versions (prototypes) of the product.
5. **Production ramp-up:** In this final phase, the product is made using the intended production system to train the workforce and work out any remaining problems in the production process.

Individual departments and individuals can rarely fulfil the requirements for the **development of mechatronic systems**. This requires the cooperation of different technical disciplines, such as mechanical, software or electronics, and non-technical disciplines. Furthermore, also customers shall be integrated in the development process. [162] This brings up the need for a **process model** displaying the development process which is linked to the product model. Hereby, relevant product information can be shared with other stakeholder of development. Those process models can provide a

[158] GERICKE/GRIES, 2009, p. 291
[159] MINKE, 2015, p. 12
[160] BROWNING, 2003, p. 50
[161] ULRICH/EPPINGER, 2012, p. 15–16
[162] MINKE, 2015, p. 12

management perspective for controlling and development perspectives that support everyone involved in product development.

After describing the principles of the battery system in chapter 2 and the method MBSE in chapter 3, this chapter gives an explanation of the term process, important process models and influencing factors such as knowledge or quality management for powertrain development.

4.1. PROCESS MANAGEMENT

A **process** in general is described to be the **conversion from input into output**. According to Schmidt (2012) processes can be defined by the type and the characteristics: [163]

- **The type of a process:** The generic description of processes with the definition of input, output, function and the description of synchronization.
- **Characteristics of a process:** The realization of a process in an application.

If the **time** is added as a further dimension, a **process flow** will develop. At the beginning of a process, necessary factors such as personnel, material or information-resources have to be procured. Processors are phasing the process and transform those factors to output, which are being distributed to further processes. Processors can be manpower or means of operation, which are necessary for the fulfilment of a process. The sum of the processes and its ranking by time reveals the overall process. The ranking by time is developed by the output which are factors for the following process. The capacity of all processors needs to be respected to avoid situations of congestion. [164]

In **process management,** this conversion of input to output becomes considerable when being subjected to regular planning, decisions, implementations and controlling. Every necessary sequence to fulfil the customer objectives can be summarized to be a **value chain**. Those sequences can be understood to be **activities to fulfil the creation of value** (definition of value within this context: see chapter 4.4.1). This value chain within an organisation usually considers the organizational structure horizontally. It develops to be a process, when a stakeholder is assigned to this value chain. Those stakeholder usually have the additional responsibilities by belonging to a vertical line structure. Process management shall ensure the success of the value chain and being responsible for continuous improvement. Hirzel (2013) stresses, that process management can only be successfully utilized when the benefits are being clearly visible by everyone involved. Therefore, he names several benefits for an organisation and for employees. Benefits for an organization can be, that the accuracy of offers is increasing or the overall quality is improving. Benefits for employees are for instance more objective performance measures or confirmed tasks. [165]

[163] SCHMIDT, 2012, p. 1–3
[164] SCHMIDT, 2012, p. 1–11
[165] HIRZEL, 2013, p. 5–10

4.1.1. WATERFALL MODEL

One of the earliest concepts of process models is the so called waterfall model introduced by Boehm (1976). [166] The waterfall model is strongly based on the **sequential evolution of typical life-cycle phases**. It is considered, that a **phase is not repeated after completion**. This implies a phase not to begin, before the subsequent phase has finished completely. For instance the requirements (see chapter 4.1.3) have to be fully specified to start with the next phase. Nevertheless, today's product development processes are highly dynamic processes. Especially requirements change dynamically over time and cannot be fully specified before the next phase. Although the waterfall model is described to be an early initial start for process modelling, the process of battery development is highly dynamic and cannot be modelled in this way. [167]

4.1.2. STAGE GATE PROCESS MODEL

The stage gate process is a management oriented model of a product development process. Therefore, the process is structured in different phases, which are separated by gates. At every gate a review takes place, if the process has reached the necessary maturity level, which is displayed in the model. Different generations of stage gate processes can be described as followed: [168]

The **first generation** describes the phased project planning which was introduced by NASA in the 1960s. In this generation, similarly to the waterfall model, phases are strictly divided. Every subsequent phase is defined to be a customer of the phase before. Thus, at the end of a phase all activities have to be finished to start with the next one. This entails waiting time due to waiting for finishing every single activity. Further, this generation focuses exclusively on technical aspects. [169]

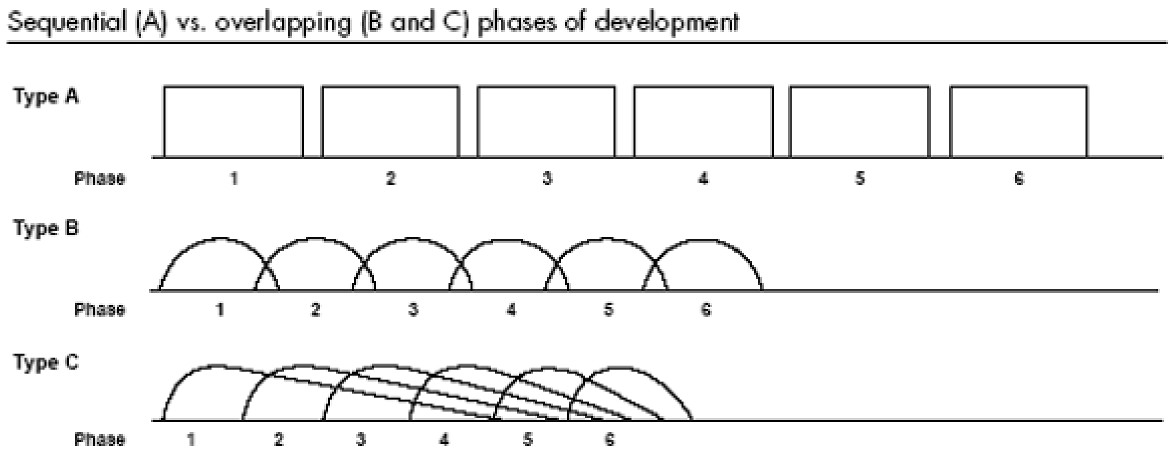

Figure 15: Sequential vs. overlapping phases of development [170]

[166] Boehm, 1976, p. 1226–1241
[167] EIGNER, 2014, p. 34
[168] BURSAC, p. 12–14
[169] COOPER, 1994, p. 3–14
[170] TAKEUCHI/IKUJIRO, 1986, p. 139

The **second generation** of stage gate processes is characterized by separate phases too. Whereas non-technical factors such as marketing also influence the review at the gates. This enables an orientation on the market. Single activities within phases can be fulfilled parallel. This increases the need for coordination but decreases the overall time needed. Nevertheless, an overlapping of phases is not possible, due to strict separation of each phase.

In the **third generation** the strict gates are being converted into so called fuzzy-gates. Therefore, phases overlap and gates can be adjusted according to each phase. This enables a start with activities of subsequent phases, before the precedent is finished. Unforeseeable changings in planning can be respected by a flexible design of the fuzzy-gates. The potential of saving time is described by Takeuchi and Nonaka (1986), which is the basis for agile product development (see Figure 15).

4.1.3. V-MODEL ACCORDING TO VDI 2206

A broadly used process model is the V-Model released by the Verein Deutscher Ingenieure (VDI) within the **guideline 2206** for mechatronic systems. This guideline originates in software development, but is used increasingly in the automotive industry. [171] The focus of the guideline is emphasised on three levels: The problem solving cycle (micro cycle), the V-Model (macro cycle) and process components for recurring working steps. [172]

In the V-Model, development and testing activities are put together according to its levels. The system process is separated in three separate process phases: [173] [174] [175]

1.) **System design:** This phase begins with the user-requirements, continues with a top-down-process with the specification and design of the overall function to be separated in sub-functions.

2.) **Domain specific design:** All concepts are enhanced in the disciplines of mechanical engineering, electrical engineering and information technology.

3.) **System Integration:** The integration and test of the developed system elements (verification and validation) and the system acceptance takes place. Therefore, this phase is a bottom up process.

All steps combined create a **V-shaped process** (see Figure 16). As stated in the VDI-guideline (2004) for the development of complex mechatronic systems, several **iterations are necessary**. [176] One strength of this model is the consistent top-down structuring of the development process. A problem will occur

[171] BURSAC, p. 16
[172] SENDLER, 2013, p. 98
[173] BURSAC, p. 17
[174] VDI, 2004, p. 29
[175] EHRLENSPIEL, 2009, p. 272
[176] VDI, 2004, p. 29

if the information base (the requirements) at the beginning of the project cannot be fully integrated due to the high uncertainty. In this case the V-Model can be separated into partial steps. [177]

As stated by Alt (2012) it is important for the interpretation of the V-Model that there is **no axis of time**. Therefore, for instance test activities can be started as soon as all for the test necessary information is available. The model shows that after the development of a system, the development of components and after the integration of the components the system implementation can take place.

Overall, the model shapes a first broad frame for the development context. This can be used to, for instance align the organisation structure in an organisation for development. Further, it can support employees of a big organization to define and classify their work. [178]

Alternatives to the V-Model are the W-Model (Anderl 2011) the 3 Cycle Model (German: 3 Zyklenmodell, Gausemeier 2006) or the 3-Layer Model (Bender 2005). In this context those models are not specified further. [179]

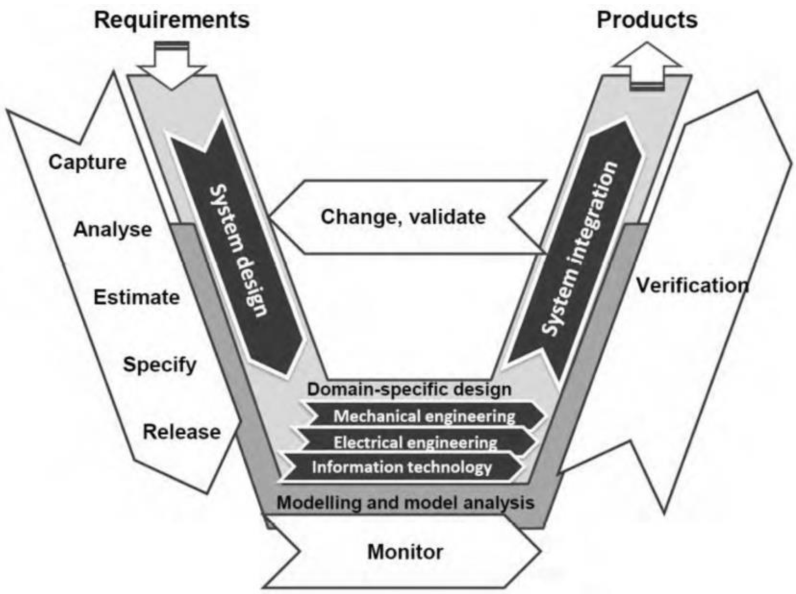

Figure 16: The V-Model [180]

Requirements Engineering

One key aspect of the V-Model, and start for the product development process is the discipline of **requirements engineering**. As described by Eigner (2012) requirements engineering "reflects more or less the abstract idea in the form of customer needs or user requirements." [181]

[177] MINKE, 2015, p. 15
[178] ALT, 2012, p. 85–86
[179] SENDLER, 2013, p. 99
[180] VDI, 2004, p. 29
[181] EIGNER/GILZ/ZAFIROV, 2012, p. 1670

The importance of requirements engineering is shown by Rupp (2012). He names handling of requirements a significant reason for possible project failures. It is further stated that the majority of mistakes in product development happen in the phases of analysing the user and elaborating the related requirements at the beginning of development. [182]

According to IEEE (1990) a **requirement** itself is defined to be: [183]

1. A condition or capability needed by a user to solve a problem or achieve an objective.
2. A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed documents.
3. A documented representation of a condition or capability as in (1) or (2).

Further, requirements can be distinguished between functional and non-functional requirements. Whereas functional requirements define the functionality that a planned system shall comply with. Non-functional requirements define the desired quality of the planned system and the boundary conditions. [184]

Requirements engineering is **defined** to be a **systematic and disciplined approach to specify and to manage requirements.** The aim is to document ideally complete customer requirements in high quality. This shall enable an early detection of mistakes. Requirements are influenced by stakeholder (such as the customer, engineers, management, end-user), who define the system characteristics or the budget and timetable. [185] Those stakeholder are the major source for requirements. Another source are documents such as norms and standards or legislations, or the feedback of already used systems. [186]

The fact that the requirements engineering process accompanies and supports the development process can be seen by the relation to the V-Model. Hereby the separation of requirements takes place in the left leg (system design) and the solution findings with the verification by defining the technical specification on the right leg. A **specification** in this context is described to be: [187]

> "A document, that specifies, in a complete, precise, verifiable manner, the requirements, design, behaviour or other characteristics of a system or component and, often, the procedures for determining whether these provisions have been satisfied."

[182] RUPP, 2012, p. 3–4
[183] IEEE, 1990, p. 62
[184] GRANDE, 2011, p. 37–38
[185] RUPP, 2012, p. 4
[186] RUPP, 2012, p. 11–12
[187] IEEE, 1990, p. 69

The **level structure** of **AVL List GmbH** explained in chapter 2.2.2 can also be brought up to explain requirements engineering in the **use case of battery development**. Hereby requirements (so called *what documents*), which are determined by the customer, are broken down into technical specifications (so called *how documents*) (see Figure 17). The subsequent z-shaped interplay can is described to be the basis for the structure of development.

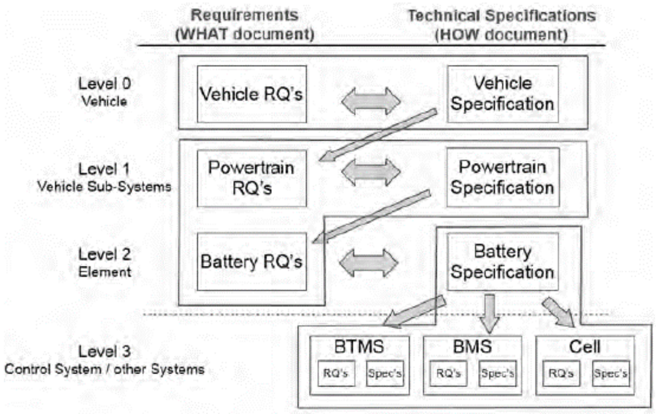

Figure 17: Different levels of abstraction in requirements engineering for battery development [188]

4.1.4. EXTENDED V-MODEL BASED ON VDI 2206

Such as described in chapter 4.1.3, the V-model defines a systematic procedure for the development of mechatronic systems. Nevertheless, it does not address all approaches of MBSE. Therefore, Eigner, Gilz and Zafirov (2012) **extend this V-model with the use of methods from MBSE**. This extended model can be subdivided in four main parts (likewise to the V-model): Interdisciplinary system design on the left wing, discipline specific detailing on the bottom, system integration on the right wing and the system life cycle and the PLM-backbone on the top. This approach shall enable a PLM/PDM connection. (PLM: Product Lifecycle Management, PDM: Product Data Management: See chapter 4.5.1) [189]

The views for modelling in product development in the left wing of the "V" are described to be: [190]

- **Modelling and specification: "**In this early specification the system is described by qualitative models, like requirement, function or system oriented models. The models are descriptive and cannot be simulated. In this view an interdisciplinary language like SysML can be used to specify the first design. A *computer-stored* common system specification model can be evolved, to support the specification process for all involved disciplines.**"**
- **Modelling and first simulation:** "In this view quantitative aspects are integrated in an interdisciplinary view. This can comprise of simulation models (in e.g. Matlab or Modelica) for multidisciplinary simulations."

[188] MINKE, 2015, p. 18
[189] EIGNER, 2014, p. 86
[190] EIGNER/GILZ/ZAFIROV, 2012, p. 1670

- **Discipline specific modelling: "**In this view the system is modelled more precisely in a discipline-specific way. These are mainly tool dependent CAx models that represent discipline-specific aspects. An example for such models can be a mechanical CAD model, which contains the concrete geometry representation and many other properties, like e.g. mass."

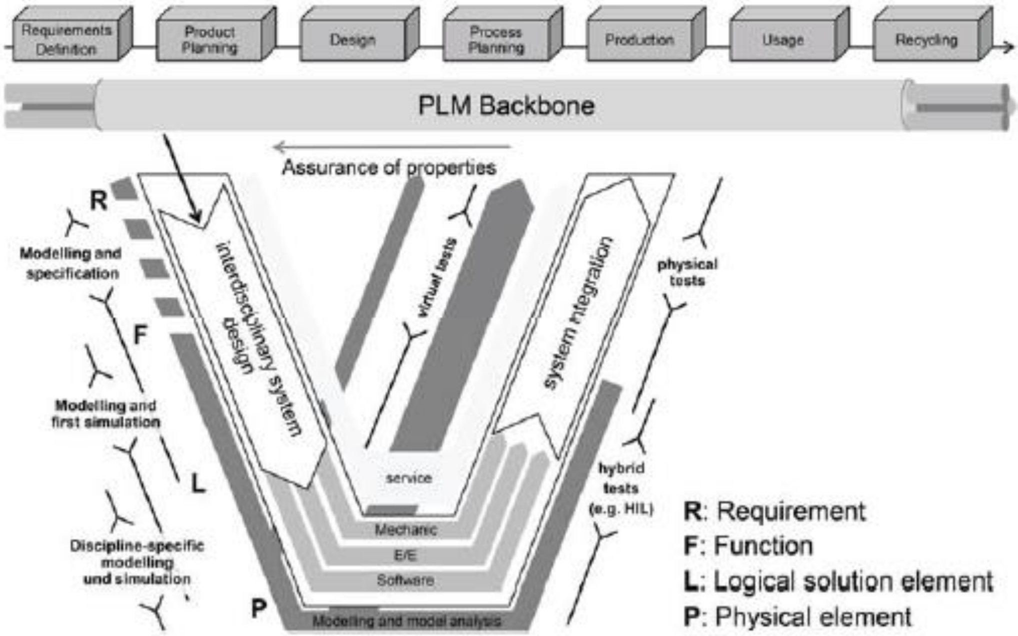

Figure 18: Extended V-Model based on VDI 2206 [191]

In addition, the **left wing of the "V" is divided into**: Requirements, functions, logical solution elements and physical elements: [192]

The **requirements (R)**, as described in the previous chapter are the starting point for development. The idea, which is specified in the requirements document needs to be translated into a logically consistent, technical requirement model. In the phase of product planning and design an interdisciplinary system design is essential for bringing all disciplines together and forming a functional solution of a technical system. The decomposition into **functions (F)** provides an initially discipline- and solution- neutral view. The functional elements are realized by the solution concept, which is described through the definition of **logical solution elements (L).** The concept includes logical and physical behaviour and structure. The system design is **supported by** formal and semi-formal languages such as **UML or SysML** (see chapter 3.3.4) and simulation-based languages, such as Matlab or Simulink. Virtual tests, at the end of interdisciplinary system design, validates the system under development against requirements and test scenarios. Based on the functional description and those first simulations each discipline can start with its discipline specific detail design. This results in **physical elements (P)** of the system, like hardware parts or software code.

[191] EIGNER/GILZ/ZAFIROV, 2012, p. 1670
[192] EIGNER/GILZ/ZAFIROV, 2012, p. 1670–1671

4.2. KNOWLEDGE MANAGEMENT

In this subchapter the necessity of knowledge management in product development is explained. Therefore, first the term knowledge, is outlined. This term is widely used but hardly defined: For instance as the common, everyday knowledge which represents the daily coherencies, or the rational knowledge. In general, as stated by Quinn et al. (1996) for **definition of the term knowledge** can be classified into: [193]

- Cognitive knowledge (**know what**) is the basic mastery of a discipline.
- Advanced skills (**know how**) are the ability to apply rules of a discipline to complex real-world problems.
- Systems understanding (**know why**) is deep knowledge of cause-and-effect relationships underlying a discipline.
- Self-motivated creative (**care why**) consists of will, motivation, and adaptability for success.

Meixner and Haas (2012) divide knowledge hierarchically into: **Symbols, data** and **information**. Whereas many symbols are becoming data, which is interpretable in a specific context and therefore information. A network of information allows the use in a field of activity, which is called knowledge. [194]

In an organization knowledge is mostly distinguished in explicit and tacit knowledge:

Explicit knowledge is conscious knowledge that can be categorized and stored in documents such as in an encyclopaedia. [195] It is methodical and systematic and is present in an articulated form. It is stored in media, not in humans and can therefore be transferred easily and be imitated, for instance by information technology. [196] **Tacit knowledge** is a form of knowledge that cannot be explained explicitly. It is very difficult to articulate and pass on, since it represents the personal knowledge of an individual. [197] According to North (2014) knowledge in an organization is only to a small extent explicit. The major part is tacit knowledge, which is personal, context-specific, and often unconscious. [198] **Knowledge** can be **transferred formal** and **informal**: In a formal way knowledge is transferred by documents or reports, informal by discussions or conversations.

4.2.1. KNOWLEDGE MANAGEMENT IN ORGANISATIONS

Knowledge in product development processes represents a central, fundamental role: "In the post-industrial era, the success of a corporation lies more in its intellectual and system capabilities than in

[193] QUINN/ANDERSON/FINKELSTEIN, 1996, p. 71–72
[194] MEIXNER/HAAS, 2012, p. 6
[195] FREY-LUXEMBURGER, 2014, p. 15
[196] NORTH/KUMTA, 2014, p. 45–46
[197] MEIXNER/HAAS, 2012, p. 8
[198] NORTH/KUMTA, 2014, p. 34

its physical assets”. [199] Braun (2014) states that knowledge is the basis for a competent handling of complexity of product development. Further, knowledge is based on the individual interpretation of information by individuals. [200]

Knowledge management is described to be a tool for handling knowledge such as this individual information. It deals with the **available knowledge in an organization**. [201] North (2014) defines knowledge in organizations to be “the product of individual and collective learning [, which is] […] embodied in products, services and systems”. It **includes many factors**, such as competencies and capabilities of employees, a company’s knowledge about customers and suppliers, know-how to deliver specific processes or intellectual property in the form of patents, licenses and copyrights. Knowledge is related to the experience of people, but only a small part of it is made explicit. Thus, knowledge is a resource, an intangible asset and forms a part of the so-called **intellectual capital** of an organization. [202]

To sum up, the **objective of knowledge management processes** is “the transformation of information into knowledge and competence in order to create measureable value in a sustainable manner.” [203]

One main aspect about knowledge management is to handle tacit and explicit **knowledge** in a way, that it is **available in an adequate form, at the necessary time and place**. The transfer of individual knowledge to collective knowledge is imperative for an organization to form a creative and collective intelligence.

<u>Introduction of knowledge management in an organisation</u>

This transfer, or conversion of knowledge can be split up, according to North and Kumta (2014) into four ways in the so called SECI-model: [204]

1.) **Socialization: From tacit to tacit knowledge:** This process of sharing experiences, such as shared mental models or technical skills can take place when, for instance a new member of a group learns through observation, imitation and practice. The shared experience is the key for value creation in knowledge based organizations.

2.) **Externalization: From tacit to explicit knowledge:** In the process of externalization tacit knowledge is being articulated into explicit concepts. An example would be a formal project description. Nevertheless, since externalisation reveals only a part of the tacit knowledge, it is good not to rely exclusively on written statements but also enhance socialization.

[199] QUINN/ANDERSON/FINKELSTEIN, 1996, p. 71
[200] BRAUN, 2014, p. 24
[201] SAUTER/SCHOLZ, 2015, p. 4
[202] NORTH/KUMTA, 2014, p. 31–32
[203] NORTH/KUMTA, 2014, p. 35
[204] NORTH/KUMTA, 2014, p. 46–47

3.) **Combination: From explicit to explicit knowledge:** Here the exchange and combination of knowledge takes place through reconfiguring existing information, which is exchanged by documents, meetings or communication networks. Sorting, adding, combining of explicit knowledge may lead to new information. Often this approach follows the economics of reuse (for instance of documents or presentations).

4.) **Internalisation: From explicit to tacit knowledge:** This takes place if explicit knowledge is embodied in implicit knowledge. It takes place, for instance, if an employee reads an operating manual in order to fulfil a task.

Knowledge that is emerging during the product development process is stored in so called **knowledge-management systems**. This increases the overview for developer during product development. New information can be typed in, existing information can be retrieved. An example for such a system is SAP for enterprise resource planning. According to a study carried out by Bursac (2016) the most used system is the storage of documents in a network, graphically implemented by the windows folder structure. A further questionnaire concerning different systems [205], on average only shows a weak performance according to efficiency, structure, security and user-friendliness. [206]

When **introducing knowledge management in an organization**, many of those barriers can hinder a successful implementation. In a study implemented by Adelsberger et al. (2002) those barriers are named to be: [207]

- **Individual barriers:** Lack of time, lack of competence, not-invented-here syndrome, lack of acceptance, fear of loss of prestige
- **Organizational barriers:** Inefficient incentive-systems, rules for reputation based on individual knowledge, cultural components that hinder knowledge management, hierarchies, knowledge management is tagged to be a management technique
- **Technological barriers:** Biased too much to IT, lack of acceptance of the system

One way to exchange tacit and explicit knowledge in organisations are so **called lesson learned processes**. Hereby knowledge is being transferred by the means of externalization and socialization. “Lessons learned represent the essence of all experiences that were made during a project” [208]. They arise while executing tasks or projects gaining insights from continuous problem resolution. All knowledge gained in former projects has to be available for future similar projects.

