Conceptional Design of a Digital Twin to Predict the Remaining Useful Lifetime of a Gearbox

Konzeptionierung eines digitalen Zwillings zur Vorhersage der Lebensdauer von Zahnradgetrieben
Master thesis by Michael Georg Frank (Student ID: 2400572)
Date of submission: March 28, 2022

1. Review: Prof. Dr.-Ing Eckhard Kirchner
Darmstadt

TECHNISCHE
UNIVERSITÄT
DARMSTADT

Mechanical Engineering Department

PMD

Mechatronic Machine Elements

Thesis Statement pursuant to §22 paragraph 7 and §23 paragraph 7 of APB TU Darmstadt

I herewith formally declare that I, Michael Georg Frank, have written the submitted thesis independently pursuant to §22 paragraph 7 of APB TU Darmstadt. I did not use any outside support except for the quoted literature and other sources mentioned in the thesis. I clearly marked and separately listed all of the literature and all of the other sources which I employed when producing this academic work, either literally or in content. This thesis has not been handed in or published before in the same or similar form.

I am aware, that in case of an attempt at deception based on plagiarism (§38 Abs.2 APB) the thesis would be graded with 5,0 and counted as one failed examination attempt. The thesis may only be repeated once.

In the submitted thesis the written copies and the electronic version for archiving are pursuant to §23 paragraph 7 of APB TU Darmstadt identical in content.

Erklärung zur Abschlussarbeit gemäß §22 Abs. 7 und §23 Abs. 7 APB der TU Darmstadt

Hiermit versichere ich, Michael Georg Frank, die vorliegende Masterarbeit ohne Hilfe Dritter und nur mit den angegebenen Quellen und Hilfsmitteln angefertigt zu haben. Alle Stellen, die Quellen entnommen wurden, sind als solche kenntlich gemacht worden. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

Mir ist bekannt, dass im Fall eines Plagiats (§38 Abs. 2 APB) ein Täuschungsversuch vorliegt, der dazu führt, dass die Arbeit mit 5,0 bewertet und damit ein Prüfungsversuch verbraucht wird. Abschlussarbeiten dürfen nur einmal wiederholt werden.

Bei der abgegebenen Thesis stimmen die schriftliche und die zur Archivierung eingereichte elektronische Fassung gemäß §23 Abs. 7 APB überein.

Darmstadt, March 28, 2022

Michael Georg Frank

Danksagung

Ausschlaggebend für das Gelingen dieser Arbeit war die stets konstruktive, verlässliche und ehrliche Zusammenarbeit mit meinem Betreuer Yanik Koch, wofür ich ihm sehr danke.

Für die fachliche Schärfung der Arbeit und den bereichendern Dialog während des Zwischenkolloquiums gebührt mein Dank Herrn Professor Kirchner.

Frau Dr. Plies-Balzer vom MechCenter der TU Darmstadt möchte ich für die persönliche Betreuung und Beratung auch über das Studienleben hinaus, während meines gesamten Bachelor- sowie Masterstudiums, von Herzen danken.

Meinen guten Freunden Uwe, Noam, Nils und Sabine Rondé, Thomas und Renate Neu, Deniel Mitrov, Max Eydt, Nico Walter, Jonas Strahl und Waldemar, Arthur, Nelli und Erika Martinevski sowie meiner Freundin Sabine Schönberger möchte ich für die Unterstützung während der ganzen letzten Jahre danken - Das ist auch Euer Abschluss!

Masterthesis

for
Herrn Michael Georg Frank Matr.-Nr. 2400572

TECHNISCHE
UNIVERSITÄT
DARMSTADT

Konzeptionierung eines Digitalen Zwillings zur Vorhersage der Lebensdauer von Zahnradgetrieben

Conceptional Design of a Digital Twin to predict the remaining useful life time of a gear box

There are many different definitions for the term Digital Twin. So far, there are some research approaches to the application of Digital Twins. In industrial applications, however, they have not yet been widely used. Based on a gear box test rig which is currently under construction, a Digital Twin is to be designed for predicting the bearing and gear life time. Existing service life models of gear box components are to be used to build the overall failure model. These are to be placed in the context of the Digital Twin and suitable interfaces to other elements of the Digital Twin are to be developed, such as the sensor system, the IoT platform and, further models and the user.
With regard to the transmission, it is necessary to analyze which data (control data, external sensors ...), interface formats (REXS, OPC UA ...) and models (CAD, MKS ...) can be used to build up the Digital Twin in different forms. For this purpose, the Digital Twin is to be built up in a modular way, whereby all interfaces are to be clearly defined, so that an extension can be guaranteed following the work. A comprehensible documentation of the issues that have arisen as well as the reasoning for decision making is crucial to sustainably develop the setup further.

Work packages:

- Research for the definition (basis FVA trend study 889I) and construction of a Digital Twin
- Derivation of a concept for the setup of a Digital Twin and application to the transmission test rig
- Definition and conceptual elaboration of the interfaces
- Development of a modularly expandable Digital Twin for the prediction of gear and bearing service life
- Documentation of the decision-making process and critical analysis of the conceptualized Digital Twin

Prof. Dr.-Ing. E. Kirchner

Fachgebiet
Produktentwicklung
und Maschinenelemente

Institute for
Product Development
and Machine Elements

pmd
Prof. Dr.-Ing. Eckhard Kirchner

Otto-Berndt-Straße 2
64287 Darmstadt

Tel. +49 6151 16 - 21180
Fax +49 6151 16 - 21181
Yanik.koch@tu-darmstadt.de

Betreuung:
Yanik Koch, M.Sc.

Ausgegeben:
17.11.2021

Abstract

In figure 1 the schematic approach of this thesis is summarized. The outcome can be categorized in four sections with similar extent. In the first section, "Service", the digital twin concept is elaborated on the basis of investigated requirements which are defined via the identification of the system stakeholder for the realization of MoL applications. The focus on service provision is enabled via the system-protagonist interaction analysis which is represented by the aggregation of use cases. The development procedure is accompanied by SysML diagrams which