[205] In this survey tested systems: Digital folder structure, document management systems, Wiki, specific databases, enterprise resource planning, PDM/PLM, Intranet
[206] BURSAC, p. 91–92
[207] ADELSBERGER/BICK/HANKE, 2002, p. 536
[208] NORTH/KUMTA, 2014, p. 133

Zeitner and Peyinghaus (2013) propose a workshop to gather all raised lessons learned at the end of a project. Everyone concerned can exchange the gained experience and knowledge in such a workshop. [209] North and Kumpta (2014) name this workshop to be a so called *after action review* (AAR). A key aspect, as being stated, is the immediate disincentive of the meeting to assure all participants are still available. Within this AAR the **discrepancy between *what was supposed to happen* and *what actually happened*** shall be elaborated. Project success and failures have to be documented by recording the key points. [210]

A common way to collect lessons learned is a document based way. Those are commonly stored in an organization's network. Here the problem arises that those documents are not used in follow-up projects. The reasons can be missing knowledge about the existence of such documents, limited access or high time effort to find such documents. [211]

4.2.2. KNOWLEDGE MANAGEMENT AND MBSE

MBSE can **support the process of knowledge management** by a model to store knowledge based on experience by linking it to single model elements. The identified challenge is the consequent data maintenance in the model.

An important factor, as shown by Adelsberger et al. (2002) is the utilization of ***easy-to-use* tools**, to **enable** a **comprehensive application of a model** in the organization. In contrast, knowledge management shall not be biased too much on the introduction of IT-solutions. Those are often used in a wrong context, since scientific behavioural aspects are not being taken into account. Further the personal surplus of value has to be apparent for employees to be accepted by them. [212] Nevertheless, the importance of knowledge makes it necessary to support all stakeholder in product development in the on time **distribution of the necessary cross-linked information**. For this purpose MBSE can foster the knowledge integration process by **appropriate graphical representation**. As described by Braun (2014) the challenge is that tacit knowledge consists of far more than product and process documentation (e.g.: bill of material, time table). Therefore, relations that describe a strategic act which promises success in a specific situation shall be represented. This enables the transmission of information to new problems.

To make such information useable by different individuals, a **common subjective interpretation** has to be possible. The basis for such a common understanding could be an abstract, independent of any situation, **Meta model**. This represents the connections of product development on a superordinate level. [213] It simplifies the step from information to knowledge and enables the connection of information across responsibilities and corporate structures.

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[209] ZEITNER/PEYINGHAUS, 2013, p. 38
[210] NORTH/KUMTA, 2014, p. 103–104
[211] LUGGER, 2016, p. 49
[212] ADELSBERGER/BICK/HANKE, 2002, p. 537
[213] BRAUN, 2014, p. 24

4.3. QUALITY MANAGEMENT

The quality of products or services is the basis for the success of many organisations. The same also applies for battery systems and the underlying development processes. Therefore, in this chapter the foundations for quality management are explained.

First, the term ***quality*** can be defined to be the "**degree to which a set of inherent characteristics fulfils requirements**" [214]. A requirement is the need or expectation (see chapter 4.1.3). Even though the term quality is basically value free it is mostly linked to a positive image. Brüggemann et al. (2015) state that the term covers following principles: [215]

- **Quality is relative:** It describes the accordance of a product or process with the desired value.
- **Quality cannot be measured:** Measurements are only possible by an indirection, since it cannot be recorded as a physical measured value.
- **Quality is a very general term:** The presence or absence of the quality of a product cannot be absolute. Only gradations in between are possible.

In product development the term quality is interpreted to be the realized explicit formulated customer objectives and the, often unconscious implicit customer expectations. [216]

Measures for quality assurance becomes more important due to the increasing complexity of interconnected systems. Traditional approaches of quality management were designed to test the system after completion of construction. Today's **approaches** increasingly try to **improve the creation processes** as an indirect effect on the products or systems quality. Therefore, process models, which have the character of framework directives and process descriptions support this fact. [217]

4.3.1. ISO 9000

Quality management in product development process is regulated by the **DIN EN ISO 9000**. This is a generic term for a family of standards. It defines the capability of an organisation to produce quality. The content of those standards is the implementation of quality management systems. This includes both, the organisational structure and responsibilities, and the necessary processes and actions for quality management. [218]

The standards of the ISO 9000 family are very universal applicable. The fundamental standards which are covered are the following:

[214] DIN EN ISO 9000:2015-11
[215] BRÜGGEMANN/BREMER, 2015, p. 3
[216] EHRLENSPIEL, 2009, p. 227
[217] REIF, 2014, p. 67
[218] BRÜGGEMANN/BREMER, 2015, p. 122–125

The **ISO 9000** describes the basics of quality management systems and defines the terminologies. In this standard, **quality management** is described to be the coordination of tasks to manage and regulate an organisation according quality. **Topics of quality management are**: Definition of the quality objective, quality planning, control assurance and improvement. [219]

In the second part, which is relevant for the considered context in this thesis, the application of the standard **ISO 9001** in software development is described. This standard **covers the demands for a quality management system** and is nowadays closely seen to be a development strategy for complex systems. The requirements of this standard apply for the entire product life cycle. [220]

In the **ISO 9004** a standard is described, which considers both the **effectiveness and the efficiency of a quality management system**. The aim of this norm is the enhancement of performance of an organization. [221]

4.3.2. SELECTED QUALITY MANAGEMENT METHODS

Especially in the early stages of development the application of quality management is necessary. Here, every past mistake, which is not removed, induces disproportionate costs in later phases of a product life cycle to remove a failure. Bremer and Brüggemann (2015) assume that with every phase, a failure is discovered later costs for removing are increasing by the factor 10. [222]

Therefore, quality management methods for failure prevention early in the product development process should be implemented. In this subchapter the method of quality function deployment (QFD) and failure mode effect analysis (FMEA) is explained:

Quality Function Deployment (QFD)

The key element of QFD is the customer involvement. The aim is to include customer objectives into the development process. Therefore, those objectives shall be broken down to technical requirements, components and to production- and verification processes. Within time many different variants of this method according to the extent and amount of incorporated elements have developed. [223] The premise of QFD as described by Goetsch and Davis is that: [224]

> "Before any product or service is designed, the producer should have a good understanding of his potential customers' needs in order to improve the likelihood that the product or service will be a market success."

[219] BRÜGGEMANN/BREMER, 2015, p. 125
[220] REIF, 2014, p. 68
[221] BRÜGGEMANN/BREMER, 2015, p. 125
[222] BRÜGGEMANN/BREMER, 2015, p. 29
[223] BAHILL/CHAPMAN, 2015, p. 24–35
[224] GOETSCH/DAVIS, 2014, p. 312

One tool for the use of QFD is the **House of Quality** (HoQ) (see Figure 19). It is used to translate what the customer wants into what the organization produces. This tool requires the organization to collect and analyse inputs from customers. Six submatrices combined form the appearance of a house: [225]

1.) The first step is to develop a set of customer needs (WHATs). Those are collected in the left arm of the house.

2.) Next, in the planning matrix, customer satisfaction data relative to the product and competing products is collected and analysed. Hereby a planned satisfaction target for the forthcoming product, improvement factors and sales points are developed.

3.) The third step, in the roof, is to state how the organization intends to respond to each customer need (also called the voice of the company).

4.) In the interrelationship matrix it is examined how the technical requirements relate to the customer needs. At each intersection cell of the interrelationship the degree of relationship shall be assessed (e.g. strong, medium, low)

5.) The fifth step is to evaluate the direction of correlation between the technical requirements, in order to take advantage of supportive correlation. Technical requirements can tend to benefit of each other or also tend to work against each other.

6.) The last step is to select the design targets (values) of the technical requirements. The design targets specify how much of the characteristic needs to be provided.

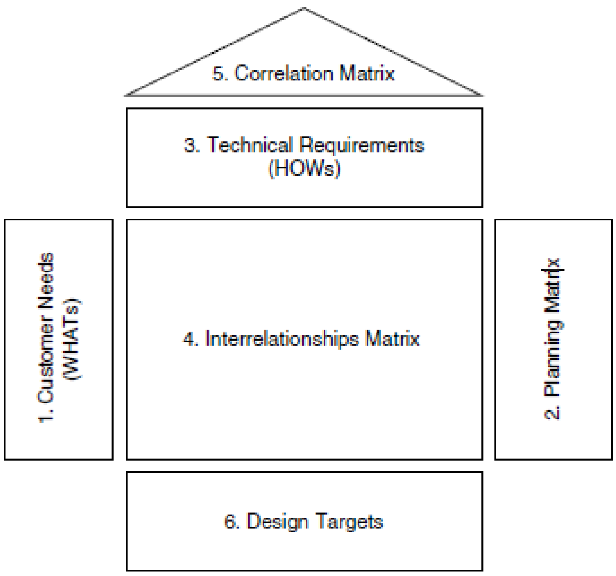

Figure 19: QFD's House of Quality [226]

[225] GOETSCH/DAVIS, 2014, p. 312–324
[226] GOETSCH/DAVIS, 2014, p. 311

The development of all matrices requires a lot of effort. As stated by Bahill and Chapman (2015) an increase of productivity can only be reached by the reuse of matrices. It is especially stressed, that the value-added by QFD is the formalized communication between engineers and customers. By introducing this method, the final product shall be an optimal fitted product. [227]

If **comparing the HOQ with MBSE**, it can be seen, that interrelationship matrices can be reused in the model. Components, functions, requirements or boundary conditions can be linked to each other. This multidimensionality quickly leads to an immense effort to display in the HOQ. As described by Lugger (2016), due to the high number of customer needs and technical requirements, the overview cannot be maintained without appropriate software solutions. Relationships of any kind can be added gradually into the model, to be coexistent at all the time. [228]

Failure Mode Effect Analysis (FMEA)

The FMEA is a formalized analytical method to identify all the potential failures of a product or process before they happen. The aim is to recognize possible weak points of a design or a process in time to preventively avoid failures. According to time of application and type of analysed object, in general it can be divided into process and design FMEAs: [229] [230]

- **Design FMEA:** Deals with a product or system or single parts of a product. The objective is the working, suitable for production, secure and reliable single part or system. It is employed during the design phase of a product or a service.
- **Process FMEA:** The analysis is looking at potential failures (errors, miscues) of a process. The process in this case can be in a factory or an office, for instance a production process, a development process, processes in hospitals or in accounting firms. The objective of this analysis are the failure free development and production of products or services.

Generally a FMEA is processed as stated by Reif (2014): [231]

First, system- elements and structures, then functions and function structures have to be identified. Afterwards, failure modes and effects need to be identified. A **failure mode** is described to be the way in which something might fail. The **failure effect** shows a potential consequence in terms of operation, function or status of those failures. In consequence a list of all planed or realized measures to avoid and detect failures shall be created. Further, a risk assessment (see risk assessment factors in Table 2) will be carried out and finally the product or process shall be optimized by implementing measures.

[227] BAHILL/CHAPMAN, 2015, p. 24–35
[228] LUGGER, 2016, p. 40
[229] BRÜGGEMANN/BREMER, 2015, p. 45
[230] GOETSCH/DAVIS, 2014, p. 282
[231] REIF, 2014, p. 270

The **objective of a FMEA** is to compare the criticality (risk priority number, RPN) of all identified potential failure modes. This establishes the priority for corrective action. Therefore, this analysis can tell the organisation where its resources should be applied. Thus, resources of a company to correct problems can be deployed to problems that are most crucial. [232]

Risk assessment factor	**Explanation**
Severity (S)	Depends on the severity of the potential failure mode's effect (From 1 to 10; 1 = no effect, 10 = maximum severity)
Probability of occurrence (O)	Depends on the likelihood of the failure mode's occurrence (From 1 to 10; 1 = very unlikely to occur, 10 = almost certain to occur)
Probability of detection (D)	Depends on how unlikely it is that the fault will be detected by the system responsible (From 1 to 10; 1 = nearly certain detection, 10 = impossible to detect)
Risk priority number (RPN)	Shows the failure mode's risk; Found by the formula: RPN = S x O x D (From 1 to 1000, 1 = no risk, 1000 = extreme risk) Automotive industry considers a RPN below 75 to be acceptable

Table 2: Risk assessment factors [233]

When carrying out an FMEA, especially the identification of systems and functions can potentially take a lot of time and therefore raise the processing costs. If those two steps are considered when using **MBSE and a (battery-) model**, it will be possible to generate system and elements as well as functions out of this model. This is possible due to the connection of functions with systems and components respectively. Further, if the knowhow (lessons learned) of past projects is implemented in the model, the failure mode effect analysis can be supported, since failure modes in similar system- or function constellations can be consulted.

Lugger (2016) endorses to model all possible failure functions for every function. Therefore, failure functions and components are related (by the relation of functions and components). If components with its functions and potential failure functions are intended to use in a project, on the one hand the system structure is predefined, on the other hand the functional structure and the structure of failure-functions can be identified. A model can then generate, based on the product design, the step of defining system elements and function for the failure analysis more or less automatically. For instance it could provide a prefilled document. [234]

[232] GOETSCH/DAVIS, 2014, p. 282–283
[233] GOETSCH/DAVIS, 2014, p. 283
[234] LUGGER, 2016, p. 41

4.4. VALUE AND VALUE MEASUREMENT IN THE PRODUCT DEVELOPMENT PROCESS

To define the positive or negative impact of model-based systems engineering on the product development process, the term value is described in detail in this chapter. For the general understanding value added and non-value added activities in the perspective of Lean Thinking are discussed. Further, current research activities concerning the return on investment when introducing SE and MBSE are highlighted.

Value engineering in general is described to be a method of raising the value of products or services through the analysis and examination of a product's or service's functions. [235] Decisions about how to allocate resources, such as time and money can be made more rationally, by knowing how much value is added by PD activities. [236]

4.4.1. THE TERM VALUE

The mere definition of **value** is: **"Something the customer will pay for"** [237]. Browning (2003) defines **value to be a ratio of benefits to costs.** In addition value is described to be a **function of both product and process attributes** and portions of that value are functions of activities and interim deliverables or results. It is further stated that the value of a process always has to exceed the value of its individual activities. [238] Given this definition a product or process would generally be described to be **valuable** if the overall benefit exceeded the costs.

Another, especially in literature very often exerted way of defining value is the approach of ***Lean Thinking***. [239] The Lean theory originated in the practices of the Toyota Motor Corporation. The approach focuses mainly on the manufacturing aspect of business, rather than the engineering and design processes. Nevertheless, it maintains that the same principles can be applied to all areas. [240] A lean condition is described to be a maximization of the value and not just the minimization of costs. [241] Womack and Jones (1996) argue that a lean way of thinking allows companies to "specify value, line up value creating actions in the best sequence, conduct these activities without interruption whenever someone requests them, and perform them more and more effectively" [242]. In addition they further suggest five principles for achieving a lean condition. [243]

The first of those five is to **precisely specify value**, which is defined as:

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[235] GOETSCH/DAVIS, 2014, p. 311
[236] CHASE, 2000, p. 14
[237] SIYAM/GERICKE/WYNN *et al.*, 2015, p. 11
[238] BROWNING, 2003, p. 49–56
[239] GERICKE/GRIES, 2009, p. 291
[240] MCMANUS/MILLARD, 2002, p. 2
[241] BROWNING, 2003, p. 49
[242] WOMACK/JONES, 1996, p. 15
[243] CHASE, 2000, p. 4

> "A capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer." [244]

If several development tasks are linked together, they form a continuously flowing stream which is called **value stream**. [245] In Lean Thinking, Womack and Jones (1996) describe it to be:

> "All specific activities required to design, order, and provide a specific product, from concept to launch, order to delivery, and raw materials into the hands of the customer." [246]

4.4.2. QUANTIFICATION OF VALUE IN PRODUCT DEVELOPMENT

The **quantification of value** in reference to a product development process is one key aspect to define if an activity adds value or not. However, the value added by a development process – let alone or an individual development activity – is difficult to quantify. This difficulty is depicted due to the different perspectives on what is valuable: Womack and Jones (1996) base their definition on customer value [247], whereas Keen (1997) suggests *shareholder value* [248] to be the driver of the modern age [249]. In this thesis the value created for a customer is given emphasis.

To measure value, Chase (2000) proposes to compose value into four key layers (see Figure 20). Here, the challenge is described to be the finding of the most influential metrics for the value of product development entities.

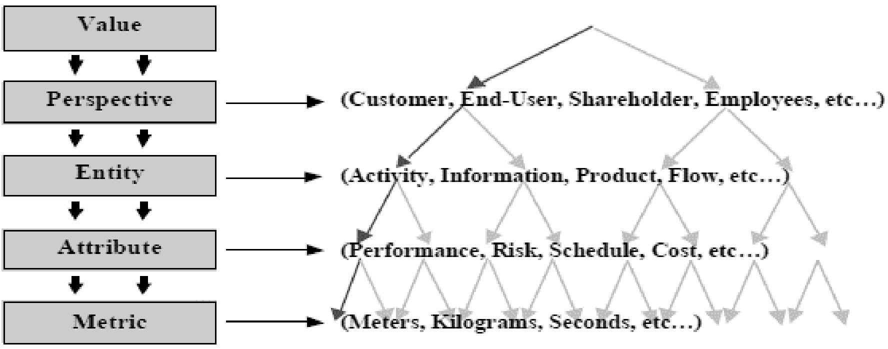

Figure 20: Dimensions of value with one sample chain [250]

In these layers, first, the **value perspective** identifies, to whom the value is delivered (e.g. customer, end user, shareholder, employee, environment). Secondly, a **value entity** describes value for the system drivers (e.g. activity, information, product, resources). Thirdly, each of those entities have

[244] WOMACK/JONES, 1996, p. 308–311
[245] MCMANUS/MILLARD, 2002, p. 1
[246] WOMACK/JONES, 1996, p. 308–311
[247] WOMACK/JONES, 1996, p. 308–311
[248] Shareholder: Economic owner(s) of an organization
[249] KEEN, 1997, p. 81
[250] CHASE, 2000, p. 7

several **value attributes** (e.g. quality, time, cost, risk) and last all attributes can be further analysed in quantitative **metrics** (e.g. meters, seconds). A challenge can be finding the most influential metrics for the value of product development entities, based on the available general characterisations of value perspectives. [251] [252]

Following this approach, the value of every process can be quantified by breaking it down into those four layers. In the following chapters value is mostly defined to be information with the attribute cost. Nevertheless, this cannot be defined overall, since the quantification always depends on the application and can change quickly.

4.4.3. VALUE ADDED IN PRODUCT DEVELOPMENT

Value added is defined to be the amount by which the value of a product is increased. The amount of value added by a product development process can be increased by adding activities as well as by removing them. [253]

Siyam, Gericke and Wynn (2015) split the creation into three main entities that add value: [254] The first entity adding value is **people**. This includes **knowledge assets** and **management**. Knowledge assets create value due to their skills and deliverables. Management adds value due to its capability to implement strategies to support improvement and to effectively utilize resources. The second entity is the **process**, which delivers value when the deliverables meet the requirements. Thirdly, value is added by **methods and technology**. Those add value indirectly to the product under development, because they reduce the development time and costs.

Additional understanding can be achieved by breaking down the product development process into stages and defining their inputs, outputs, constraints and enablers, which addresses the so called **flow** through the product development process. The only value the customer of a product is maintaining within this flow, are the **final deliverables** at the end. The interim inputs, activities and outputs enable the production of the final deliverables. Hence, those also affect the value, both in terms of benefits and costs. The value provided by the output of one activity, is a function of the quality of the input. Poor quality inputs results in poor quality outputs, even though the activities are 100% value-adding ("garbage in, garbage out"). [255]

Value creation by information and knowledge

Mc Manus and Millard (2002) describe the flow to be **information** that flows through the process and compare it to the physical material flow through the manufacturing process. [256] Browning (2003)

[251] CHASE, 2000, p. 6–7
[252] SIYAM/GERICKE/WYNN *et al.*, 2015, p. 12–13
[253] BROWNING, 2003, p. 56
[254] SIYAM/GERICKE/WYNN *et al.*, 2015, p. 15
[255] BROWNING, 2003, p. 51–56
[256] MCMANUS/MILLARD, 2002, p. 3

names the reason for producing information to be the increased certainty about the ability of the design to meet requirements. The information is adding value if it decreases the risk, that the product will be something else than it is supposed to be. Therefore, the **reduction of risk** is seen as one main aspect of a value adding activity. Examples for information adding values are: [257] Trying, analysing, evaluating, testing, experimenting, demonstrating, verifying, and validating. This value creation process is being illustrated in Figure 21.

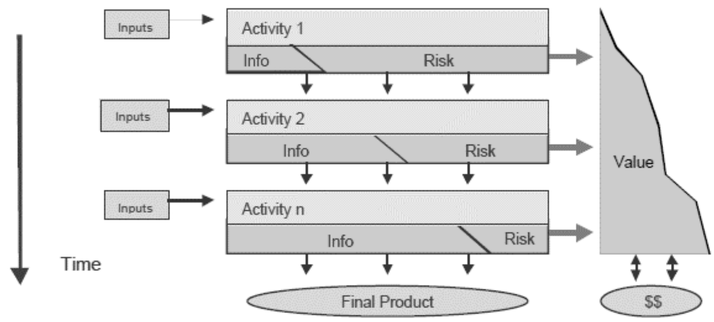

Figure 21: Value creation process [258]

Nevertheless, as stated by Chase (2000) in case of a failed project with no final deliverable, the value may not be zero due to the significant amount of latent knowledge that has been created. [259] Therefore, the flow of information to reduce the risk in product development is described to be only one aspect of knowledge based value creation. North and Kumta (2014) describe information to be one step on the so called **knowledge ladder** (see Figure 22). Here, the necessary steps for gaining knowledge and the further steps for approaching competitiveness are being displayed. This process is described to be necessary for knowledge-based value creation. [260]

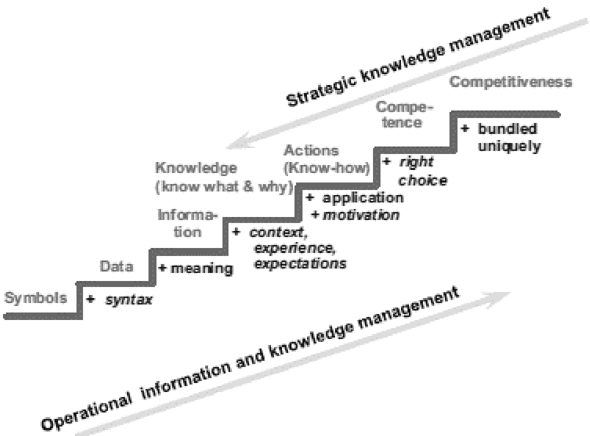

Figure 22: The knowledge ladder [261]

[257] BROWNING, 2003, p. 50–54
[258] CHASE, 2000, p. 9
[259] CHASE, 2000, p. 12
[260] NORTH/KUMTA, 2014, p. 31
[261] NORTH/KUMTA, 2014, p. 32

Such as described in chapter 4.2, and displayed in the knowledge ladder, knowledge consists of **information**, **data** and **symbols**. Similarly, as explained before, knowledge in this ladder is distinguished between cognitive knowledge (know what), systems understanding (know why) and advanced skills (know how). Value is created when the right choice of knowledge is applied at the right moment, which is termed **competence**. Core competencies of a company are a combination of skills and technologies that deliver value to the customer. They exist only when the knowledge meets the task. Those competencies: [262]

1. Are not easy for competitors to imitate.
2. Can be re-used widely for many products and markets.
3. Must contribute to the end consumer's experienced benefits.

Competitiveness is described to be a unique bundle of competencies of people or organizations. Thus, the bundle of competencies is not matched by other organizations. [263] To create measureable value by information being transformed into knowledge and competence each step of the knowledge ladder has to be build. Systems to fulfil the bottom up view (operational information and knowledge management) are described in chapter 4.2.1. To define the competencies of an organization a top down (strategic knowledge management) is necessary.

4.4.4. NON VALUE ADDED ACTIVITIES

Besides value adding activities, every process has a certain amount of **non-value adding activities**, which are mostly necessary for the completion of a process. In Lean-Thinking those activities are **called *muda*** [264]. For the specification of all different activities those can be, according to Womack and Jones (1996) divided into: [265]

- **Type 1 *muda***: Activities that add no value but are necessary and therefore should be made highly efficient.
- **Type 2 m*uda***: Activities that add no value and are unnecessary and therefore should be eliminated.

When describing muda in the development process, different approaches can be found. For instance, Browning (2003) names rework and iteration to be the main driver for cost and schedule overruns. [266] A reasonable overview is given by Mc Manus and Millard (2002). They analyse the flow in a process and highlight that by transforming information from the initial state of raw data to the final product,

[262] NORTH/KUMTA, 2014, p. 35
[263] NORTH/KUMTA, 2014, p. 31–36
[264] Muda: Japanese for *waste*.
[265] WOMACK/JONES, 1996, p. 20
[266] BROWNING, 2003, p. 51

not every task adds value. Some raw data results in not further to be utilized information. Therefore, they use the seven manufacturing categories and add wastes coming up in the product development process (see Figure 23).

	Waste	Description
1	Overproduction	too much detail, unnecessary information, redundant development, over-dissemination, pushing rather than pulling data
2	Transportation	information incompatibility, communication failure, multiple sources, security issues
3	Waiting	information created too early or unavailable, late delivery, suspect quality
4	Processing	unnecessary serial effort, too many iterations, unnecessary data conversions, excessive verification, unclear criteria
5	Inventory	too much information, poor configuration management, complicated retrieval
6	Unnecessary Movement	required manual intervention, lack of direct access, information pushed to wrong sources, reformatting
7	Defective Product	lacking quality, conversion errors, and incomplete, ambiguous, or inaccurate information, lacking required tests/verification

Figure 23: Definition of waste in the product development process [267]

4.4.5. RETURN OF INVESTMENT WHEN IMPLEMENTING SE AND MBSE

When implementing new processes and technologies there shall be a return of the prior investment in a reasonable timeframe. In businesses this comparably hard number shows how much benefit one can receive from an investment. In general the formula is described as:

RoI = (Gain from Investment – Cost of Investment) / (Cost of Investment)

In **systems engineering** the discussion about **value added** is relatively young. The first attempts of SE were in highly complex and very critical for safety areas of the aviation and aeronautics industry. There, the implementation of SE was mainly based on an increase of quality and security. A discussion about the economical application of SE started when being introduced in the private sector. Whereas the assessment of the contribution to value added is, according to Tschirner and Ackva (2016), “facing a dilemma”: [268] Investments in new technologies and methods shall have as short as possible time of amortization (usually expected to be less than 24 month). SE, in contrast is an approach, where the effects are evolved in the long run, from start of development to the end of a product life. This means that in early phases of a product’s life cycle a higher effort has to be accepted to be balanced out in later phases of development. [269]

To overcome this difficulty Tschirner and Ackva (2016) compare the introduction of SE to the introduction of a modular product system: First the efforts are very high, because new processes have to be introduced, people need to be trained, and a new role (the systems engineer) in addition to the project manager has to be accepted. Over time the benefits outweigh the efforts. [270]

[267] MCMANUS/MILLARD, 2002, p. 4
[268] TSCHIRNER/ACKVA, 2016, p. 34
[269] SHEARD/MILLER, 2000, p. 2–9
[270] TSCHIRNER/ACKVA, 2016, p. 34

In a quantitative study conducted by Honour (2004) the results indicate that an **optimal SE effort** is **approximately 15-20%** of the total project effort. Further he states, that the SE effort improves development quality and has positive effects on cost compliance, schedule compliance, and subjective quality of the project. [271]

Sheard and Miller (2000) expose a rather **critical view**, defining the RoI if implementing SE. They state that "a meaningful ROI can be computed only after the resources have been committed and systems engineering process improvement projects have been completed within your own organization using your own definitions of *return* and *investment*." They highlight that hard fact numbers in different environments cannot be compared to calculate a possible effort and possible savings when introducing SE. Instead of comparable numbers of a RoI, they state convincing management and employees is possible by: Justification in retrospect, anecdotes, peer pressure, and discussions about the value of systems engineering.

When comparing the results of **RoI in MBSE** several, only very ambiguous studies can be found:

In a study realized by Saunders (2011), it is stated that adoptions of elementary MBSE has demonstrated significant reductions in requirements errors. According to Saunders a **reduction of 68% in specification defects** since MBSE practices have been introduced, is being observed. Therefore, he conducted an analysis over a 5 year period covering 4 traditional requirements definition programs and 3 programs using the MBSE approach. [272]

In an aerospace industry case study 4 programs are compared: Three using a document-based engineering approach and one using the MBSE approach. Findings are made on several different aspects: On the one hand the **number of defects** is **halved** in the MBSE program (compared to the second lowest) and 90% less compared to the program with most defects. On the other hand the total number of man hours, when comparing the **relative costs**, was **highest** within the program using model-based systems engineering. [273]

All in all, comparable numbers for the implementation of MBSE can hardly be found. Nevertheless, the overall value is always being stressed and described to outrun the investment costs.

4.5. MBSE AS PART OF PRODUCT LIFECYCLE MANAGEMENT IN PRODUCT DEVELOPMENT

The foundation and necessity of model-based product development has been explained in chapter 3.3 already. Models are used for the description and specification. Multidisciplinary complex technical problems can be described and structured in an abstract way. MBSE focuses strongly on the system-modelling approach. Hereby the administration of accruing information is not being considered.

[271] HONOUR, 2004, p. 1222
[272] SAUNDERS, 2011, p. 17
[273] DELLIGATTI, 2014, p. 11–17

Product lifecycle management (PLM) offers solutions for the further processing of information. [274] Therefore, it is described in this chapter. Further, the concept of service engineering and the approach of *computer supported collaborative work* is being examined briefly.

4.5.1. PRODUCT LIFECYCLE MANAGEMENT

Generally spoken, PLM manages products and product portfolios from the beginning of their life, including development, growth and maturity, to the end of life. PLM is a **concept for the integration of all information arising in the lifecycle of a product**. Its objective can be described to be the increase of product revenues, the reduction of product related costs and the maximization of value of the product portfolio and current and future products. [275]

A basic principle of PLM is the role of *the product* as the heart of an organization. Those products define a company and are the source of a company's revenue. Due to PLM those **products are under control across the lifecycle**. The results are less risk and fire-fighting actions. Such as described by Stark (2011) a product in PLM can be defined by several different forms: From a manufactured product to software and services. [276] Although battery development is based on development rather than production, the implementation of a view on the whole product lifecycle cannot be neglected.

The foundation of PLM is lying on the so called **product data management** (PDM). The approach of PDM is the handling of product specifications such as CAD (Computer-aided Design) files and requirement documents in terms of version management, change processes, and product configuration. Further it shall make all data accessible for the following lifecycles. Modern PDM systems contain **data interfaces** to **CAD** and **ERP** (Enterprise Resource Planning) software and therefore cannot be seen as standalone system solutions. The aim of an introduction of a PDM system is the **increase in quality** and the **decrease of time and costs** of the product development process. The final result shall be the complete reproducibility of configurations and the work state of the product. [277] Therefore, today PDM can be seen as a system integrated into PLM, since it is mainly based on the approach of design and engineering in product development.

4.5.2. THE INTEGRATION OF MBSE AND PLM

PLM and MBSE are two different approaches for product development. They both evolved from different requirements but face very similar objectives. Different to MBSE, PLM systems themselves are a document-based approach. They are handling documents and correlating metadata. As stated by the German chapter of INCOSE (Gesellschaft für Systems Engineering e.V.) (2015) future PLM must incorporate more structured information with meaning and follow a stronger model-based approach

[274] EIGNER, 2014, p. 282
[275] STARK, 2011, p. 1
[276] STARK, 2011, p. 10
[277] SENDLER/WAWER, 2008, p. 41–45

than it does today. Therefore, they initialize the concept of **Model-based Engineering (MBE)** when integrating MBSE and PLM. [278]

To enable PLM systems for the further processing of information generated in a system model, PDM data models have to be expanded by the system models generated in the early phase of the product development process. Thereby the **functional and behaviour based models**, integrated in PLM can be the **medium for tracing changes of requirements**, **functions and behaviour**. As described by Eigner (2014) different phases of the development process call on different model information. During the development of the system, information flows directly into the system model. This information can be requested during the phase of system integration. [279] The **availability of results of MBSE** over the whole product lifecycle can have **several different benefits**: On the one hand requirements and system components specifications are the natural reference for manufacturing quality control and acceptance tests. On the other hand business process models, use cases and functional models can be used for the preparation of the final product and project documentation.

To implement this vision, a new integrated software architecture has to be developed. While in classical development product and project management are very often isolated, in modern development both disciplines shall be enabled to store and retrieve all information in a central location. This so called ***single source of truth*** shall prevent failures and unnecessary iteration steps. The name for such an architecture is the **Service Oriented Architecture (SOA)**. This approach enables it to retrieve user specific information at the right time. It is not necessary to know the origin or the physical distribution of information. Thus, every user can retrieve all relevant information from the system model. [280]

4.5.3. SERVICE ENGINEERING AND COMPUTER SUPPORTED COLLABORATIVE WORK

Service Engineering involves the **systematic development and design of innovative services**. It is facing the problem of creating new innovative services with the engineering approach of creating new products. Therefore, it provides processes and workflows, which can be used to enable or create the service, based on stakeholder needs with the corresponding set of tools to enable the preliminary defined service. [281] The central objective of service engineering is similar to product and software development, services to be developed systematically. It shall be possible to offer services with the desired quality and efficiency economically on today's market. [282]

One major approach of service engineering are so called **cooperative tools**. Information technology (**IT**) to support service engineering serves two different roles: On the one hand to provide software to support the development team during the development process. On the other hand to enable new

[278] Gesellschaft für Systems Engineering e.V., 2015, p. 2
[279] EIGNER, 2014, p. 282–284
[280] LUGGER, 2016, p. 43–44
[281] MINKE, 2015, p. 64–66
[282] BULLINGER/SCHEER/SCHNEIDER, 2006, p. 4–6

development, or adapt information or communication systems, which has to be fulfilled in almost all projects concerning service engineering. [283] During the integration of MBSE into the battery development especially the first role is of importance.

The **computer supported collaborative work (CSCW)** represents a technical possibility of digital collaborative work. Here, different information technology work equipment is being utilized to support work, communication and learning processes. [284]

According to Bullinger, Scheer and Schneider (2006) CSCW tools shall support following aspects: [285]

- **Support of communication:** Project specific information needs to be exchangeable between different user (e.g. per email or in a community area)**.**
- **Support of coordination:** Every user shall be guided through the tasks by an adaptable process model. This includes the description of the methods, the process and the utilization of user programs. If necessary, external user programs such as a PDM-system can be launched. The perspective shall be adapted according to the defined user role in a project.
- **Support of cooperation:** A central visualisation of the, to be developed product or service shall enable the collaborative work in processes with in itself divided tasks. Here, the useful application of process modelling is based on a module library. To enable user to independently form and adapt modules, a specific guideline for the application to ensure consistency in this view is necessary.

The basic functionality allows **multiple user** to upload and store, classify and retrieve documents inside the system. This is enabled by a **web-based user interface**, which enables a flexible access to the various stored documents. The system can be **structured by *metadata*** describing different attributes and elements in a system. [286] A CSCW shall comply with different organisational and system requirements. For instance single user have to be willing to contribute different knowledge resources to the planning process. Since development projects vary strongly due to different requirements or customer objectives, the user interface has to be flexible to facilitate the individual adjustment. Further, a supportive tool shall be developed and utilized unrestricted to enable the connection to already existing systems and data bases. [287]

By the term **Enterprise 2.0** the use of social software and **web 2.0** concepts is propagated. Here, the interactive use of web interfaces by users is possible already. Those web interfaces enable the evaluation of the information content uploaded to a web based information platform (e.g. Wikipedia). Hereby, the efficiency and effectivity of product development processes can be increased. One

[283] BULLINGER/SCHEER/SCHNEIDER, 2006, p. 5–6
[284] BRAUN, 2014, p. 110
[285] BULLINGER/SCHEER/SCHNEIDER, 2006, p. 656
[286] MINKE, 2015, p. 67
[287] BULLINGER/SCHEER/SCHNEIDER, 2006, p. 655

popular tool, offering such support, is **MS Sharepoint**. This web based tool offers web 2.0 functionalities for the CSCW. Besides document management of MS Office tools, such as Word or Excel, also so called Wikis can be arranged and tagged by metadata. Those Wiki-pages are easy to edit web sides to for instance centrally store information. Further so called Workflows can be support of coordination. An example are automatically generated email notifications to remind user of upcoming deliverables. [288]

Taking into account systems engineering, model-based systems engineering and its basic principles, CSCW can be seen as a widely used tool architecture to enable the core ideas. When including a process model, connected to the product model by metadata as well as a way to handle complex project constellations, an easy to use platform for every user can be created. [289] This cooperative working environment to develop products is enabled by the core ideas of service engineering and can be integrated into a Service Oriented Architecture.

[288] BRAUN, 2014, p. 110
[289] MINKE, 2015, p. 68

5. METHODOLOGY, SYSTEMATIC APPROACH AND RESEARCH ENVIRONMENT

In this chapter the methodology and the systematic approach of integrating and evaluating MBSE in the traction battery development process are presented. Therefore, the consulted design research methodology is described and applied to the use case of this thesis. Further, the research environment and all preceding activities to implement MBSE in the process of battery development are introduced.

5.1. RESEARCH METHODOLOGY: DESIGN RESEARCH METHODOLOGY

As described by Eckert, Clarkson and Stacey (2003) many various different research methodologies can be found in literature. One fulfilling all specific requirements of technical oriented research is the design research methodology (DRM). [290] It introduces a generic procedure model suitable to derive concrete research measures. The structure derived from this generic model in this thesis can be seen in Figure 24.

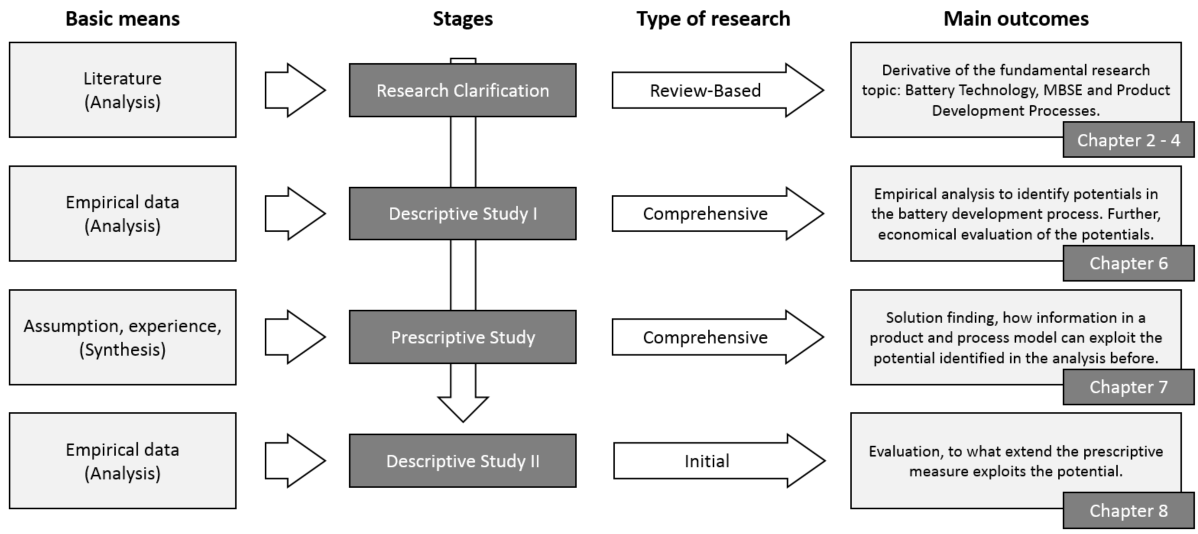

Figure 24: Systematic procedure of this thesis based on the DRM [291]

DRM consists of four connected stages, with different means and outcomes. The main process flow is described to be linear. Nevertheless, many iterative steps, between the different stages enable information to be exchanged whenever needed. The phases can be clustered into different types of research. A **review-base study** is based only on the review of literature. A **comprehensive study** includes a literature review, as well as a study in which the results are produced by the researchers (e.g. an empirical study). An **initial study** closes a project and involves the first few steps to show the consequences of the result. Study outcome shall be prepared to be used by others. [292]

[290] ECKERT/CLARKSON/Stacey M. K., 2003, p. 1–11
[291] Own illustration, based on: BLESSING/CHAKRABARTI, 2009, p. 15
[292] BLESSING/CHAKRABARTI, 2009, p. 18

The **different stages** according to literature and adapted in this thesis can be described as follows: [293]

The first stage of the methodological framework, the **research clarification**, is a fundamental literature research study to elevate the background of the work and formulate a realistic and worthwhile research goal. This is mainly done by searching the literature for factors influencing the task clarification. Based on those findings, an initial description of the existing information is developed. This first stage is implemented in the chapters 2, 3 and 4. The main outcome of this review-based study in those 3 chapters are a detailed summary of the three core topics covered in this thesis: Battery technology; Systems engineering and model-based systems engineering; Product development processes.

The intention of the second stage, the **descriptive study I**, is to determine which factor(s) should be addressed to improve task clarification as effectively and efficiently as possible. At this stage those crucial factors cannot be clearly determined by evidence found in literature. Therefore, observation and interviews have to be conducted to obtain a better understanding of the existing situation. The implementation of this stage is described in **chapter 6**: In a comprehensive study, interviews are conducted to establish and clearly describe problems in the current situation of battery development. Further, to rate those situations, a questionnaire has been prepared. The economic rating gives an estimation on the impact of potential failures in the process.

In the third stage, the **prescriptive study**, support is developed to address the problems described in the stage before. Here, the understanding of the existing situation helps to correct and elaborate the initial description of the desired situation. This description represents the vision on how addressing one or more factors in the existing situation would lead to the realized, desired improved situation. Various possible scenarios are developed. The focus is addressed on the most promising scenarios, highlighted in the descriptive study I. Also, the understanding of the various interconnected influencing factors obtained in the first stage, are used for the further development. In this thesis, this prescriptive, comprehensive study is realized by three functional solutions and a mock up demonstrating the solutions gained. A detailed explanation of the approach and the results is given in **chapter 7**. The elaboration of the Mock-Up is leveraged by a parallel thesis of Müller (2016). [294]

In the final stage, the **descriptive study II**, the impact of the support and its ability to realize the desired situation is investigated. In a study the applicability and the usefulness of the results are evaluated. The study shows, whether it is feasible to spend less time on the development process and how the quality of the process can be increased. This final stage is described in **chapter 8**: A workshop with possible future user is conducted. A final initial study realized in a questionnaire shows the possible improvement by the implementation of the prescriptive study.

[293] BLESSING/CHAKRABARTI, 2009, p. 15
[294] MÜLLER, 2016

5.2. RESEARCH ENVIRONMENT AND PRECEDING ACTIVITIES

To achieve the objectives of this thesis a cooperation with the company **AVL List GmbH** is established. The requirements for information and the applicability of the solution are only evaluable in real development environments. As described in chapter 1.2 the main scope in powertrain development, evaluated in this thesis is the **battery system**. The implementation of new and already established technologies and the complexity in the field of battery development requires from the organisation a high degree of individual specification on the one hand and simultaneously competence with the handling of interdisciplinary topics on the other hand. [295]

5.2.1. GLOBAL BATTERY COMPETENCE TEAM

The development team, dealing with the comparable new topic of traction battery development at AVL List GmbH is being named **Global Battery Competence Team**. This team consists of various different departments, each dealing with single process steps, such as design or simulation. Every development team formed by diverse trained and educated experts (e.g. mechanical and electrical engineers) and being led by a project manager. Those experts are located on various different locations (e.g. Graz, Istanbul, Regensburg and Los Angeles) and therefore deal with different cultural backgrounds.

5.2.2. SYSTEMS ENGINEERING LABORATORY

To handle the technological complexity of a battery system (see chapter 2), the organization AVL List GmbH introduced measures on many different levels: One is the interdisciplinary approach of **systems engineering** and **model-based systems engineering**. Different departments already have first approaches and defined processes to implement product models. Those departments are supported by a central contact point called the **Systems Engineering Laboratory**. This central contact point enables departments to gain and exchange knowledge concerning SE. Therefore, this initiative has the objective to support different approaches in various departments concerning SE and MBSE. Due to being detached of the business units, centrally aligned in the organization, this initiative can highly influence the strategic orientation of the methodology development. All employees are member of different departments and additionally contribute to this initiative. One project, mainly executed by the Global Battery Competence Team, but highly supported by the SE-Laboratory is the project **Model-based Battery Development (MoBat)**, as outlined in the following chapter. The thesis is described to be one subproject of MoBat, the aim of which is to realize an economic analysis of the possible implementation of MoBat in the environment of battery development.

[295] FRITZ, 2013, p. 93

5.2.3. MODEL-BASED BATTERY DEVELOPMENT (MOBAT)

The defined objective of MoBat is to implement MBSE in the process of battery development. This project shall give a better understanding of the system and the sub systems of a battery implemented in electrified vehicles. Customer objectives shall be understood quicker and with better quality in order to be implemented in an optimum way. Gained knowledge and developed system elements shall be reused across several different projects. All in all, MoBat shall make battery development at AVL List GmbH more effective and more efficient.

To achieve this main objective, different subprojects have been launched. In particular two closed master theses are the foundation for the subject. [296] [297] In those theses a battery model is established in SysML and is transferred to a multi domain matrix. As a consequence a CSCW-tool, implemented with Sharepoint, integrating all information elaborated in the battery model has been built and tested. Due to the reuse of this battery model and the findings made by the CSCW-tool, the work is explained briefly in the following chapters.

Further, two parallel scientific subprojects also contribute to the development of MoBat and therefore to this thesis: Müller (2016) describes a MBSE approach for a demand specific visualization of information in product development. [298] Einkopf (2017) develops a guideline for the selection of effective and situation specific methods. [299]

5.2.4. BATTERY MODEL ESTABLISHED IN SYSML

The first start to integrate MBSE in battery development, is realized by a product model documented with the widely established System Modelling Language (SysML). In this context this product model is built and described by Lugger (2016) with the program PTC Integrity Modeller, which is commonly used at AVL List GmbH. This first approach to model the traction battery targets especially the components, the functions and the relations combining those two. The, in this model utilized diagrams are: [300]

- **Block definition diagram** (structure diagram): To model the system structure of the components according to the AVL level structure.
- **Internal block diagram** (structure diagram): To model the horizontal connection between the components of the same level.
- **Activity diagram** (behaviour diagram): To model the single activity processes from triggering to fulfilment of a function and to integrate influencing parameters onto the functions.

[296] LUGGER, 2016
[297] MINKE, 2015
[298] MÜLLER, 2016
[299] EINKOPF, 2017
[300] LUGGER, 2016, p. 50

In this battery model the traction battery system (level 2), the single components (level 3) and the subcomponents (level 4) are displayed. The physical connection of the components on level 3 can be seen in Figure 25. Here, the components are modelled according to the basic concepts of systems engineering: Systems with system boundaries are established and interfaces between those systems are defined.

The same principle is applied to the functions: High level functions are broken down in defined sub-functions fulfilling one high level function. The interaction of all functions is modelled in the activity diagram. Finally, the relationships of functions and components is established.

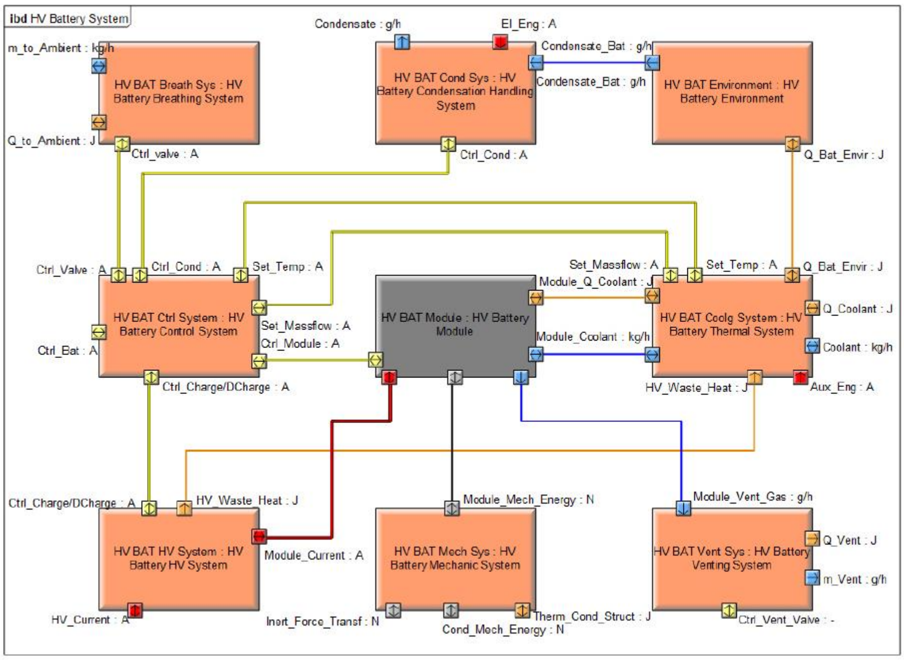

Figure 25: Interface-Model of the components in the battery system [301]

Lugger (2016) names the **benefits of this model** to be the quick conceiving of function-flowcharts and structure- or function trees in the form of block-diagrams. Despite those benefits clear **disadvantages** are: The necessary extensive initial training to use the model, the nonexistence of a process model and the nonexistence of an interface to a project management tool. [302]

As a consequence the model is used as an **expert tool by a very few employees** only. Therefore, it is currently not maintained and developed any further. Although, the documentation with SysML is established mainly in the discipline of requirements engineering in different areas of AVL List GmbH, this model is currently not used in the means of battery development. The additional value is limited on the structured documentation, used for the next stage of development, explained in the following chapter.

[301] LUGGER, 2016, p. 51
[302] LUGGER, 2016, p. 53

5.2.5. DOMAIN MATRIX MAPPING

As described in the previous chapter, SysML has the great advantage of mapping technical dependencies and relationships. The mapping of non-technical domains, such as tasks or deliverables is not modelled in the SysML battery model. One way to simply represent dependencies and relationships of all different kinds is the so called **domain matrix mapping (DMM).** Different to an Entity-Relationship-Model (ERM), in matrix representation specific sub-instances can be connected to other specific sub-instances (for instance a component with a function). The matrices are built similar to the **house of quality (HoQ)** (see chapter 4.3.2). Four different kinds of DMMs used in the subsequent model can be explained as following: [303]

- **Intra-Domain-Matrix** (also called Design-Structure Matrix - DSM): Dependencies of same domains can be displayed (e.g.: component and component). This is a squared matrix, where in rows and columns the same sub-instances are displayed.
- **Inter-Domain-Matrix:** Dependencies of different domains can be displayed in this matrix (e.g.: component and function).
- **Combined intra-domain and inter-domain matrix:** The combined plot of the first two matrices to display dependencies among each other.
- **Multi-Domain-Matrix (MDM):** Here, different to the matrices before, dependencies are calculated, depending on previously defined dependencies of other domains. For instance a component influences a function and a task influences a component, therefore, the function is also influenced by the task.

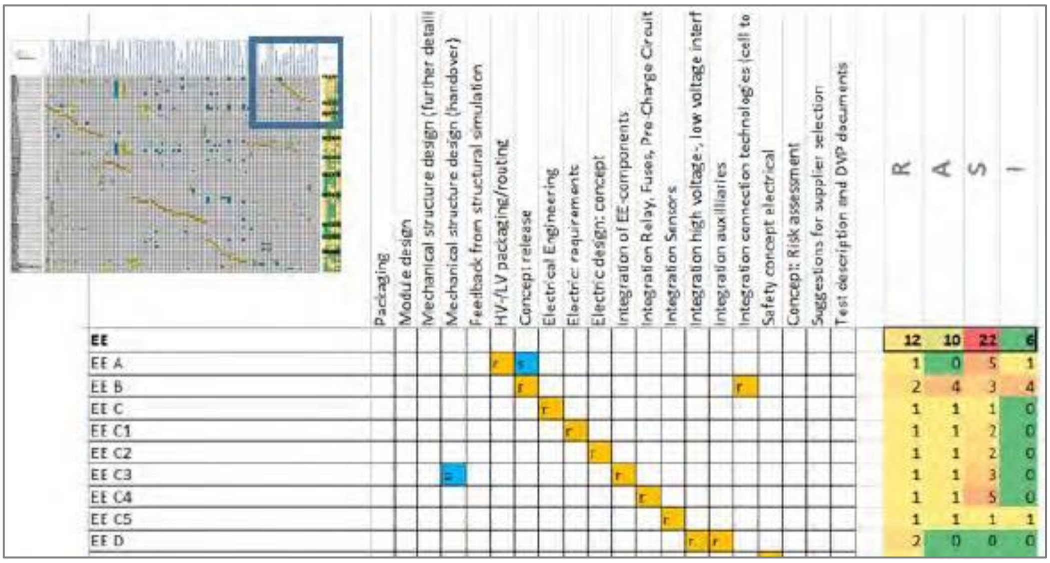

Figure 26: Section of the inter-domain-matrix of Tasks and Stakeholder [304]

[303] LINDEMANN, 2009, p. 49–57
[304] MINKE, 2015, p. 79

Since the use of this modelling technique is described to be comparable simple, this approach is applied to model the dependencies of the battery system and combined with the process of battery development. The first approach is worked out by Minke (2015). Here the **tasks and stakeholder** are mapped in an **inter-domain-matrix**. The mapping is based on the allocated role of a stakeholder. A connection could be either R (responsible), A (accountable), S (supportive) or I (informed). This connection can be seen in Figure 26. [305]

Similar to the stakeholder other dependencies, such as components depending on functions, are mapped and displayed in MS Excel. The **overall MDM** is displayed in Figure 27. This MDM can be split up into **4 main areas**: The first displays the **target system** including the boundary/constraints, the customer objectives and the requirements. The next area, **Verification & Validation**, includes simulation and testing. The **product model** in the centre includes the functions, components and the properties / characteristics of each. The last area displays the **process**. Here tasks, stakeholder, deliverables and resources are included. The product model is implemented by converting the SysML-model explained before by Lugger (2016). All other areas are only partly filled by interviewing experts in all departments of the Global Battery Competence Team by Lugger (2016) and Minke (2015).

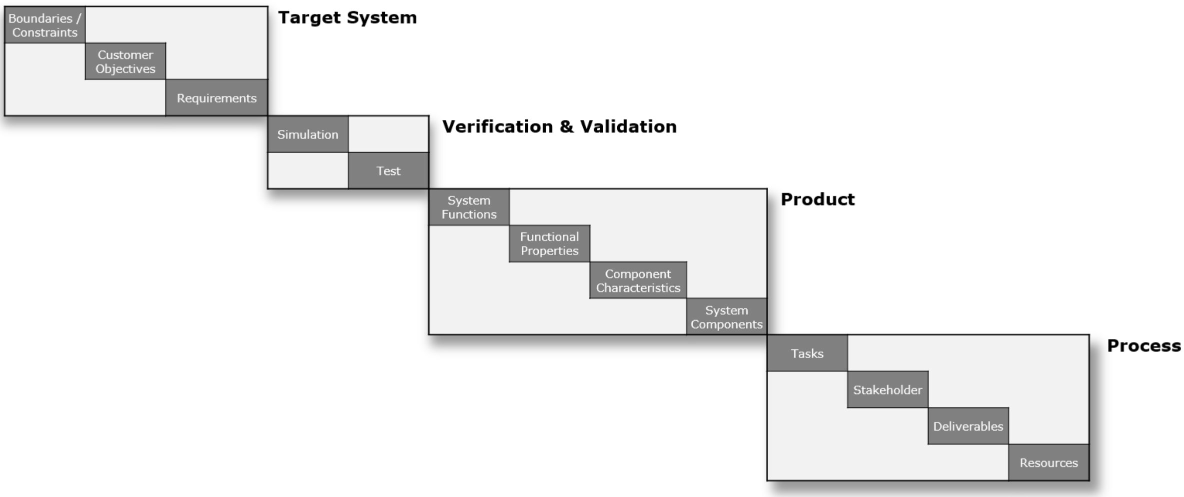

Figure 27: Multi Domain Mapping of the product and process model [306]

Since the dependencies of the battery development process (tasks, stakeholder, deliverables, and resources) are also part of this MDM, this model is a possibility to **combine the development process and the product (battery-) model**. Nevertheless, it has certain disadvantages: Possible arising mistakes when mapping single domains, can hardly be found. Further the amount of data stored in the MDM quickly exceeds the possibilities in excel. Such a table can hardly be used in every day project work. Finally, the high complexity, Lugger (2016) calculated the possible entries to be 11.990 when having 10 domains in each single matrix, makes an efficient and effective use very hard to realise. [307]

[305] MINKE, 2015, p. 78
[306] Own illustration, based on: MINKE, 2015, p. 47
[307] LUGGER, 2016, p. 55–56

5.2.6. SHAREPOINT DEMONSTRATOR

In order to prepare the data modelled in the MDM and make it accessible for the development, a CSCW-system (see chapter 4.5.3) has been built as a technical possibility to design a digital collaboration. On this account MS SharePoint server is used as a web interface (with WEB 2.0 functionality for the CSCW). This server and the user interface can be accessed by the Web-Browser creating an information system for stakeholder.

The user interface is implemented externally based on a specification given by the project team. The server is filled with all information gathered in the MDM described before. The system covers main functionalities as described by Lugger (2016): [308]

- Displaying **all generic domains of the product model** (boundary conditions, customer objectives, requirements, function and components). Those domains can be changed and adapted to every project's needs. For a better view the components and functions can be clustered, based on the approach of SE, in so called hyperbolic tress (see Figure 28).
- An easy to gather view on the **status of a domain**. Every colour of each domain given in Figure 28, can have a different meaning (for instance, red: This component is declared to be not suitable according to a verification method). This enables the implementation of the function verification and validation.

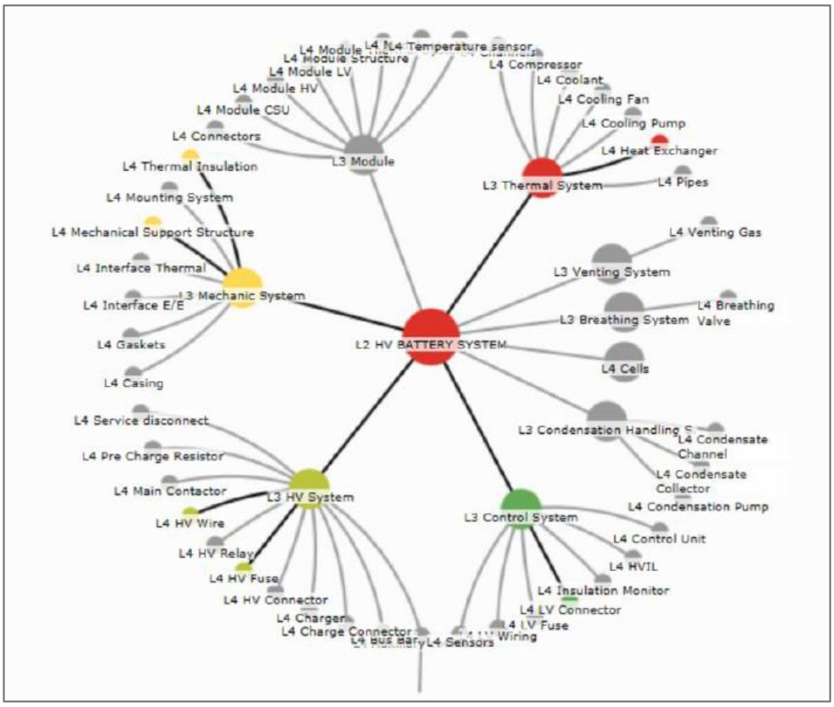

Figure 28: View of components in an hyperbolic tree [309]

[308] LUGGER, 2016, p. 58–63
[309] LUGGER, 2016, p. 59

- The **process view** with **tasks, deliverables and stakeholder** implemented in a generic way, is accessible and adaptable. Project management functions such as a Gantt chart format of the tasks can be displayed.

- **Process driven project controlling**: Tasks can have different states and can be assigned to stakeholder. Automatic email notifications can be set as reminders for specific milestones, or if a new task is assigned to a stakeholder. This enables, due to containing all relevant roles needed in the environment, and assignment to those roles, a personalized view of all tasks and deliverables concerning the logged in user.

- A **wiki system** connecting knowledge (wiki-pages) with metadata (battery and process model). Here all knowledge concerning battery technology, single components and the environment can be stored, and retrieved again easily by the metadata.

As a **pilot run** this system was utilized with 43 students in a 4 months lasting project. This project took place at the **Karlsruhe Institute of Technology** in close cooperation with AVL List GmbH. The objective was the finding of innovative ideas concerning battery development. Therefore, the students were split up in 7 teams. The process (deliverables at certain milestones) was preliminarily defined and uploaded to the MS SharePoint server.

An **evaluation** concerning the tool has been carried out by Einkopf (2017): [310]

The **achieved results** of 16 participating students proves, that **most user do not see the additional value given by the special form of representation**. Further, not all functions were used constantly. This result highlights the difficulties of implementing a CSCW-system on the one hand, and of the functional accessibility of a product model on the other hand. Another problem raised is that the information uploaded onto MS SharePoint server cannot be downloaded and therefore used to train the generic battery model.

Although the achievement of those results concerning the function of the CSCW-tool implemented in MS SharePoint, the overall principle of a direct access on the battery model is perceived very well. It enables a very quick understanding of the system battery and an easy to use function of project control. Especially the very high rate of access on the additionally implemented function of battery Wiki shows the necessity for a knowledge management system.

Therefore, the battery model and the tool enabling access onto the model are developed further in the program MoBat. The necessity for the program is evaluated in the elaboration outlined in the subsequent chapters.

[310] EINKOPF, 2017

6. DESCRIPTIVE STUDY I: POTENTIALS IN THE TRACTION BATTERY DEVELOPMENT PROCESS

In this chapter, according to DRM (see chapter 5.1), the first descriptive study takes place. The outcome of this study shall evince potential scenarios for a possible use of model-based systems engineering in the process of battery development at AVL List GmbH. The **research-question** asked at the beginning of this chapter can be formulated as following: **How does the increasing complexity economically affect the development process and involved stakeholder?** The answer to this question shall give an insight understanding of the battery development process on the one hand, and shall highlight scenarios, where MBSE can improve the overall development process, on the other hand.

6.1. DESIGN OF THE STUDY

For the execution of the study the format of a so called process failure mode effect analysis (pFMEA) is chosen. The benefit of this format is the already existing in depth knowledge of this methodology (although mainly used in the form of a design FMEA) in the analysed (engineering-) environment of AVL List GmbH. This enables a high acceptance by the involved interview partners and by the organization as final customer of the results of this study.

To conduct the first steps of the pFMEA, interviews help to get an overview and a high number of failure modes and effects. In a further study the figured out failure modes are evaluated and assessed by the means of a self-administered questionnaire.

6.1.1. PROCESS FMEA

This formalized analytical method shall identify all possible potential failures before they happen (see chapter 4.3.2). The process being analysed is the on a daily bases realized process of developing batteries in the research environment AVL List GmbH. Those failures, are documented by both variables: The **failure mode** and the **effect**. Nevertheless, the variable of failure in this pFMEA here is being interpreted to be a form of documentation of failures concerning the process happening in every day development. The effects of single failures are a combination of already happened negative effects, and realistic possible future effects arising due to the event of a failure.

Tschirner and Ackva (2016) give one example in which the pFMEA is applied in a very similar environment. Here, the pFMEA is extended by the effort to implement a measure. This enables the authors to **calculate the return on investment** when implementing systems engineering (see chapter 4.4.5). Each failure is described by its mode and the effect. Next, the risk level before and after the measure is evaluated. For the calculation of the ROI they extend the measure by the effort to be implemented. The level of risk and the costs for implementing the measure are being set in relation for calculation of the ROI (see Figure 29) [311]

[311] ENDLER/STEFFEN/Lohberg A. *et al.*, p. 157–167

Nr.	Funktion	Fehlerursache	Fehlerfolge	B	A	E	RPZ	Maßnahme	B'	A'	E'	RPZ'	Aufwand	RoI	Kommentar
1	Akteure und Stakeholder ermitteln	Es werden Akteure oder Stakeholder vergessen	1) Dem System fehlen Use Cases 2) Für nicht berück-sichtigte Anwender kann das System unbrauchbar sein	9	6	8	432	M1: Systemfunktionalitäten modular aufbauen	9	4	4	144	9.600 €	30,0	Kommentar
								M2: System-Review der Akteure und Stakeholder	9	2	1	18	19.200 €	21,6	Kommentar
								M3: Akteure und Stakehol-der ermitteln: Anwender befragen, Recherchen, ...	4	1	1	4'	9.600 €	44,6	Kommentar

Figure 29: Extended pFMEA to evaluate the SE-RoI [312]

Application of the pFMEA in the environment of battery development:

When the pFMEA is applied in the field of battery development it is split up into three major parts: In this first descriptive study, the left part of the pFMEA is completed. The **measures to overcome analysed failures** are elaborated in the following **chapter 7**. The **further assessment** of the implemented measures is evaluated in the second descriptive study (see **chapter 8**).

This first descriptive study in itself is again split up into two levels: First, interviews take place to establish modes and effects of failures. The method and design of the interviews is described in chapter 6.1.2. The next step is the evaluation of the risk priority number (RPN) of the failure modes and effects. Therefore, the failures are clustered and evaluated in a questionnaire. The RPN is adapted to the special use case (see chapter 6.1.3).

6.1.2. INTERVIEWS

The reason for conducting interviews in the research environment is to identify potential failures happening in the everyday process of developing batteries. This gives a detailed insight of the use case and better understanding of potential scenarios for the implementation of MBSE. In this subchapter, the methodology of the scientific background and the methodology of the interviews which are conducted is explained.

Background of a technique for conducting interviews:

The interview, as a part of a survey method, is a basic technique for gathering accurate and genuine information directly from the relevant stakeholder. A requirement for conducting interviews is, that the respondent is able to provide usable expertise and can explicitly express the knowledge. Further, the interview-partner has to be committed to the interview and committed to invest the necessary time to complete the interview. [313] On the other side, the person conducting the interview (interviewer) has to shape the interview by asking and anticipating questions and answers. In general the interviewer asks questions to one or more stakeholder and documents different answers.

[312] TSCHIRNER/ACKVA, 2016, p. 35
[313] RUPP, 2012, p. 13–14

To conduct the interviews in a methodological way, an approach, described by Hermanns (2010) is chosen. Equally to most explained interview techniques in literature, the process is split up into different phases and can therefore be divided into following general steps: [314]

- First, an interview needs to be **prepared**: Here especially the so called ***framework*** is important. The interview-partners have to be found and selected. The interview has to be planned precisely in terms of a location (interview environment), time and topic (research question). The interview-partner has to be informed beforehand about the reason for being interviewed and the expectations of the interviewer.

- Next, the interview is **performed**: In the first minutes of the interview, the interviewer has to create a situation which is open and relaxed to enable the interview partner to answer all questions without any concerns. In a **clear briefing**, the interviewer has to introduce what the interview is about (topic, who is responsible, what will happen to the information), and how the interview is being conducted (who is the interviewer, who can be present, where the interview takes place and how long it lasts). During the interview **concrete, easy to understand questions** have to be asked. The interviewer shall show neutral interest and document the answers given unbiased and precisely. When all questions are answered, the interview partner has to be informed about upcoming events (e.g. when the results will be published).

- Lastly the different answers have to get **evaluated** and interpreted. The interview has to be analysed by means of different criteria and validated if the interview partner stated plausible answer. Further, the results and the interpretation shall be **communicated** to the interview partners.

Expert interviews at the Global Battery Competence Team of AVL List GmbH:

During the phase of conducting interviews the before described stages are being passed. To maintain as many different answers as possible, and give every interview partner the possibility to steer the interview into different directions, the form of an interview with open answers is chosen.

First the **departments and stakeholder have to be identified**. This procedure takes place to generate a differentiated mixture of different departments and diverse backgrounds and fields of the interview partners. All in all **15 interview partner** are selected to contribute to the evaluation, due to the insight knowledge into the process of battery development. All interview partners are employees of AVL List GmbH and members of the Global Battery Competence Team, **located in 6 different departments**: Design, Reliability, Battery-system, Electric/Electronics, Project Management and Sales.

[314] HERMANNS, 2010, p. 360–368

Further, the **questions for the interview** are formulated as followed. Here the obvious aim is to fill the pFMEA in terms of failure modes and effects:

1.) Where do you see unnecessary effort in your daily work?

2.) What effect does this unnecessary effort have on your daily work?

The expected answers of the interview partners can be described to be non-value added activities. As outlined in chapter 4.4.4 those activities, so called *muda*, can differ very much, according to the tasks of each interview partner. To ensure an open and unbiased explanation of the interview partner no conditions such as specific topics are determined.

In the next step the time and location for the interviews is chosen. Each interview took a time slot of approximately **20 to 30 minutes** and has been held in the **informal environment** of the coffee kitchen.

During all conducted interviews, the interview partners have been **briefed about the research question** and informed that all **documentation takes place anonymously**. To ensure input by every stakeholder, every interview takes place with one interview partner each. Every interview partner is able to give several examples with detailed information of failures that had happened already according to each ones experiences. The **documentation** takes place by the record of named failure modes and failure effects in the pFMEA directly during the interview.

The results of those interviews can be found in 6.2.1.

6.1.3. SELF-ADMINISTERED QUESTIONNAIRE

In the self-administered questionnaire the next part of the before described pFMEA is evaluated: The **risk priority number** (RPN). With this questionnaire a higher number of stakeholder shall be attained. Another reason for conducting this questionnaire is to evaluate all named failures and evaluate their significance on the process of battery development. Similar to the chapter before, first the scientific background for conducting self-administrated questionnaires, and secondly the here used method are being described in this subchapter.

Background of a technique for conducting a self-administered questionnaire:

A self-administered questionnaire is a very vital part of the so called survey process (similar to the interview). As stated by Brace (2013) a "poorly written questionnaire will provide data that are incorrect". [315] It is used to **conduct a structured interview with a series of questions**. The purpose is to carry out a standardized interview and reach a high number of interview-partners. The advantage can be described to be the most inexpensive and fastest way to conduct a survey. Additionally the survey in form of a link or a file can be easily send out to potential respondents and can be answered

[315] BRACE, 2013, p. 7

not limited in time or place. A disadvantage is a, on average, very low response rate as well as no opportunity for clarification in real time. [316] To minimize the rate of low response the questionnaire has to be prepared and constructed well. Leung (2001) and Brace (2004) give a guideline for the design of a questionnaire and the process to realize a questionnaire: [317] [318]

First it has to be **decided what to ask**. It can be distinguished between information that the interviewer is primarily interested in (**dependent variable**), information explaining the dependent variables (**independent variables**) and other factors that may distort the results (**confounding variables**).

The wording of individual questions shall be **short, simple and precise**, due to being less confusing and less ambiguous. Also, only the level of detail required shall be asked to avoid unnecessary effort.

Further, it should be ensured that **every participant** of the questionnaire **shall have the necessary knowledge** for answering the questions. Therefore, the participants of the questionnaire, similar to the interview, have to be selected carefully. Although, a higher number of possible participants can be reached easier, a blind distribution can lead to a very low participation and wrong partners for the interview.

The **format of response** can either be **open** or **closed.** The open format allows respondents to formulate their own answers. The format can be used even if a comprehensive range of alternative choices cannot be compiled. Alternatively, the closed or forced choice format is predefining answer possibilities. It is easier and quicker to fill in, but limits the interview partner to choose from the given answers. Further, it is comparably easier to analyse and report the results. There are several different types of closed formats, such as a choice of categories, a Likert style scale (e.g. from strongly disagree to strongly agree), checklists or rankings. In a survey both formats can be mixed, for instance by giving a list of options, with the last option *others* and space to fill in other alternatives.

The **questions** can be **arranged** in various forms. Nevertheless, it shall be arranged to go from general to particular, easy to difficult and started with closed questions. At the beginning, an introduction or a covering letter shall briefly explain the purpose of the survey and the importance of the respondents' participation. Further, who is responsible for the survey and a statement that guarantees the confidentiality of the survey shall be given.

After a questionnaire had been conducted, it is necessary to spend a significant amount of time to **evaluate and analyse** the gathered data. Therefore, it is necessary to plan analysing before conducting the survey, to ensure a meaningful evaluation and all data to be useful.

[316] SCHÖGGLER, 2014, p. 16
[317] LEUNG, 2001, p. 187–189
[318] BRACE, 2013, p. 105–115

Self-administrated Questionnaire at the Global Battery Competence Team of AVL List GmbH:

This survey at AVL List GmbH takes place in the form of a self-administrated questionnaire and results from the guideline stated above. To answer the research question, an evaluation of the established failures needs to be fulfilled. Such as described before, the objective of the survey is to evaluate the risk priority number (RPN) given in the pFMEA. The questionnaire is conducted with an online-tool called *LimeSurvey* [319]. On the one hand this tool is selected in order to ensure an anonymous and secure handling of data. On the other hand this tool allows a simple and straight forward process of preparing the survey. An example for the design of the questionnaire is given in Figure 30.

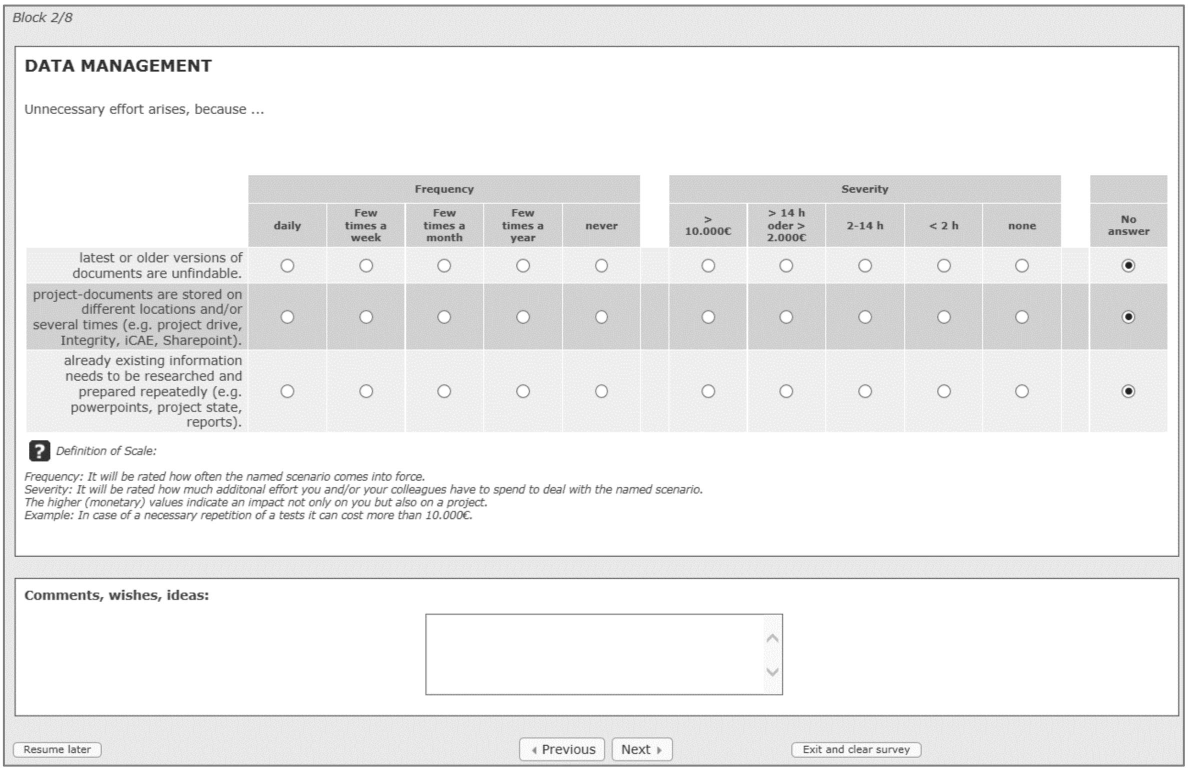

Figure 30: Self administrated questionnaire, Block 2: Data Management [320]

The first question to answer is **what to ask**: The evaluation of the RPNs of all discovered and documented failures is not conducive for reaching the goal of an economic evaluation: On the one hand many failures are covering similar scenarios, on the other hand the evaluation of the RPN of the large amount of documented failures is not needed. Therefore, all evaluated failure modes and effects are **clustered to 24 frequently occurring scenarios**. All scenarios have precise and briefly described failure modes, and the same effect: Unnecessary effort arises. This enables a very simple and comprehensible evaluation of all stated failure modes in the questionnaire. For instance, a scenario to be evaluated is formulated as followed: Unnecessary effort arises, because tasks are not formulated sufficiently.

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[319] https://www.limesurvey.org/; Date of access: 2nd of November 2016

[320] Own illustration. Based on: https://www.limesurvey.org/; Date of access: 2nd of November 2016

The next step is to **decide on the participating departments and stakeholder**. Since, with the survey everyone involved in the Global Battery Competence Team should be reached, all members (70 employees, involved in various different departments) are decided to be invited to participate. All participants are informed in detail about the reason of the survey and about the process of this questionnaire such as the options for response.

Although the **survey is conducted anonymously**, an allocation to the practising stakeholder role is being fulfilled in the survey: The first question asked is, to select, **what stakeholder-role a participant is identifying itself with**. Here multiple answers are possible. The choices of stakeholder-roles given are: Management, Project Management, Sales, System Engineer, Engineer and Test Engineer. Also a last option *others* and space to fill in other alternatives is being given.

To give a clear picture and easy to comprehensible sequence of the survey, all 24 scenarios are **split into 7 different blocks**: Project Management, Data Management, Requirements Engineering, Knowledge Management, Verification & Validation Process, Meetings and Stakeholder Roles. Each block is to be answered individually. This enables every participant to process the questionnaire temporarily free and step by step.

Finally, the **format** of the questionnaire is chosen to be mixed: Both open and closed. For every scenario the participant has to evaluate the RPN and is able to give comments, add failure modes or effects of failure. For a clear understanding, and detailed evaluation, the **RPN** for the classical pFMEA **has been adapted**, as described below.

Adaption of the risk priority number:

The RPN, such as described in chapter 4.3.2 is compound by severity (S), probability of occurrence (O) and probability of detection (D). Each single factor is rated on a scale and multiplied together to form the RPN. In the course of this evaluation the classical RPN has been assessed and adapted to the needs of the retrospective view in this thesis:

- **Severity:** Due to the failures in the process of development, unnecessary additional effort to deal with the named scenario arises. This effort can be expressed in both money and time (e.g.: the time to find information or the costs to realize a new test).
- **Probability of occurrence:** Here, this factor is reshaped to the **frequency of occurrence** per year. Hence, it is rated how often the named scenario comes into force on average.
- **Probability of detection:** The definition of the probability of detection is not necessary in the retrospective view. Therefore, the probability of detection is set to be 1 for all failures.

The objective of this survey is to reach many different stakeholder. Therefore, the evaluation has to be as simple as possible. The participant needs a **translation and concretization of the numbers** into intuitive known sizes. Further, the number of possible options needs to be reduced to ensure the assessment to be quick and easy. For this reason the scale 0-3-5-7-10 is translated with a non-linear scale as being displayed in Table 3. The size for the evaluation of the frequency are resulting due to the remaining steady factors between each steps. With those factors it can be ensured that with the same RPN 5 x 7 = 7 x 5 also the calculated costs per project and year are the same. This evaluation enables on the one hand a relative comparison between different scenarios, and on the other hand by multiplication of the translated severity and frequency it can be defined to what extend money is spend per year and projected for those scenarios (unnecessary effort). To calculate the average of the overall costs, the frequency and severity is transformed/translated by linear interpolation. Both averaged numbers multiplied equal the total costs arising due to the unnecessary effort stated in the scenarios.

Frequency:	**RPN**	**Answer to choose:**	**Equals in: Days / Year**
(per year)	0 3 5 7 10	Never Few times a year Few times a month Few times a week daily	0 2,555 14,6 73 365
Severity:	**RPN**	**Answer to choose:**	**Equals in: € / year and project**
(per occurrence in one project)	0 3 5 7 10	None < 2h 2 - 14h > 14 h oder > 2000 € > 10.000 €	0,00 € 70,00 € 400,00 € 2.000,00 € 10.000,00 €

Table 3: Translation of the RPNs into frequency and severity [321]

Reference projects at the Global Battery Competence Team

To evaluate the result and compare the calculated negative value, the average project costs in a year are given: The development of traction batteries is, both in the industrial environment of automotive industry and at the use case of AVL List GmbH, a comparable young industry (see chapter 5.2.1).

The average development costs for a single development project is 341.108 € based on 49 finished projects. The average duration is a bit over half a year (0.56 years). Therefore, the **average costs for one project per year are 608.975 €.** Although, this average sum is varying greatly it shall give a comparable figure. Those development costs in this perspective cover all expenses (e.g.: test, material, staff, travel costs) spent to finish a project. A ***project*** in this case always pertains **the development and test, or parts of such, of a traction battery system for electrified vehicles**. The total number of employees involved in such a project is very difficult to quantify, since this number depends on many alternating factors such as size and involved consulted departments. Nevertheless, there are approximately 70 members of the Global Battery Competence Team, responsible for every project.

[321] Own illustration.

6.2. RESULTS

The overall results of this first descriptive study are displayed in this chapter. All results have been evaluated and presented to the participating stakeholder. This enables very detailed discussions concerning unnecessary effort in the process of battery development and is a major step to evaluate the implementation of MBSE in this process.

6.2.1. INTERVIEWS

During the interviews **15 different interview partners** have answered the two questions raised: Where do you see unnecessary effort in your daily work? What effect does this unnecessary effort have on your daily work?

The results of the interviews show many, partially similar results. In total **193 failure modes** with failure effects have been assessed. To further process those failure modes, they are clustered to 24 scenarios evaluated in the questionnaire (see chapter 6.2.2). Some exemplary statements of the cluster ***Knowledge Management*** are displayed in Table 4. Due to the execution of the interviews in German, all original results are given in German. The subsequently summarized scenario (marked in grey) is a result of all failure modes clustered.

Mode of failure:	**Effect of failure:**
Lessons Learned (LeLe) werden erst am Ende des Projektes in einem LeLe-Meeting retrospektiv erarbeitet.	LeLe werden in den Folgeprojekten nicht effektiv angewandt.
LeLe werden vor allem auf Level Projektmanagement, nicht jedoch auf anderen Ebenen durchgeführt.	LeLe können nicht in die Projekte eingebunden werden.
Auf LeLe können nicht zugegriffen werden bzw. können nicht in vertretbarer Zeit aufgefunden werden (Wissen ist vorhanden, aber niemand weiß wo es ist).	LeLe werden nicht verwendet und gleiche Fehler treten immer wieder auf.
LeLe wird in einem Dokument (Word, PPT) in das Projektlaufwerk abgelegt; Wird nicht/selten als Grundlage für weitere Projekte verwendet.	Gleicher Fehler tritt mehrmals auf.
LeLe sind stark vom Projektleiter abhängig.	Erkannte Fehler werden in Folgeprojekten nur bei "LeLe-PL" miteinbezogen.
Unnecessary effort arises, because already gained knowledge from previous projects is not being used.	

Table 4: Exemplary results of the interviews: Statements concerning Knowledge Management [322]

[322] Own illustration.

As it can be seen in the stated modes of failures and especially effects of failures, many interview partner come up with very similar scenarios. This is a result of the same working environment of all interview partners and shows the urgency of some failures. This multiple mentioning of similar failures can be used for a prioritization. The subsequent evaluation in the questionnaire can also be seen as validation for the given interviews, since it shows how often single failure modes happen on average.

Summarizing, the response in all conducted interviews is very helpful to establish a better understanding of the research environment and to provide a basis for the economic evaluation. All given statements are documented and clustered to be utilized further in the subsequent studies.

6.2.2. SELF-ADMINISTERED QUESTIONNAIRE

The questionnaire, as the second step of the first descriptive study has been distributed in the Global Battery Competence Team. Therefore, it was out to 70 employees. In total the **survey achieved 23 returns**. As described before, the survey is split into 7 blocks, raising closed questions. The result is the monetary negative value per average project and year.

First, participants have **identified themselves with stakeholder roles** (multiple answers possible):

- Management (6)
- Project Management (11)
- Sales (2)
- System Engineer (10)
- Engineer (9)
- Test Engineer (4)
- Others (1): Technical Expert

This highlights the fulfilment of the necessary diversity of the respondents. A clear trend to project manager and system engineers emphasizes the main target group for the implementation of MBSE.

In the following the results of the closed questions are clustered in the same order as being asked in the questionnaire (see Table 5). As described, every participant has had to evaluate the frequency and the severity of unnecessary effort caused by different scenarios. Although, based on the use case battery development, all scenarios, arising from the interviews, outline everyday problems emerging in the environment of product development.

Besides the subject evaluation of the financial value of unnecessary effort, additional expanding open questions in the survey give the possibility to state comments or to add further scenarios. Some statements, important especially for the prescriptive study (see chapter 7) are summarized in Table 6. Here, the allocation is equal to the seven blocks used before. As documented in Figure 30 both open and closed question of one block are stated among each other on the same window.

Unnecessary effort arises, because…	(F) Frequency (Avg.)	(S) Severity (Avg.)	Risk Level F x S	Risk Level in € per year and project
Project Management				
…tasks are not formulated sufficiently.	4,75	5,62	26,70	11.723 €
…open tasks are processed too late, because they are not prioritized.	4,48	4,95	22,18	4.498 €
…overall project objectives are not sufficiently defined, coordinated and accessible (e.g. no basis for decision).	4,13	6,48	26,76	14.803 €
…it is not clear who is responsible for which task (in the project).	3,18	4,9	15,58	1.403 €
…it is not recognizable, how occupied employees are (e.g. assigned task is done insufficiently, because employee is at maximum capacity).	3,91	4,4	17,20	2.424 €
…the overall project status is not comprehensible.	2,8	2,94	8,23	164 €
…deliverables are not sufficiently specified or tailored to customer needs.	3,95	6,16	24,33	11.013 €
Document Management				
….latest or older versions of documents are unfindable.	4,32	4,29	18,53	2.961 €
…project documents are stored on different locations and/or several times (e.g. project drive, Integrity, iCAE, SharePoint).	5,71	4,43	25,30	10.840 €
…already existing information needs to be researched and prepared repeatedly (e.g. PowerPoints, project status report)	4,1	4,57	18,74	3.013 €
Requirements Engineering				
...requirements are overlooked, because they are not stored uniformly and structured.	3,47	5,93	20,58	6.180 €
…the status of requirements (each or overall) is not clear.	3,71	4,85	17,99	2.569 €
…necessary requirements and changes of requirements are not transmitted to the relevant stakeholder.	4,17	6,19	25,81	9.102 €
...identical or nearly identical requirements are processed two or more times.	2,73	4,43	12,09	712 €
…it is not clear at the project start, which requirements are not or only insufficiently feasible.	4,32	7,18	31,02	25.890 €
Knowledge Management				
…results of benchmark studies cannot be compared.	4,06	5,38	21,84	6.337 €
…already gained knowledge from previous projects (Lessons Learned) is not being used.	4,47	7,82	34,96	47.962 €
…necessary information from past projects are not accessible.	4,44	5,81	25,80	11.817 €
Verification and Validation Process				
…tests are not sufficiently specified.	3,57	5,64	20,13	5.482 €
…it cannot be traced which test results are available already.	2,33	3,5	8,16	303 €
…test specification have to be set up in a new way.	3,79	6,08	23,04	9.193 €
Meetings				
…meetings are not scheduled in a structured manner (e.g. there is no agenda, arbitrary invitation of participants, etc).	4,78	4,81	22,99	4.899 €
…no documentation (e.g. content, resolution, etc.) is executed during meetings.	4,39	4,55	19,97	3.554 €
Stakeholder-Roles				
…stakeholder-roles are not specified.	3,73	5	18,65	2.789 €

Table 5: Result of the self-administered questionnaire [323]

[323] Own illustration.

Requirements Engineering	**By what channels are you informed if requirements change?**
	9 x Mail 2 x SharePoint 2 x Harddrive
	In what platform do you process requirements?
	3 x Excel + Integrity PTC Lifecycle Manager 6 x Excel 2 x Integrity PTC Lifecycle Manager
	Comments
	I need a, for everyone available requirements engineering tool I need a clear allocation of roles
Knowledge Management	**Why are actions from documented Lessons Learned not used in running projects?**
	No insight on LeLe due to restrictions Not documented sufficiently The knowledge (LeLe) of other projects is missing There is no consequent implementation of LeLe Knowledge-transfer does not work sufficiently Employee turnover; Changing stakeholder roles Resources are missing; Process is not defined Location of LeLe info not known Due to lack of time
	Which types of information are not accessible?
	All documents on the project SharePoint Requirements & specifications Decisions in a project and the supporting documents/knowledge Whole projects Reports, datasheets Fundamental solutions and concepts are not separated
	Comments
	We need a conscious implementation of Lessons Learned Benchmarkstudies shall be compared Knowledge database with concept solutions and design guidelines
Meetings	**Comments**
	Culture of meetings is not sufficient Depends on the project manager The general amount of meetings shall be reduced Agenda and Minutes of meetings are never sent out Arbitrary invitation to meetings is a result of unclear responsibilities
Stakeholder	**How do unspecified and unassigned Stakeholder roles generate additional effort?**
	It is unclear who is responsible for what task in a project By the initial training of new employees Double or not done tasks due to unclear responsibility

Table 6: Selected additional questions and answers of the questionnaire [324]

[324] Own Illustration.

6.3. INTERIM CONCLUSION

This two-step evaluation of the potentials in the process of battery development highlights and evaluates very comprehensively different scenarios of unnecessary effort in the process of battery development.

Even though only a small number of the established scenarios is validated in the questionnaire, it is shown that most scenarios are rated to have a very strong negative impact on the daily process of battery development. The **overall additional unnecessary effort** is estimated to be **199.637 € per year and project**. For instance, not utilizing already gained knowledge shows a major potential to exploit. Many respondents miss a sufficient documentation, or have no access to documents.

Nevertheless, not all failure modes and effects established in the interviews appeared to have the same great impact for every interview partner: For instance, there is hardly no unnecessary effort arising because the overall project status is not comprehensible. This can be explained by the varying and different view of every interview partner, causing differing failure modes and effects.

Summarizing, all scenarios (see the top 7, above 10.000 € in Figure 31) evince the **necessity for a change and the need for solutions**. The evaluated scenarios show how the increasing complexity affects the development process and involved stakeholder economically. The outcome of this review is enhanced by the feedback given, when presenting to and discussing with several different stakeholder at AVL List GmbH. To evaluate, if the potential can be used by implementing a process and a technical battery model will be discussed in chapter 7.

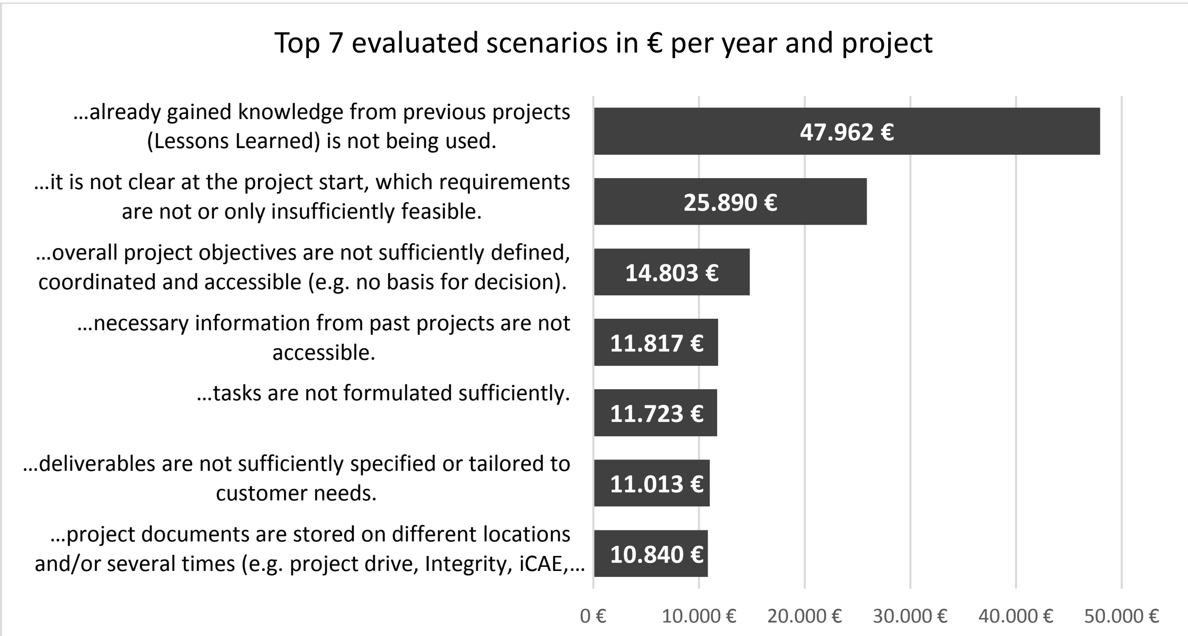

Figure 31: Evaluated scenarios above 10.000 € [325]

[325] Own illustration.

7. PRESCRIPTIVE STUDY: SOLUTIONS FOR THE EVALUATED POTENTIALS WITH MBSE

In this chapter the second study of the previously introduced design research methodology is explained and the results are presented. This prescriptive study enables the development of a CSCW-tool to address the factors described in the chapter before. Therefore, the **research-question** to be answered in this study can be formulated: **How can information in a product and process model exploit the potential identified in the analysis before?** The answer to this question shall give a foundation to assess solutions and consult valid feedback of the stakeholder involved in the development process.

7.1. DESIGN OF THE STUDY

The design of the prescriptive study is split up in two phases. First in a **creative workshop** all potentials are formulated as requirements and solutions how a model can be implemented in daily work are established. In a second phase the illustration of the solutions, a digital **Mock-Up** is built. The plan, elaboration and implementation of this digital Mock-Up is focus of the parallel thesis of Müller (2016). [326]

The focus in this study is addressed on the most promising scenarios, highlighted in the first study. Therefore, the results have been split up into **3 main cluster**, in which solutions shall enable a reduction of the unnecessary effort: Reuse of Information, Requirement-Engineering and Sales-Process.

7.1.1. CLUSTERS OF SCENARIOS

The three top scenarios of the precedent study (chapter 6.3) are causing almost 30 % of the revealed and evaluated unnecessary effort. During the analysis of those scenarios it can be determined, that actions to be taken to reach the targeted system are also appropriate for other scenarios. The further allocation of all the scenarios in the 3 clustered areas, results in many different requirements for one cluster arising from all those scenarios. Further, not allocated scenarios are clustered in a fourth, which is only marginally considered. In the following the 3 clusters are being explained to be used further in the workshops and the Mock-Ups.

1.) <u>Reuse of Information</u>

Just as described in chapter 4.2 knowledge management is playing a significant role in today's product development. The resource knowledge forms an intangible asset of the intellectual capital of an organization. A tool for handling knowledge and individual information shall create measureable value in a sustainable manner. [327] The questionnaire underlines the necessity of a fully working, easy to comprehend and always available tool to manage knowledge. The top scenario: "…already gained knowledge from previous projects (Lessons Learned) is not being used" can be generalized to the

[326] MÜLLER, 2016
[327] NORTH/KUMTA, 2014, p. 31–35

reuse, availability and findability of information. In this way the first cluster ***reuse of information*** is formed, which in **total accounts for 40.08 %** of the unnecessary effort (see Table 7).

Unnecessary effort arises, because…	**% of total unn. effort**
…already gained knowledge from previous projects (Lessons Learned) is not being used.	24,03 %
…necessary information from past projects are not accessible.	5,92 %
…project documents are stored on different locations and/or several times (e.g. project drive, Integrity, iCAE, SharePoint).	5,43 %
…results of benchmark studies cannot be compared.	3,17 %
….latest or older versions of documents are unfindable.	1,48 %

Table 7: Cluster 1: Reuse of information [328]

2.) <u>Requirements management</u>

Just as described in chapter 4.1.3 handling requirements is a significant reason for project failures. The majority of mistakes happen in the phases of analysis at the beginning of product development. [329] The highest unnecessary effort (…it is not clear at the project start, which requirements are not or only insufficiently feasible) targets a future oriented view. With the other scenarios the second cluster ***requirement management*** is formed, which in **total accounts for 22.28 %** of the unnecessary effort (see Table 8).

Unnecessary effort arises, because…	**% of total unn. effort**
…it is not clear at the project start, which requirements are not or only insufficiently feasible.	12,97 %
…necessary requirements and changes of requirements are not transmitted to the relevant stakeholder.	4,56 %
...requirements are overlooked, because they are not stored uniformly and structured.	3,10 %
…the status of requirements (each or overall) is not clear.	1,29 %
...identical or nearly identical requirements are processed two or more times.	0,36 %

Table 8: Cluster 2: Requirements Management [330]

3.) <u>Generic deliverables in a process model</u>

The third cluster of potentials describes the absence of coordination of objectives with customers and the translation into tasks. As described in chapter 4.1 final deliverables are the value a customer is paying for. [331] Therefore, those deliverables need to be coordinated in a best possible way and the information shall internally be available to every employee. A process model, as part of project management shall enable the benefit of more accurate offers to the customer, or better confirmed

[328] Own illustration.
[329] RUPP, 2012, p. 3–4
[330] Own illustration.
[331] SIYAM/GERICKE/WYNN *et al.*, 2015, p. 11

tasks for single employees. [332] With the other scenarios the second cluster ***generic deliverables as process model*** is formed, which in **total accounts for 19.59 %** of the unnecessary effort (see Table 9).

Unnecessary effort arises, because…	**% of total unn. Effort**
…overall project objectives are not sufficiently defined, coordinated and accessible (e.g. no basis for decision).	7,42 %
…tasks are not formulated sufficiently.	5,87 %
…deliverables are not sufficiently specified or tailored to customer needs.	5,52 %
…it is not clear who is responsible for which task (in the project).	0,70 %
…the overall project status is not comprehensible.	0,08 %

Table 9: Cluster 3: Generic deliverables as process model [333]

7.1.2. CREATIVE WORKSHOPS

Workshops in general can have various different forms and be conducted for any number of reasons. Basically they can be described to be **working on a shared and commonly understood topic with different mind-sets.** [334] Similar to interviews, workshops need a preparation, they are performed and an evaluation is done at the end. During the workshop itself it is necessary to instruct and guide a previous prepared working method. [335] To collect many different ideas, the method applied in the carried out workshop in this phase is a creativity technique: Brainstorming.

As the name suggests, **brainstorming** can be circumscribed to be *using the brain to storm a problem*. It is a method to collect ideas, previous knowledge and associations covering a specific subject. Here, all ideas, thoughts and suggestions can be expressed and collected. The basis of this method is, that it depends rather on the quantity of ideas than the quality. Everyone shall be able to express all ideas without facing any criticism. Already expressed ideas can be complemented and/or developed further by other participants. [336] Osborn (1979) developed four basic rules to foster idea generation at a successful brainstorming: [337]

- Come up with as many ideas as you can
- Do not criticize one another’s ideas
- Free-wheel and share wild ideas
- Expand and elaborate on existing ideas

[332] HIRZEL, 2013, p. 9–10
[333] Own illustration.
[334] MINKE, 2015, p. 63
[335] EBERT, 2008, p. 129–131
[336] REICH, 2007, p. 1–3
[337] OSBORN, 1979

During the execution of a brainstorm several factors shall be respected, such as listed by Reich (2007): [338] On the one hand, the size of the group needs to be big enough to gain a group-dynamic effect, on the other hand small enough to enable communication with everyone. The **ideal size** is given with **four to 20 participants**. The brainstorming should be **managed by a neutral person** who does not influence the statements. This person shall give a short introduction, supervise and enhance communication and if digressing bring the group back to the subject. Further, a **minute writer** documents all contributions.

Every brainstorm can be clustered in different phases, which need to be passed through successively: [339]

1.) **Preparation:** The questions and the topic need to be formulated. All necessary material has to be available (paper-cards, pencils, flipcharts). A facilitator and a keeper of the minutes has to be defined.

2.) **Creative phase, Collection of ideas:** In this phase every participant shall express ideas freely. It has to be monitored that the before stated rules are observed. For easier visualisation, documentation and clustering, it can be worked with flipcharts and paper-cards.

3.) **Summary, Structuring:** The facilitator repeats all ideas according to documentation. A structure can be worked out together to facilitate the documentation and further processing of the ideas.

4.) **Analysis of all ideas:** Ideas are being analysed, and criticism can be placed. Not useful ideas can be rejected.

Although this method generates a very high number of ideas, Feinberg and Nemeth (2008) name brainstorming to also impede creativity. They state that the *brainstorming-rules* can hinder creativity. [340] Despite this, the technique is used in a framework of a workshop at AVL List GmbH, as described further.

Creative Workshops at AVL List GmbH

When conducting the workshop in the environment of battery development the phases stated before have been conducted. The workshop has lasted for 3 hours in two separated rooms to ensure the possibility of separate group work.

First, in the phase of **preparation** a clear aim and question is defined. Therefore, the 3 clusters (described in the previous subchapter) are used to differentiate all scenarios in three core topics. The question to be answered is similar in all three core topics and is similar to the research question to deal

[338] REICH, 2007, p. 4
[339] REICH, 2007, p. 5–6
[340] FEINBERG/NEMETH, 2008, p. 1–15

with in this chapter: How information in a product and process model can exploit the identified potentials. A further aim is to elaborate sketches of the functional tool (so called ***wireframes***). Those shall give a rudimentary impression of the idea and the features implemented. [341] The visualisation roughly shows the structure of the tool and the implementation of the features. The wireframe in this case is pictured as a draft first in form of pencil drawings and then further digitalized by a hand drawing program on a tablet.

Next, **a team of 8 employees is gathered.** Every participant has knowledge of SE and MBSE and 4 participants have in depth knowledge in the process of battery development. This diversification shall enable both a biased and unbiased view on the requirements for a CSCW-tool.

For a common understanding of the problem a short hand out describing the aim of the workshop and giving an agenda is sent out beforehand. The aim and the agenda are also explained at the beginning of the workshop.

For each cluster **the creative phase** is realized. Therefore, it is split up in two activities: First, in an analysis of the situation all scenarios are introduced and discussed to evaluate **requirements for a CSCW-tool**. Further, in the actual creative part, ideas on how the **information in a product and process model can exploit the potential** are gathered.

Since all ideas are documented during the creative phase on a flipchart, it enhances an **analysis and structuring** according to the described next phase. For a better understanding, and a deeper discussion the solutions are sketched by hand. This form is easy, quick and cheap to realize by a pen and paper and results in a foundation for discussion.

Finally, all sketched ideas of functions for a CSCW-tool environment are digitalized. All ideas, sketches and requirements are used to be developed further in a so called Mock-Up.

7.1.3. MOCK-UP

In software development a Mock-Up is defined to be the visual design of a graphical user interface of a, to be developed tool. It contains the main features and the main content. A mock-up is the further development of a wireframe, which is transferred into layout and design. It is used to gain feedback of the stakeholder. [342] Mock-Ups can be implemented easily as drafts or PowerPoints or in higher sophisticated tools. Those enable a more detailed sketch and simplify the process by providing typical graphical elements of programs as templates. This facilitates an easy implementation in HTML which can be used by a standard internet browser (such as Internet Explorer). In the context of this work the so called tool *Pencil* [343] is used. This free of charge tool has the advantage of free access and ensures data security. The most important utilization for Mock-Ups in this research is the evaluation of the

[341] DIERK, 2016
[342] DIERK, 2016
[343] http://pencil.evolus.vn/, Date of access: 5th of November 2016

measures (see chapter 8). Further, the MockUps can be used for the development of the front end of future CSCW-tool.

7.2. RESULTS

In this chapter the results of the workshop and the subsequent implementation into a Mock-Up are presented. Besides the idea finding phase of the workshop, it has taken a major effort to prepare the scenarios, the requirements for a CSCW tool and to implement all in the Mock-Up. A focus on the graphical implementation and the preceding scientific elaboration are substance of Müller (2016) and therefore not explained in detail in this thesis. Nevertheless, the Mock-Up plays a major role for the illustration of all ideas and contributes to several different discussions.

The first task in the workshop has been to determine **general requirements for a CSCW-tool**. During elaborating those requirements it becomes clear, that it is necessary to arrange from high level to detailed level, such as from general conditions of the tool to details such as a toolbar or a single button. In this broadly general discussion, requirements for this very general condition were elaborated. Some selected results can be seen in Table 10 (structured according to the time of being mentioned). This list shows the versatility of the, to be observed requirements when introducing a CSCW-tool.

RQ ID	Name	Detailed description
1	Fulfilment of the central needs of all Stakeholder	All Stakeholder needs have to be gathered and fulfilled. This shall increase acceptability of the new tool.
2	Results shall be reusable	Results of benchmark-studies and customer projects shall be reusable.
3	Worldwide accessibility	The tool and the underlying information have to be accessible worldwide
4	Coordinated naming	Naming of parts, tasks, deliverables etc. have to be coordinated. The handling of different names (e.g. customer, internal departments) has to be facilitated.
5	Multiuser	Simultaneous work of several user has to be possible.
6	User Right Management	A sophisticated user right management needs to ensure a regulated access of data.
7	Multi language	It has to be enabled to work in various languages (Default language must be English).
8	Central model	The data collection must happen in a central (product / process) model.
9	Tutorials	Tutorials shall enable an easy first use.
10	Easy handling	Intuitive operation of the tool shall enable an easy to use environment.
11	Speed	The time to download information must be as low as possible (worldwide).
12	Security	Security of data must be guaranteed at all time.
13	Reduction of effort	The use must not effect an additional effort overall.
14	Reports	Automatic reports must be generated (in PDF for the customer).
15	Customized view	Every stakeholder shall have a different (customized) view with the most important information.

Table 10: Selected requirements for a CSCW-tool [344]

[344] Own illustation.

7.2.1. CLUSTER 1: REUSE OF INFORMATION

Information of current or past projects is not available. The scenario is responsible for a major part of the unnecessary effort that arises. This emphasizes the need for a solution based on MBSE in the context of product development:

A model in context of MBSE is a central point of access and structured place for storing cross-linked information (see chapter 3.3.1). This could enable to overcome the stated problems. Also the access on information generated in other or past projects is necessary for the success. This accessibility can be generated by a generic model. A **generic model** is filled by all previously build models and further information (such as data from benchmark-studies). Therefore, it contains all relevant functions and components with all interactions and context information. From this generic model, a **product model** for the current product development process can be derived. It is the task of product development to generate a physical structure based on the system reference model.

<u>Overview of the measure:</u>

- Elements of information, which are not included in the model, can be addressed by the model as central point of access.
- Elements of information can be generated by lessons learned (for instance in the form of a FMEA or textual) or by benchmark programs.
- The model offers a consistent structure and assigns coordinated terms which are understood by all involved stakeholder. This can be supported by a term management system for synonyms. There are, for instance different names used by different departments or customers for the same component (e.g.: Housing and casing).
- Information can be attached to model elements (functions, components, requirements, and tasks) and therefore be recovered and accessed easily.
- Combinations of model elements (such as task A and function B) narrows down and facilitates the search for specific information.

This measure can be **explained with an example** (see Figure 32), which is also used to evaluate the measure in chapter 8: During a past project, **employee 1** had found out that that the function *electrical connection* between the components *fuse* and *high voltage cable* cannot be established due to high vibrations. This was tested and failed. Therefore, a measure was worked out, implemented and tested again. This employee did connect this element of knowledge of the effective measure with the elements requirements, functions, test and components in the project's product model. This context is transferred in the generic reference model, since this kind of component, function and requirement can be found in every traction battery. **Employee 2** can call up this information in a recent project. This can be done by a search for the component/function in connection with the current requirements.

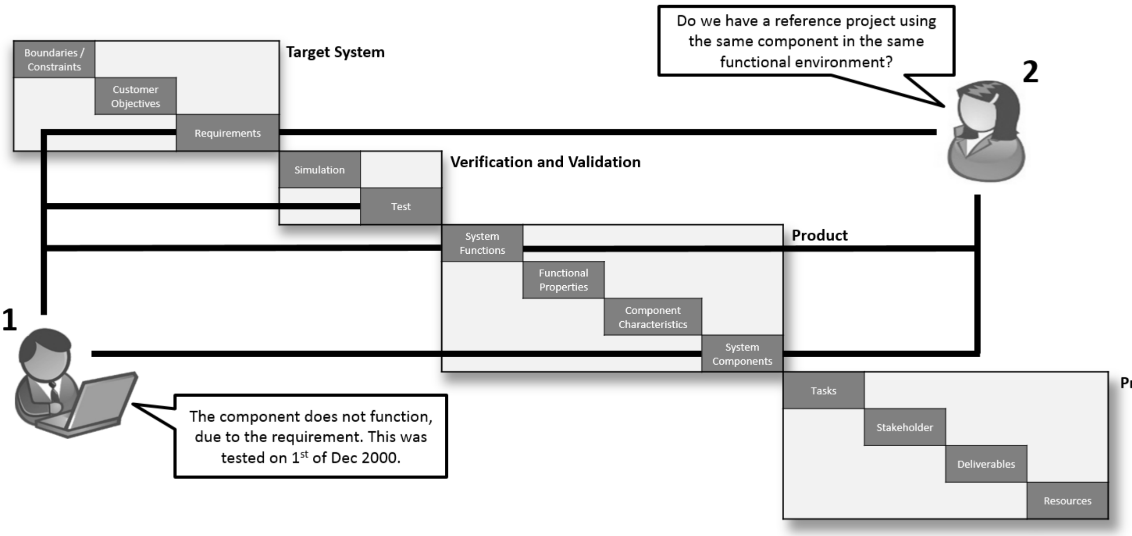

Figure 32: Exemplary visualisation of measure 1: Reuse of information [345]

Implementation in the Mock-Up:

Due to the high amount of information the generic model can quickly become very complex. The visualisation and the interaction with data have to facilitate the handling of data. Specific relevant information and its context have to be visible. Therefore, every development engineer is assigned to components in the development environment. The model element component can be seen as a point to enter the tool for the specific functions of this cluster.

Here, the measures are introduced, similar to before by the example of a fuse. This view is available for every component deposit in the product model. The functions can be explained as following (see Figure 33):

The component as central element is displayed. Around the component all connections and the kind of connections to other components are displayed in form of coloured arrows. By the plus sign the component can be edited. Properties of components can be added and changed. Functions describe the system behaviour of the component. Those are directly linked and can be used as access point for information. With the button *catalog* lists of already known information (data from previous projects or data from benchmark studies) can be viewed.

For the entry and search of lessons learned two possibilities are given, which are both available in the menu bar. First, knowledge elements can be added and read in the current view. Therefore, by enabling the function *add new*, a single element or a connection arrow in the current view can be chosen to add information. In a separate window this information can be specialized and the combination of model elements selected. In the same way information (lessons learned) can be read: When enabling the function *read*, elements with allocated knowledge are highlighted. This knowledge

[345] Own illustration.

can then be easily accessed at any time. Secondly, an alternative *list view* gives the possibility to manage knowledge in the traditional form with columns and rows.

Data and knowledge that cannot be added as model elements can be made available by the button *assigned links*. All stored information (properties, requirements and functions) at which the file or link is uploaded, is stored as Meta data. The advantage of this assignment is the easier retrieval of those files.

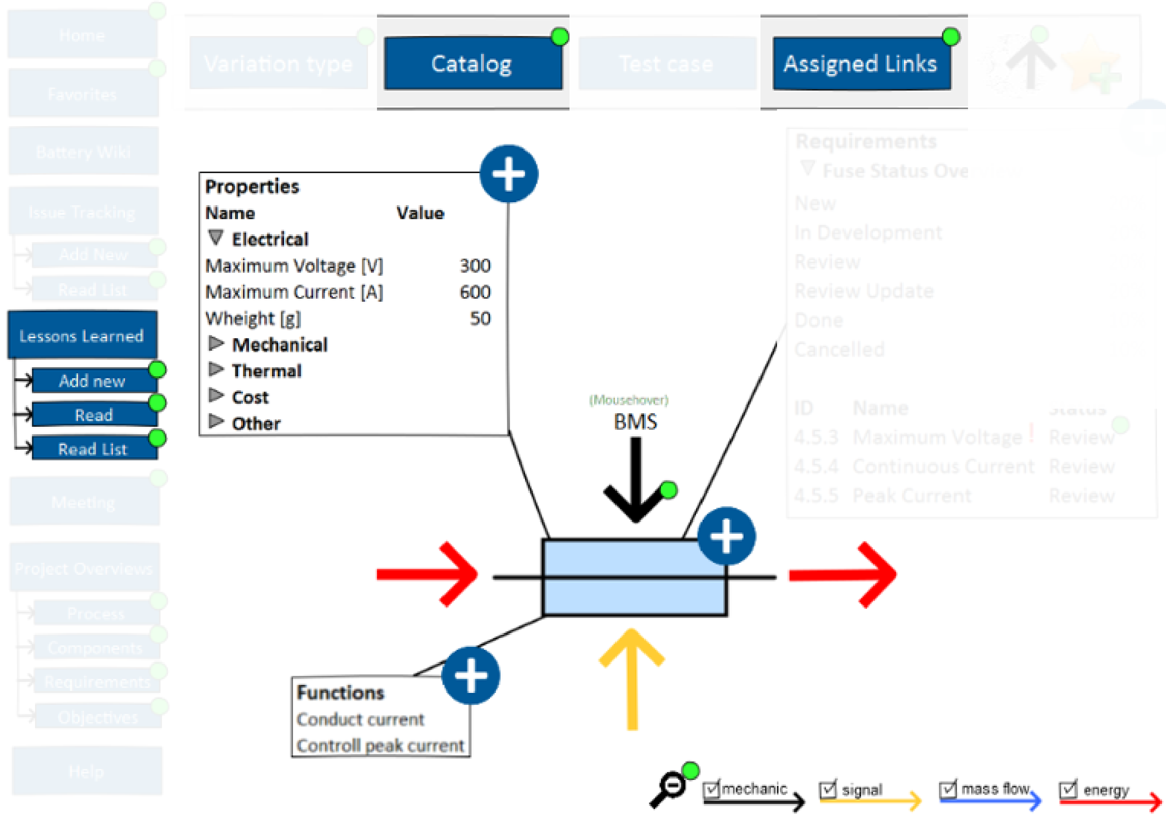

Figure 33: Detailed component view of the Mock-Up [346]

7.2.2. CLUSTER 2: MBSE AND RQ-ENGINEERING

The second cluster deals with the challenge of a quick and sustainable assessment of requirements. At the use case of battery development at AVL List GmbH the tool PTC Integrity Lifecycle Manager is a software used for requirement management. Nevertheless, as shown in the questionnaire (see chapter 6.2.2) there are several failures arising although this tool is used. Further the constant use of this software solution is neglected to some extend since today 60 % of all information according requirements is still send out by email. This distribution of requirements out of integrity can be seen to be inadequate. Here, the objective can be described to be the allocation of all in integrity stored requirements. Further, the generic model with all connections between requirements and stakeholder enables the acceleration of the feasibility of single requirements. By mapping new requirements to a

[346] Own illustration. Based on Müller (2016).

generic list of requirements, all information possessed in previous projects is available instantaneously in the phase of a feasibility review.

Overview of the measure:

- Specific customer requirements are connected to the generic requirements in the model. This is possible for all new requirements requested by the customer, which only change by the value but not in the principle function.
- Critical requirements can be identified by the model:
    - By the comparison with already specified requirements it can be assessed if the requirement is targeting for the organisation unknown values (for instance a very high voltage).
    - Due to the connection in the generic model value ranges of interacting requirements can be assessed according to new combinations.
    - New, up to today never processed requirements can be identified.
- The connection of requirements to responsible stakeholder (in previous and current projects) simplifies the allocation of responsibilities and fosters the collection of already generated information.

Implementation in the Mock-Up:

Requirements are connected by the functions and components and are displayed in the component view (see Figure 34).

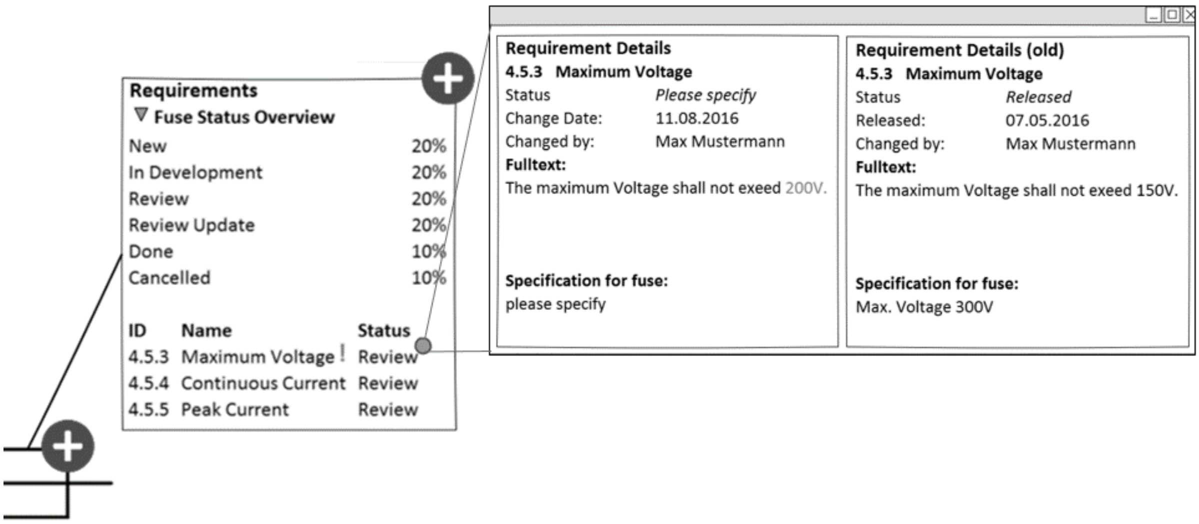

Figure 34: The function requirements management in the Mock-Up [347]

[347] Own illustration. Based on Müller (2016).

The relevant requirements for one component and an overview according the status of each requirement are displayed. Changes of requirements are highlighted with an exclamation mark. In the pop up of one requirement Meta data and the specification for this component can be found. The changes concerning the latest update are highlighted.

The context and analysis function provided by the model are added to the classical list of requirements. Every domain can be inserted by the “+-button” in the form of a column. Requirements that are identified to be critical or new are marked by the red exclamation mark (see Figure 35).

ID	Name	Value	Assigned Functions	Assigned Components	Related Requirements	Related Stakeholder	New	In Development	Review	Review Update	Done	Cancelled	Comment
4.5.3	Maximum Voltage	! 400V	3	10	30	3		3	1	3	3		
4.5.4	Continuous Current	300A	2	4	! 20	1						4	
4.5.5	Peak Current	1000A			10	2							
4.5.8	Dichtigkeit						!						

Figure 35: The extended list of requirements with context information [348]

7.2.3. CLUSTER 3: GENERIC DELIVERABLES IN A PROCESS MODEL

The sales process takes place in close consultation with the customer to define objectives that need to be achieved by the development. In a sales talk with a customer technical development objectives and process objectives (deliverables at certain milestones) are defined. Since the overall value of the process is described to be something the customer will pay for (see chapter 4.4), those deliverables have to be defined in detail and made available for everyone involved. The deliverables, as the final or interim product of the value stream, define all process characteristics such as tasks or resources. Most importantly, as described by Browning (2003) [349], those deliverables have to be coordinated and best possible documented to enable an optimum start of a project (*garbage in, garbage out*). To simplify this coordination certain measures concerning a process and product model can be implemented.

<u>**Overview of the measure:**</u>

The **technical objectives** contain on the one hand **explicit requirements** and on the other hand **implicit expectations** of top level characteristics and its priorities. One main aspect implemented in this measure is to enable stakeholder in the sales process to display implicit knowledge (see chapter 4.2). Therefore, this knowledge can be addressed and converted to be explicit by an interactive software interface.

In a so called ***scatter-band*** (see Figure 36) customer and sales person can **vote on top level objectives** (for instance: performance, safety, cost). Those are chosen in comparison to existing benchmark

[348] Own illustration. Based on Müller (2016).
[349] BROWNING, 2003, p. 51–56

attributes of already finished benchmark studies. The, according to the expertise of AVL List GmbH, technical feasible area is shown with the blue range. Therefore, the customer can decide on where the objectives of to be developed battery are being emphasized on. A clear objective of the precise description and connection of certain objectives in the battery model enables the representation of dependencies: For instance, cost are increasing when efficiency is being emphasized. Here, the attributes in this *scatter-band* are based on the benchmark attributes according to the AVL Battery Benchmark process. These can be adapted concerning current customer needs.

Further, agreed on customer objectives are the start for a new product model, based on the generic battery model. Therefore, all discussed and fixed objectives are always available during the project.

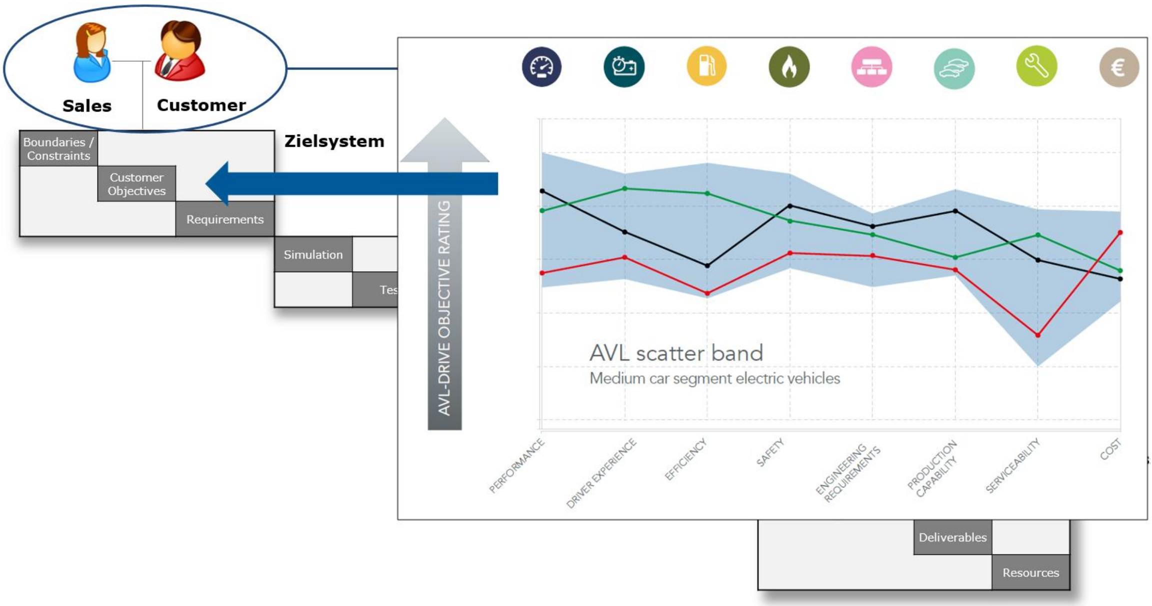

Figure 36: AVL scatter band for evaluating high level objectives [350]

Another main scenario addressed with this measure, as described in chapter 7.1.1 are the, **with the customer aligned tasks and deliverables**. Those objects concerning the **process** are preset in the generic model: The model contains broken down tasks, inputs and outputs (necessary sub-deliverables). In a preceding process a sales person can **choose and define certain deliverables** chosen from a generic list and align those with the customer. Since every generic deliverable is broken down into tasks which have certain resources (time, costs), a **first assessment of expenditure** can be fulfilled quickly. If necessary, new deliverables can be added to the generic process model. The feedback of the development team, trains the generic model and enhances the assessment of expenditures. This feedback (or lessons learned) can therefore be incorporated easily and be made available for both the process of sales and development.

This enables the definition and coordination of explicit deliverables at certain milestones in the process of battery development which can also be used in several different phases of development.

[350] Own illustration. Based on AVL List GmbH (2016)

Implementation in the Mock-Up:

In the Mock-Up a new project can be created. Therefore, the user is being lead through the definition of technical and process objectives. This starts with an overview of the battery development process with the essential phases and milestones. Those are interactive and contain the belonging deliverables. Here, the required deliverables can be selected.

Further, in the view of the scatter-band (see Figure 36) high level customer objectives can be chosen, as described before. Additionally to the scatter band the customer can select priorities in a so called *sunburst-diagram* (see Figure 37). In this diagram priorities of top level characteristics on level 2 can be set intuitively. This can support the process of decision making during the project. Also here changes and correspondences of single fields influences the technical possible size of other fields. Nevertheless, in this form of diagram the overall maximum size (for instance 100 %) is always fixed.

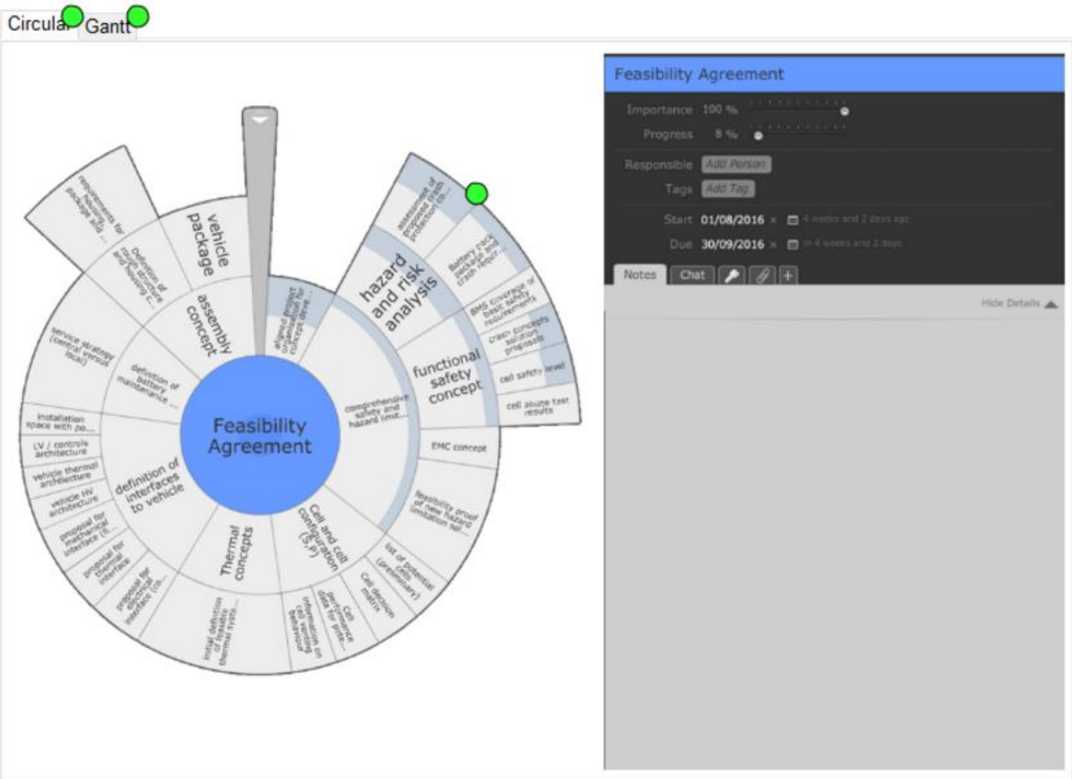

Figure 37: AVL scatter band for evaluating high level objectives [351]

Following those first two steps, a new project will be added and a new product and process model are generated based on the generic battery model. During the development project, a goal map or a classical Gantt chart give the opportunity to manage the project. Everyone involved in the development process can adapt or change the deliverables and the connected tasks. This can be achieved in the view *deliverables* (see Figure 38). Here, besides data according the selected deliverable, the exact specification of each deliverable can be viewed. According to the hierarchical order in the

[351] Own illustration. Based on Müller (2016).

process, sub- and super- deliverables can be viewed, as well as related tasks. Further, also the task itself to achieve a certain deliverable can be specified, or compared to tasks carried out already.

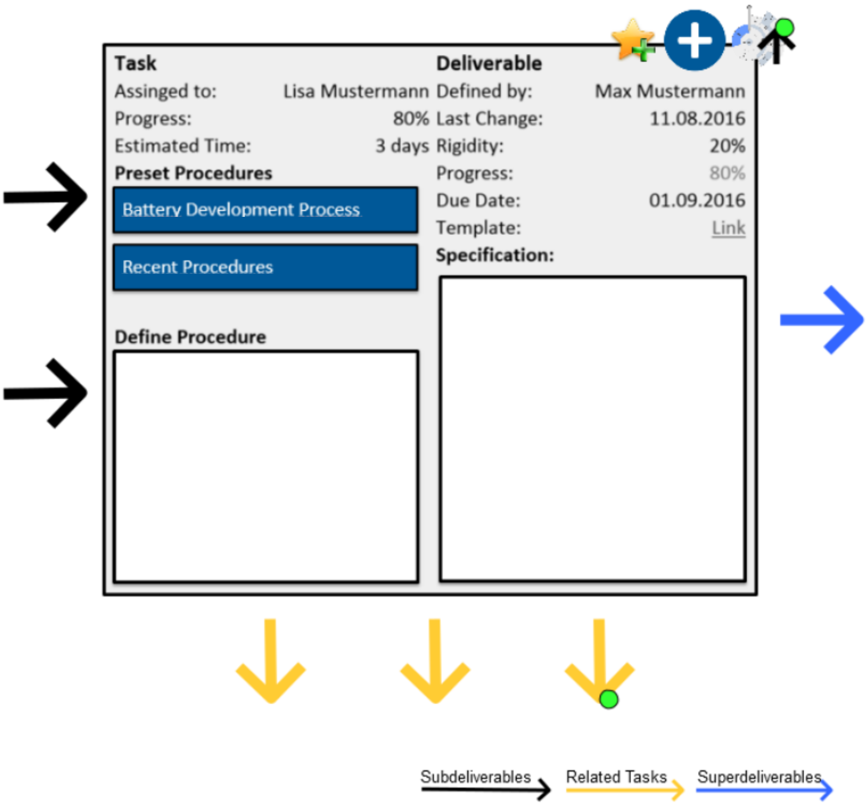

Figure 38: Exemplary view of a deliverables and task [352]

7.2.4. OTHERS

Besides the in chapter 7.1.1 presented clustered scenarios, nine out of the 24 originally described failure modes cannot be avoided by the previously described measures. Those nine scenarios account for the last 16.7 % of the unnecessary effort. Even though the low prioritization according to the survey, possible measures to be implemented are worked out and introduced in Appendix A.

Besides the realisation of the described measures in the Mock-Up, several other functions have been discussed and applied. For instance favourites (components, functions, requirements, etc.) can be managed on a front, navigation (home-) page. Here, also the most important changes are displayed to be eaasily and quickly accessible. A login system ensures data security and a user specific customization of the tool. An issue-tracking list enables an overview of open or previously changed issues (for instance negotiations with the customer). Also, Meetings can be scheduled, according to components and functions enabling easy and correct invitations (depending on the set responsibilities). Further figures of the Mock-Up and those functions can be seen in Appendix B.

[352] Own illustration. Based on Müller (2016).

7.3. INTERIM CONCLUSION

All evinced potential of the first descriptive study can be addressed with measures enabled mostly by a generic battery model. These measures are the foundation for a possible software solution (CSCW-tool), shown here in a Mock-Up.

This tool for the implementation of MBSE differs from the current state of technology significantly: By the combination of the product and process model and by an easy to comprehend tool-surface, all features are connected and form the one single source of truth. Detail views of components or deliverables, which display information specifically for one user in development or sales, are compiled from the overall model. The model stores and enables the further use of data accruing in the development process. This trains the generic model and enables an over the time more and more sophisticated basis for development.

Although this model is based on experience and implicit knowledge, new and innovative components and functions shall not be left out. On the contrary, adding new innovative features will enable the competitiveness of AVL List GmbH. The model needs to be easily adaptable for this approach. Furthermore, the generic model as basis for every development project enables a more sophisticated project start with already prefilled documents and time tables. This enables developer to spend time more concentrated on new and innovative components, features, functions, etc.

The very intensive discussion in the workshop concerning requirements and the specification for a CSCW-tool show the complexity on the one hand and the anxiety of a further tool to be used in the process on the other hand. Hence, the functions and this tool were elaborated in the next, final study.

8. DESCRIPTIVE STUDY II: EVALUATION OF MBSE IN THE BATTERY DEVELOPMENT PROCESS

This second and last descriptive study, according to the DSM (see chapter 5.1), enables an evaluation of the introduced measures. Here, the impact of the support and its ability to realize the desired situation is investigated. With the basics laid in the prescriptive study, an evaluation in the Global Battery Competence team with potential future user is made possible. To enhance the study the research question asked, at the beginning of this final phase can be described to be: **What overall benefit does the enhanced preparation of information create?** This final, comparably short study is realized in a final presentation with a succeeding self-administrated questionnaire which shows the possible improvement by the implementation of the prescriptive study.

8.1. DESIGN OF THE STUDY

In this study employees, who have been interviewed in the first descriptive study already, evaluate the measures according to effect and the quality of the implementation in the Mock-Up. This step enables the third part of the FMEA: After the definition of the measures, the RPN has to be re-evaluated. This approach allows a new evaluation of each failure established.

Since this questionnaire can be seen as a complementary, similar study to the first research, the **scientific background for this questionnaire** is the same as described in chapter 6.1.3.

Presentation and questionnaire in the Global Battery Competence Team of AVL List GmbH:

To ensure a precise and comprehensive result, the measures described in the previous chapter have to be explained in detail. This is enabled in the presentation with a simultaneous rather critical discussion and a succeeding questionnaire.

The **target group** of this survey is defined to be all employees who have participated in the preceding studies. Similar to the first study, a diversified group of different employees shall allow a critical discussion. Although, due to time issues, not everyone completes the questionnaire, comments (positive and negative) during the presentation are documented and clustered (see chapter 8.2). For an appropriate size of the group and high number of returned questionnaires, two one-hour workshops are conducted.

Both workshops have the same agenda: First, a **short overview** of the results of the first descriptive study should give a detailed and insight understanding of the reason for conducting those meetings. Secondly, the measures are introduced in detail. Therefore, the functions of each measure are presented in a first step. The mock-up is demonstrated in the second step. If necessary every participant is able to try out single features of the Mock-Up. Finally, a questionnaire shall assess each measure.

For a simple **design of the questionnaire** two closed questions are asked:

- Is the measure implemented well in the Mock-Up?
- To what extend does this measure (if fully implemented) improve the relevant scenario?

The first question can be evaluated on a Likert-style scale (strongly agree to strongly disagree). For the second question it can be chosen with checkboxes between 0 % - 100 % in an interval of 25 %. Further, an open box allows to state comments according to the measures. The questions need to be answered for every scenario. Therefore, the questionnaire is split up into four cluster (3 cluster, as described in 7.1.1, and the cluster *others,* as described in 7.2.4). Besides the presentation all measures are shortly introduced on the questionnaire.

8.2. RESULTS

In this study 15 employees of different departments, all member of the Global Battery Competence Team, have took part in the meeting and 8 (cluster 1) / 7 (cluster 2-3 and other) have handed in the questionnaire.

The results of all participants with all comments, in the original design of the questionnaire are attached in Appendix C. Since the original questionnaire has been conducted in German, the results shown in this attachment are also in German. The results of this survey and the conclusions are specified in the following subchapters.

8.2.1. CLUSTER 1: REUSE OF INFORMATION

The evaluation of the first cluster shows that the implemented measures are received very well: [353]

The unnecessary effort for the main scenario (*already gained knowledge from previous projects (Lessons Learned) is not being used*) can be **reduced by 72 % to below 13.500 € per year and project**, if the measure is fully implemented. Also the implementation in the Mock-Up is rated positively. Although this positive rating it is stated by a respondent that the problem can only be solved if “all knowledge is recorded correctly”.

With the same measure of reusing information other unnecessary efforts arising in other scenarios such as *results of benchmark studies cannot be compared* or *necessary information from past projects are not accessible* can be solved. Those scenarios are rated between 59 % and 85 %. Further, comments are stated according the necessary implementation of concern and change management. Also, it is mentioned that a pre-filled model is necessary to “immediately indicate the additional value”. The biggest challenge is seen to be that to ensure consistent data “every stakeholder needs to use the system every day”.

[353] Cf. questionnaire cluster 1 in Appendix C

All in all, the feedback and the consequent discussion according the first cluster shows, that knowledge management in a process and product model can be a valid way. Nevertheless, the easy to understand representation of knowledge is a key factor for a CSCW-tool to be accepted by every stakeholder. This is necessary to ensure a complete information flow through the model. A comparison of the old and new risk level, as done in the pFMEA, is displayed in Table 11.

Unnecessary effort arises, because…	**Original risk level in € per year and project**	**% of reduction of risk level**	**New risk level in € per year and project**
…already gained knowledge from previous projects (Lessons Learned) is not being used.	47.962 €	71,88 %	13.489 €
…necessary information from past projects are not accessible.	11.817 €	59,38 %	4.801 €
…project documents are stored on different locations and/or several times (e.g. project drive, Integrity, iCAE, SharePoint).	10.840 €	60,71 %	4.259 €
…results of benchmark studies cannot be compared.	6.337 €	84,38 %	990 €

Table 11: Comparison of old and new risk level: Cluster 1 [354]

8.2.2. CLUSTER 2: MBSE AND RQ-ENGINEERING

In the cluster two the evaluation show quite similar results as in the previous cluster: [355]

According to the 7 participants who completed the questionnaire, the unnecessary effort which arises due to the main scenario (*it is not clear at the project start, which requirements are not or only insufficiently feasible*) can be **reduced by 64 % to below 10.000 € per year and project**. Further, the implementation in the mock-up is rated to be implemented well. Nevertheless, comments of the respondents show that the problem causing this scenario is often "a misunderstanding of customer and organisation" which can "hardly be solved by a software solution".

Unnecessary effort arises, because…	**Original risk level in € per year and project**	**% of reduction of risk level**	**New risk level in € per year and project**
…it is not clear at the project start, which requirements are not or only insufficiently feasible.	25.890 €	64,29 %	9.246 €
…necessary requirements and changes of requirements are not transmitted to the relevant stakeholder.	9.102 €	67,86 %	2.926 €
...requirements are overlooked, because they are not stored uniformly and structured.	6.180 €	83,33 %	1.030 €
…the status of requirements (each or overall) is not clear.	2.569 €	75,00 %	642 €
...identical or nearly identical requirements are processed two or more times.	712 €	67,86 %	229 €

Table 12: Comparison of old and new risk level: Cluster 2 [356]

[354] Own illustration.
[355] Cf. questionnaire cluster 2 in appendix C
[356] Own illustration.

Also the further unnecessary effort arising in this cluster is rated to be significantly lower if the measure of a product model is implemented to store and connect requirements. Accordingly, participants assess the effort to be reduced by 67 % to 83 %. A condition for a possible implementation is the "immediate documentation of all requirements in PTC Integrity Lifecycle Manager".

This evaluation illustrates the overall advantage of consistent requirement management in a product model. The necessity of always accessible up to date requirements can be fulfilled by the CSCW-tool, as shown in the Mock-Up. The results of this cluster, compared to the old risk level are demonstrated in Table 12.

8.2.3. CLUSTER 3: GENERIC DELIVERABLES IN A PROCESS MODEL

In this cluster the measure concerning a process model is also ranked to significantly reduce the unnecessary effort arising due to the given scenarios: [357]

The main scenario stated (*overall project objectives are not sufficiently defined, coordinated and accessible (e.g. no basis for decision)*) is evaluated to **reduce the risk level by 75 % to 3.700 €**. Also the function of conceiving a new project based on the generic deliverables and objectives realized in the Mock-Up is rated to be implemented sufficiently. It is highlighted in the discussion that the possibility to train the properties of deliverables and tasks such as the time or costs could be a major contribution to the process of offer creation. Nevertheless, it is stated that "most problems accrue due to a "lack of communication".

Unnecessary effort arises, because…	**Original risk level in € per year and project**	**% of reduction of risk level**	**New risk level in € per year and project**
…overall project objectives are not sufficiently defined, coordinated and accessible (e.g. no basis for decision).	14.803 €	75,00 %	3.701 €
…tasks are not formulated sufficiently.	11.723 €	80,00 %	2.345 €
…deliverables are not sufficiently specified or tailored to customer needs.	11.013 €	75,00 %	2.753 €
…it is not clear who is responsible for which task (in the project).	1.403 €	83,33 %	234 €
…the overall project status is not comprehensible.	164 €	66,67 %	55 €

Table 13: Comparison of old and new risk level: Cluster 3 [358]

Besides the main scenario also the other 4 scenarios are rated positively: A reduction of 66 % to 83 % could be possible according to the 7 participants of this survey. Such as the first two clusters all scenarios are highly related on each other. For instance, overall project objectives can only be defined if the deliverables are formulated sufficiently (scenario 3). Therefore, it is recommended by the participants of the workshop to follow the process of first enabling tasks and deliverables to be formulated sufficiently and then coordinating them based on the project with the customer.

[357] Cf. questionnaire cluster 3 in appendix C
[358] Own illustration.

All in all, the measure based on the process model fully implemented can solve the given scenarios to a major extend. Nevertheless, it requires a lot of coordination to formulate tasks, deliverables and stakeholder roles (responsible) to be documented in a generic process model. Evidently, the trainable process model enables this coordination and can ensure a consistent documentation that can be used in the sales process to define and coordinate objectives with the customer. The overall result of this cluster is pictured in Table 13.

8.2.4. OTHERS

Finally, the efficiency of implemented measures are rated for the last cluster of scenarios causing unnecessary effort. Here the measures are not defined and discussed in detail. Therefore, this cluster is only presented and elaborated shortly at the end of the workshop. The questionnaire, filled out by 7 participants, shows a quite varying but comparable lower result: [359]

- For instance the function of extracting test specifications out of the product model is rated to reduce the unnecessary effort by 66 % to 3.100 €. The reuse of test specifications, especially for standard test, is evaluated "to be possible".
- The unnecessary effort arising in meetings (e.g.: *Meetings are not scheduled in a structured manner*), seems to arise due to "neglecting the rules". Thus, the measure to invite stakeholder according to their responsibilities stated in the model cannot fully improve the meeting culture. Here, the unnecessary effort is reduced by 50 % to 2.450 €.
- Especially the specification of stakeholder-roles (tasks, responsibilities, resources) can hardly be improved by the process model and a CSCW-tool. As stated by a participant, "a software cannot solve this problem". These roles have to be defined before implementation since the distribution of information strongly relies on these definitions.

Although the focus is not being laid on those last scenarios. It can be seen that easy to elaborate and implement measures can reduce the unnecessary effort in total by an average of over 50 %.

8.3. INTERIM CONCLUSION

Overall, the total value added by a combined product and process model is expressed here in a reduction of unnecessary effort. According to this second descriptive study this reduction is significant and implies a great potential for projects conducted in the environment of battery development by implementing the introduced measures. **In total** the result shows an **improvement by 68 %** to a **remaining unnecessary effort of 64.831 €** (see top 7 scenarios in Figure 41).

Nevertheless, the comments and statements given by the respondents show, that the implementation of the measures in a CSCW-tool on the one hand, and the roll out of the, to be used product and

[359] Cf. questionnaire cluster *others* in appendix C

process model on the other hand demands further actions and measures. Many comments highlight difficulties that can arise, when introducing a model as a single source of truth. Undoubtedly, a reduction of all unnecessary effort to a full extend is impossible due to remaining efforts to necessary operation and maintenance of the model. Also, a further in depth prefilling of the model is necessary to provide an immediate additional value for the user.

As a result, this last study finalizes the pFMEA with the last evaluation of the new, improved risk level. A clear overall additional value is identified and expressed in a monetary sum. Although, as stated in the comments, additional in depth measures have to be implemented, this survey proves the need for a combined product and process model to overcome the unnecessary effort described.

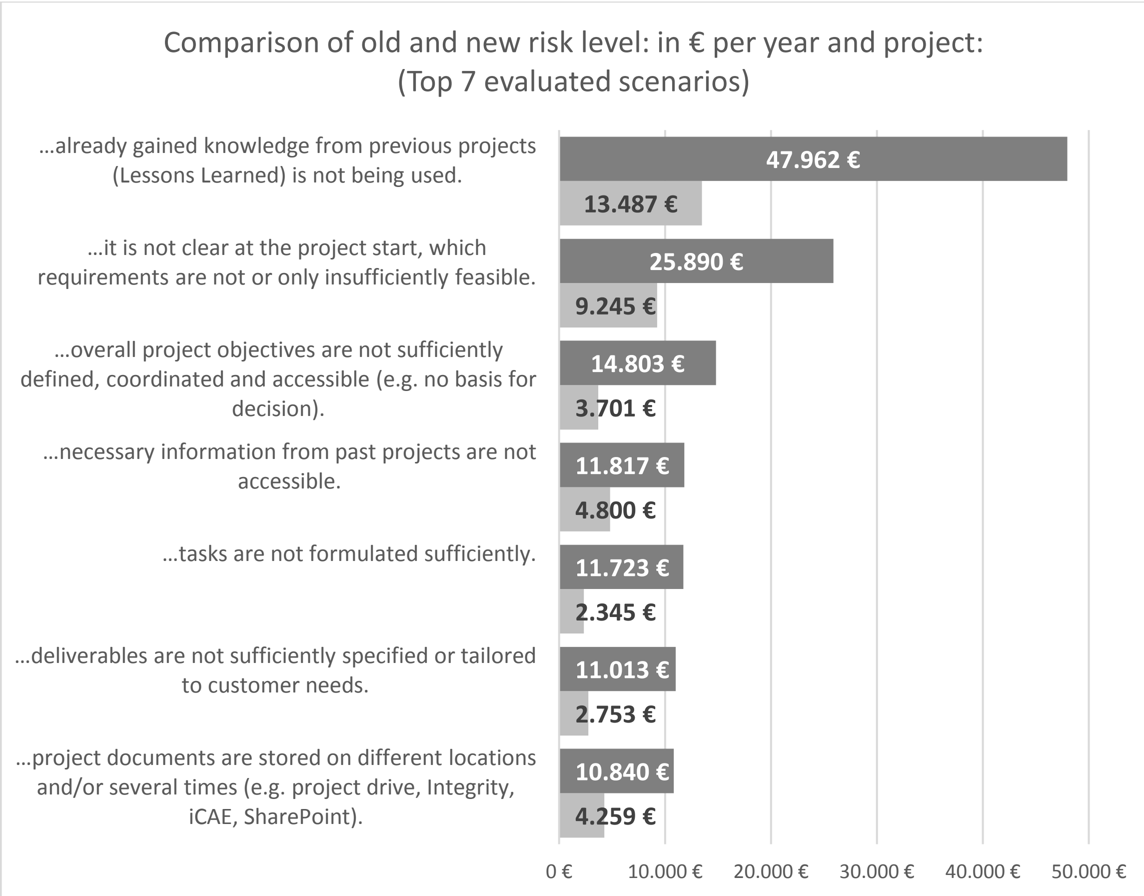

Figure 39: Comparison of the old (dark) and new (light) evaluated top 7 risk levels [360]

[360] Own illustration.

9. CONCLUSION AND OUTLOOK

MBSE and product development are considered in the very realistic young environment of traction battery development for automotive applications. Due to this rather new technology on market and especially for AVL List GmbH the challenges, such as **decreasing cycle times** or **new, innovative and complex products** play a significant role.

The first evaluation of this thesis demonstrates that everyday problems, such as no access to information or no utilization of already gained knowledge, results in a high amount of unnecessary effort. As described by Bursac (2016) the success of a company depends on how fast an organization can **acquire, spread and apply new knowledge**. The results of **24 identified scenarios** causing an evaluated unnecessary effort of **199.637 € per year and project** confirms this view: It emerges that the application and reuse of knowledge strongly influences the development process. The overall evaluated unnecessary effort highlights the need for solutions such as knowledge or quality management and displays the complexity stated before.

The introduction of MBSE in the environment of battery development faces many different hurdles. Such as stated in chapter 7.3 a possible solution needs to integrate several aspects of a model, such as the product traction battery and the development process. Thus, the findings allow to **adapt the approach of MBSE specifically to the identified scenarios** and rank a possible implementation according to the urgency. Further, the Mock-Up of a software solution enables in depth discussions and realistic tests of a CSCW-tool based on the process and product model implemented in the everyday process.

The last study proves the need for MBSE to overcome the unnecessary effort. Therefore, a second qualitative study discusses different solutions in order to evaluate to what extend unnecessary effort can be reduced due to the application of MBSE. The value added by MBSE in this research is expressed in a reduction of unnecessary effort by **a total of 68 %.** Although, additional in depth measures have to be implemented, this survey proves, that with a prefilled model, immediate additional value can be approached.

Outlook at AVL List GmbH:

Besides the described unnecessary efforts concerning knowledge management, the focus of the research environment is laid on requirements and project management. This thesis gives an estimation of what steps are necessary to implement measures in a CSCW-tool. Those measures are described in the cluster in chapter 7.2.

Concerning the third cluster (*generic deliverables in a process model*) a possible implementation has been discussed and evaluated. To prepare necessary steps which have to be achieved to implement MBSE, the **five-step improvement** process by Friedenthal (2012) can be utilized, such as described in chapter 3.3.5.

Overall, the **product and process model** have **to be filled further** in detail and a **user interface** shall enable employees to utilize all information of the models. Such as described in this thesis, the model needs to be expandable and has to be trained by every project. Therefore, a necessary **artificial intelligence** to **identify patterns** shall be introduced. This enables knowledge management on a daily bases, and prevents an overflowing of the necessary regular maintenance of the model. Further, **barriers,** as described in chapter 4.2.1, need to be **inhibited**. For instance, the individual barrier *lack of time* shall be opposed by a **sufficient number of employees** to be working exclusively on the introduction of the tool, or by consulting an external service provider.

An **initial assessment** of the **RoI** of such an implemented tool in the area of sales and project management is realized with the support of the Systems Engineering Laboratory. The necessary steps to be taken can be described as following (see Figure 40):

On the side of **expenses**, various measures have to be taken: In a first phase, a **detailed specification**, planning and selection of an **external supplier** needs to be fulfilled. Afterwards, the battery model to integrate all necessary information on the one hand and a user-interface to enable the access to this information on the other hand shall be built by the external supplier. Additionally, this supplier has to be coordinated by an internal expert. All future user of such a solution have to be trained, and in an ongoing process the maintenance and further development has to be fulfilled.

Potential savings can be balanced against all necessary expenses: The application in a project always faces a necessary **learning curve** to be implemented. When fully implemented, it is necessary to plan time for the utilization of the user interface and to process all data. Further, a ramp-up face with a very low number of projects is planned. All combined possible savings, such as described in chapter 8.2.3, lead to a **return on investment after approximately two years**.

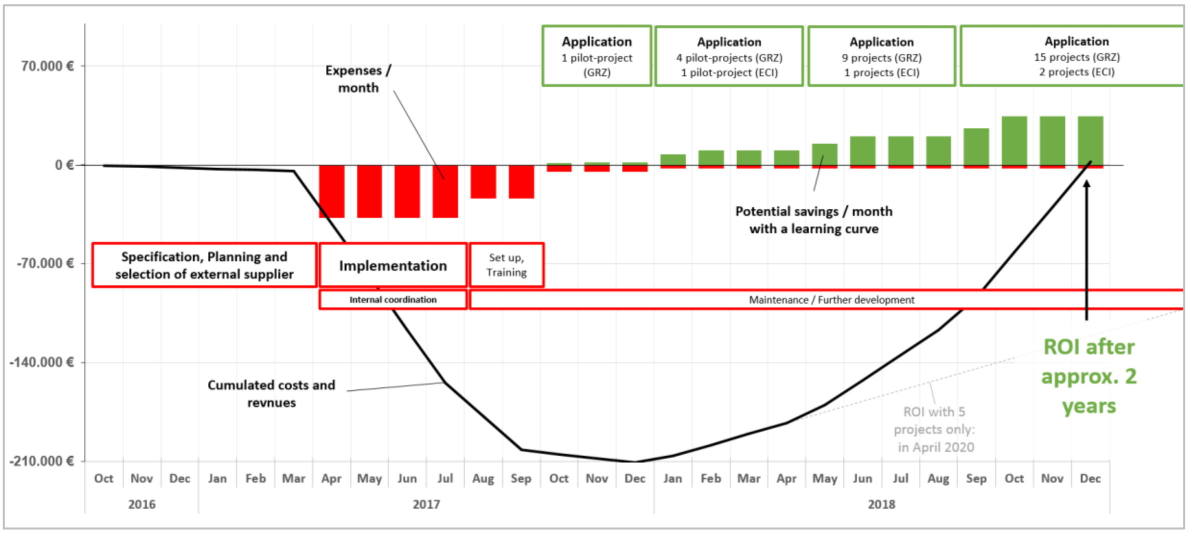

Figure 40: ROI of the implemented CSCW-tool [361]

[361] Own illustration.

LIST OF ABBREVIATIONS

AAR	After Action Review	**MS**	Microsoft
BEV	Battery Electric Vehicle	**OEM**	Original Equipment Manufacturer
CAD	Computer aided Design	**OMG**	Open Management Group
CPS	Cyber-Physical System	**PDM**	Product Data Management
CSCW	Computer Supported Collaborative Work	**pFMEA**	Process Failure Mode Effect Analysis
DMM	Domain Matrix Mapping	**PHEV**	Plugin Hybrid Electric Vehicle
DoH	Degree of Hybridization	**PLC**	Product Life Cycle
EV	Electrified Vehicle	**PLM**	Product Lifecycle Management
FMEA	Failure Mode Effect Analysis	**QFD**	Quality Function Deployment
GfSE	Gesellschaft für Systems Engineering e.V. (Association of German Engineers)	**RoI**	Return on Investment
HoQ	House of Quality	**RPN**	Risk Priority Number
HV	High Voltage	**SE**	Systems Engineering
INCOSE	International Council of Systems Engineering	**SOA**	Service Oriented Architecture
ISO	International Organisation for Standardization	**SOC**	State of Charge
IT	Information Technology	**SysML**	System Modelling Language
LeLe	Lessons Learned	**UML**	Unified Modelling Language
MBE	Model Based Engineering	**V&V**	Verification and Validation
MBSE	Model Based Systems Engineering	**VDA**	Verband der Automobilindustrie
MHEV	Mild Hybrid Electric Vehicle	**VDI**	Verein Deutscher Ingenieure
MoBat	Model-based Battery Development	**XML**	Extensible Mark-up Language

Table 14: List of utilized abbreviations

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APPENDIX A – OTHER POSSIBLE MEASURES TO BE IMPLEMENTED

Unnecessary effort arises, because…	% of total unn. Effort	Measure
1.) Project Management		
…open tasks are processed too late, because they are not prioritized.	2,25%	In the process model it can be prioritized, amount different projects. A problem is identified to be the inquiry of the prioritization.
…it is not recognizable, how occupied employees are (e.g. assigned task is done insufficiently, because employee is at maximum capacity).	1,21%	Due to the connection tasks <-> Stakeholder in the process model it can be tracked who is occupied to what extent. The exact tracking can be difficult due to labour rights.
2.) Document Management		
…already existing information needs to be researched and prepared repeatedly (e.g. PowerPoints, project status report)	1,51%	Report functions can be defined and specified with all stakeholder.
5.) Verification and Validation Process		
…tests are not sufficiently specified.	2,75%	Test specifications can be automatically extracted from the product model.
…it cannot be traced which test results are available already.	0,15%	Test results are connected to the model and therefore available for every stakeholder.
…test specification have to be set up in a new way.	4,60%	Necessary information are to a great extend available in the model. The automatic creation of a document (e.g. PDF) can be defined. The definition and agreement on test specification was not part of this thesis is not implemented in the model (yet).
6.) Meetings		
…meetings are not scheduled in a structured manner (e.g. there is no agenda, arbitrary invitation of participants, etc).	2,45%	With model elements relevant stakeholder can be identified and invited. This improves to locate relevant stakeholder but not the meeting culture per se.
…no documentation (e.g. content, resolution, etc.) is executed during meetings.	1,78%	It can be documented in the model directly: For instance, changes of requirements, issues (issue tracking), deliverables, etc. can be linked and tracked in the model.
7.) Stakeholder-Roles		
…stakeholder-roles are not specified.	1,40%	Roles of individual stakeholder are defined by the allocation of tasks and deliverables in the process model. Nevertheless, the definition in the organization cannot be supplanted in the model

Table 15: Additional measures according to workshop [362]

[362] Own illustration.

APPENDIX B – ADDITIONAL FIGURES AND FUNCTIONS OF THE MOCK-UP

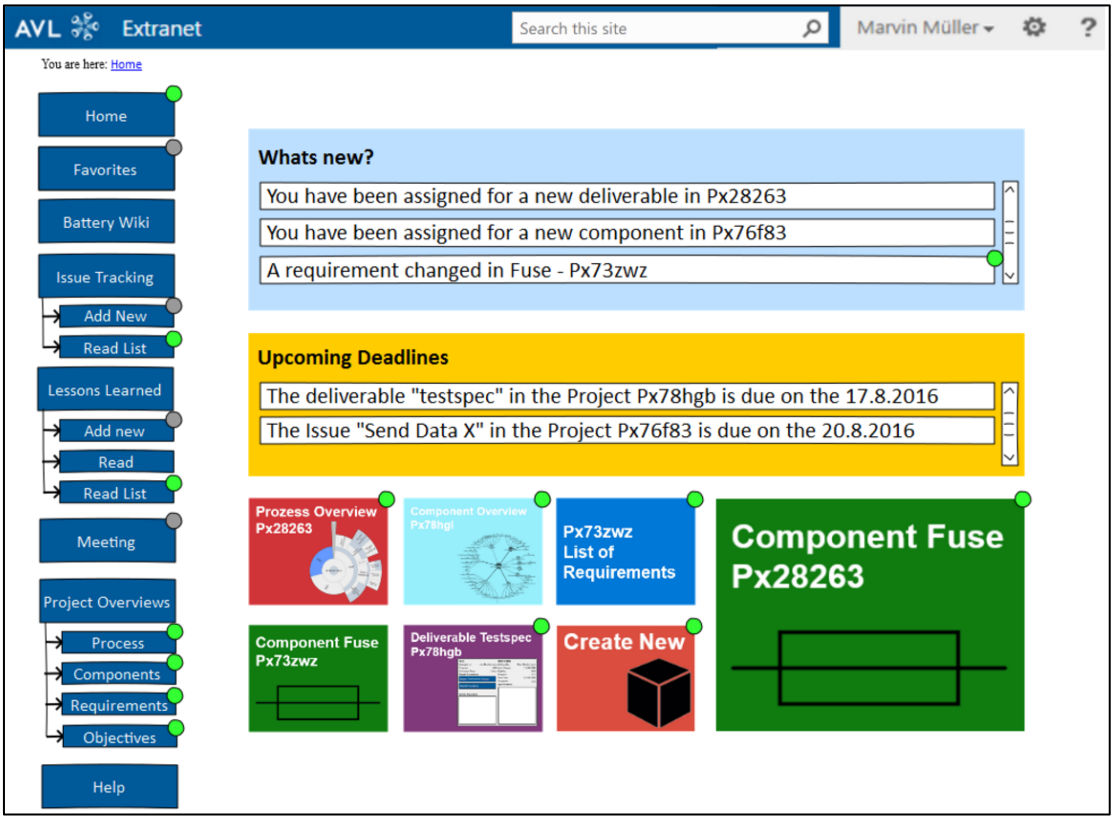

Figure 41: Home (initial) page, with a side bar (left) and to choose favourites [363]

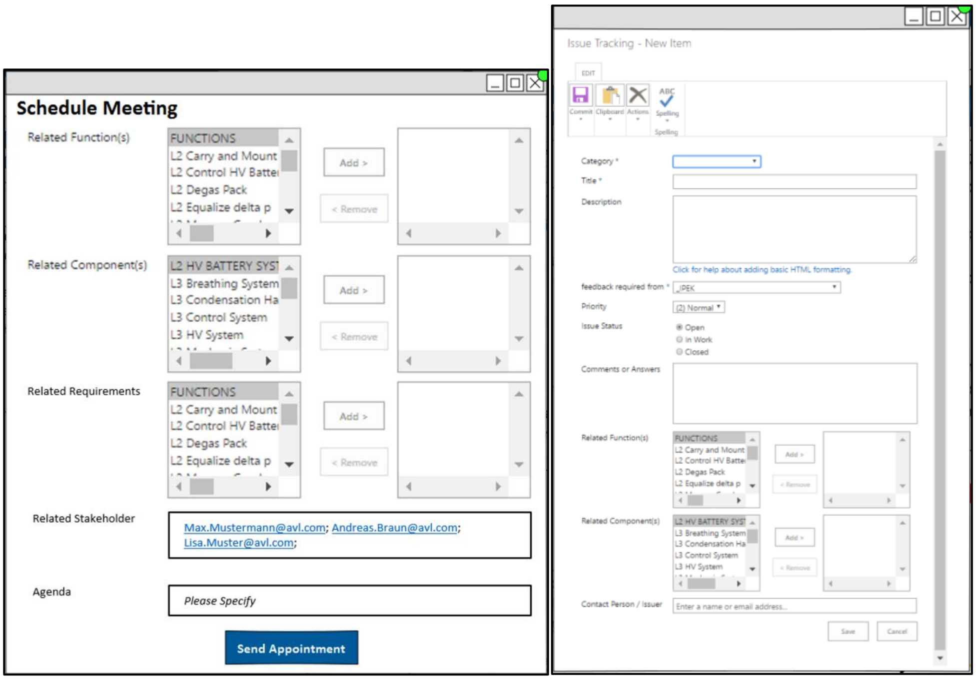

Figure 42: Scheduling a meeting (left) and issue tracking / lessons learned (right) [364]

[363] Own illustration. Based on Müller (2016).
[364] Own illustration. Based on Müller (2016).

APPENDIX C – RESULTS OF THE DESCRIPTIVE STUDY II

Cluster 1: Wiederverwenden von Informationen — Anzahl der Teilnehmer: 8

Maßnahme	Es entsteht unnötiger Mehraufwand, weil...	Diese Maßnahme ist im Mock-Up gut umgesetzt.					Diese Maßnahme, optimal umgesetzt, löst das Problem zu:						Kommentare, Wünsche, Ideen	Mittelwert: Maßnahme löst Probleme zu (Im Durchschnitt aller Antworten):
		trifft voll zu	trifft eher zu	trifft eher nicht zu	trifft gar nicht zu	Enthalten	100 %	75 %	50 %	25 %	0 %	Enthalten		
Informationen können über die Verbindung zu abgestimmten und einheitlich benannten Modellelementen strukturiert abgelegt und dadurch wiedergefunden werden. Verlinkung zu unterschiedlichen Elementen engt die Suche ein.	...bereits erarbeitetes Wissen aus vergangen Projekten (Lessons Learned) nicht verwendet wird.	3	4	1	0	0	2	4	1	1	0	0	- Ergebnisse aus LeLe sollen in Design-Guidelines niedergeschrieben werden - Das Problem entsteht auf einer höheren Ebene als auf der Komponentenebene, daher geringere Auswertung - Implizites Wissen ist schwer abzubilden - Das erarbeitetes Wissen korrekt eingespielt wird - Könnte man vielleicht intuitiver einbringen und nicht als eigenen Menüpunkt - Man wird nie alles erfassen können, da sehr viele Lessons-Learned eine bestimmte Historie haben, die erstmal niedergeschrieben werden muss	71,88%
	...notwendige Informationen aus vergangenen Projekten nicht zugänglich sind.	1	6	0	0	1	2	2	2	1	1	0		59,38%
	...Dokumente in Projekten immer an verschiedenen Orten und/oder mehrmals abgelegt werden.	4	2	0	1	1	2	2	1	1	1	1		60,71%
	...Ergebnisse aus Benchmark Studien nicht verglichen werden können.	2	5	0	0	1	4	3	1	0	0	0		84,38%
	...aktuelle oder ältere Versionen eines Dokumentes nicht auffindbar sind.	0	5	1	0	2	2	1	2	2	0	1	- Für eine detaillierte Aussage müsste das MockUp detaillierter sein	60,71%

Kommentare, Wünsche, Ideen
- Einbindung des Concern/Change Managements
- Wenn eine Informationsablage von Anfang an nicht in einem Tool möglich, wird es kaum bis gar nicht nachgezogen
- Es muss eine Grundbefüllung mit LeLe und anderen Informationen geben, um den Mehrwert sofort ersichtlich zu machen
- Ob die Maßnahme wirklich umgesetzt ist, kann ich erst nach intensiverer Testphase sagen
- Einschränkung bzgl. NDA's --> Verschiedene Herstellerinformationen dürfen in anderen Projekten oft nicht verwendet werden
- Immer Voraussetzung: Korrekte Handhabung jedes Mitarbeiters
- Die Softwareumsetzung scheint mir sehr aufwendig zu sein (vergleichbar mit der Einführung eines PDM-Systems bzw. SAP)
- Die größte Herausforderung ist, dass hier alle Stakeholder mitmachen und das System wirklich benutzen. Alsbald jemand zB ein neues Requirement nicht einträgt, gibt es einen "Bug"

Figure 43: Evaluated measures; Cluster 1: Reuse of Information [365]

[365] Own illustration.

Cluster 2: Requirements Engineering — Anzahl der Teilnehmer: 7

Maßnahme	Es entsteht unnötiger Mehraufwand, weil...	Diese Maßnahme ist im MockUp gut umgesetzt.: trifft voll zu	trifft eher zu	trifft eher nicht zu	trifft gar nicht zu	Enthalten	Diese Maßnahme, optimal umgesetzt, löst das Problem zu: 100 %	75 %	50 %	25 %	0 %	Enthalten	Kommentare, Wünsche, Ideen	Mittelwert: Maßnahme löst Probleme zu (Im Durchschnitt aller Antworten):
Neue Anforderungen oder neue Kombinationen von Anforderungen können identifiziert werden, da Anforderungen strukturiert im Modell abliegen. Durch die Verknüpfung über andere Elemente zu Stakeholdern kann Expertenwissen schnell eingeholt werden.	...es bei Projektbeginn nicht ersichtlich ist, welche Requirements nicht oder nur unzureichend umsetzbar sind.	1	5	0	0	2	2	1	3	1	0	0	- Wichtig ist, dass vor Projektbeginn die RQs gut abgestimmt werden - Das liegt aber oft an fehlenden Anforderungen oder Missverständnissen von Kunden oder AVL-Seite. Kann nur bedingt durch eine Software geklärt werden	64,29%
	...notwendige Requirements und Änderungen von Requirements nicht an die zuständigen Stakeholder übermittelt werden.	2	4	1	0	0	2	2	2	1	0	0	- Voraussetzung: Zeitnahe Pflege der Requirements in Integrity - Dokumentieren von Anfragen / Vorschlägen? - Dazu bedürfte es eine verbindliche Definition der Stakeholder	67,86%
	...Requirements übersehen / überlesen werden, da diese nicht einheitlich und strukturiert abgelegt sind.	0	4	1	1	1	2	4	0	0	0	2	- Es muss auf die Historie von RQs immer einsehbar sein	83,33%
	...es nicht eindeutig ist, in wie weit Requirements bereits bearbeitet worden sind (Status der Einzelnen und Gesamtstatus).	3	2	1	0	1	3	1	1	1	0	2		75,00%
	...identische oder nahezu gleiche Requirements doppelt oder mehrfach bearbeitet werden.	2	3	1	1	0	2	2	2	1	0	1		67,86%

Kommentare, Wünsche, Ideen
- Priorisierung System PHEV, BEV eventuell sinnvoll, da Zielanforderungen unterschiedlich für diese Systeme
- Ob die Maßnahme wirklich umgesetzt ist, kann ich erst nach intensiverer Testphase sagen

Figure 44: Evaluated measures; Cluster 2: MBSE and RQ-Engineering [366]

[366] Own illustration.

Cluster 3: Angebotslegung und Prozessmodell

Anzahl der Teilnehmer: 7

Maßnahme	Es entsteht unnötiger Mehraufwand, weil...	Diese Maßnahme ist im MockUp gut umgesetzt.: trifft voll zu	trifft eher zu	trifft eher nicht zu	trifft gar nicht zu	Enthalten	Diese Maßnahme, optimal umgesetzt, löst das Problem zu: 100 %	75 %	50 %	25 %	0 %	Enthalten	Kommentare, Wünsche, Ideen	Mittelwert: Maßnahme löst Probleme zu (Im Durchschnitt aller Antworten):
Deliverables werden aus einer Liste ausgewählt und mit dem Kunden spezifiziert. Sie werden auf spezifische Taskoutputs heruntergebrochen.	...allgemeine Projektziele nicht hinreichend und eindeutig abgestimmt und einsehbar sind.	3	2	0	1	1	2	2	2	0	0	1	- Aktuell technische Möglichkeiten der Firma in einem Sales-Tool abgebildet - Bei nicht erfüllbaren RQs -> Rote Lampe in der Oberfläche signalisiert Problem	75,00%
	...Tasks im Projektalltag nicht hinreichend und eindeutig ausformuliert sind.	2	4	0	0	1	1	4	0	0	0	2	- Die Probleme liegen meist in der Kommunikation	80,00%
	...Deliverables nicht ausreichend spezifiziert oder auf den Kunden zugeschnitten sind.	2	2	2	0	1	2	3	2	0	0	0	- Setzt voraus, dass der BDP aufgelöst und umgesetzt wird	75,00%
	...es nicht eindeutig ist, wer für welchen Task (im Projekt) zuständig ist.	2	3	0	1	1	2	4	0	0	0	1		83,33%
	...der Gesamtprojektstatus nicht nachvollziehbar ist.	2	3	1	0	1	2	1	2	1	0	1	- Für den Gesamtprojektstatus sind mehr Infos erforderlich	66,67%

Kommentare, Wünsche, Ideen
- Mögliche Vorgehensweise: 1.) Deliverables bewerten; 2.) Deliverables von Projektzielen abhängig und skalierbar machen; 3.) Deliverables im Modell vernetzen, um die Dauer und Kosten der Tasks zu trainieren

Figure 45: Evaluated measures; Cluster 3: Generic deliverables in a process model [367]

[367] Own illustration.

Cluster 4: Sonstiges — **Anzahl der Teilnehmer: 7**

Es entsteht unnötiger Mehraufwand, weil...	Maßnahme	Diese Maßnahme, optimal umgesetzt, löst das Problem zu: 100%	75%	50%	25%	0%	Kommentare, Wünsche, Ideen	Mittelwert: Maßnahme löst Probleme zu (Im Durchschnitt aller Antworten):
...Testspezifikationen immer neu aufgesetzt werden müssen.	Informationen sind im Modell vorhanden. Extraktion (zum Beispiel per PDF) kann definiert werden.		4	2			- Reuse schein möglich (vor allem für Standardtests) - Oft sehr spontane Änderungen die "on the fly" umgesetzt werden; Wäre aufwendig zu dokumentieren	66,67%
...Meetings nicht strukturiert geplant werden. (Bsp.: Es gibt keine Agenda, willkürliche Einladung von Teilnehmern, etc.)	Über Modellelemente können relevante Stakeholder identifiziert werden.	1	2	1	2	1	- Das liegt an den Handelnden Personen und an mangelnder Akzeptanz der Spielregeln - Meetingkultur	50,00%
...offene Tasks zu spät bearbeitet werden, da diese nicht priorisiert sind.	Über das Prozessmodell können projektübergreifende Priorisierungen durchgeführt werden.	1		4	2		- Das liegt meist an Überlastung der Mitarbeiter und an mangelndem Fachwissen - Wenn Priorisierung möglich, dann 75% (zur Zeit: 25%)	50,00%
...Tests nicht ausreichend spezifiziert werden.	Extrahierte Testspezifikationen enthalten alle Informationen	1		2	3		- Das liegt meist an Überlastung der Mitarbeiter und an mangelndem Fachwissen - Standardisierung Testspecs	45,83%
...keine Dokumentation (Bsp.: Inhalte, Beschlüsse, etc.) bei Meetings geführt wird.	Dokumentation kann direkt im Modell durchgeführt werden.	1		4	1	1	- Das liegt an den Handelnden Personen und an mangelnder Akzeptanz der Spielregeln - Teil der Meeting-Kultur	46,43%
...bereits vorhandene Informationen neu zusammengetragen und aufbereitet werden müssen.	Reportfunktionen können definiert werden.	2	1		3			58,33%
...nicht erkennbar ist, welcher Mitarbeiter wie ausgelastet ist. (Bsp. Zugewiesener Task unzureichend ausgeführt weil Mitarbeiter voll ausgelastet ist.)	Über das Prozessmodell kann nachverfolgt werden, welche Mitarbeiter mit welchen Tasks ausgelastet sind.	2	1		2	2	- Das geht nur sehr bedingt, Mitarbeiter können in mehreren Projekten eingesetzt werden - Link zu SAP - Gefährlich: Oft werden Tätigkeiten über oder unterschätzt	46,43%
...nicht nachvollzogen werden kann, welche Testergebnisse bereits vorliegen.	Testergebnisse werden an Modellelemente angehängt.	3		3	1		- Annahme: Test kann als Task verfolgt werden	67,86%
...Stakehholder-Rollen nicht spezifiziert sind.	Stakeholderrollen sind über die Verbindung im Prozessmodell spezifiziert.	0	0	3	1	3	- Eine Software kann dieses Problem nicht lösen	25,00%

Figure 46: Evaluated measures; Cluster: Other [368]

[368] Own illustration.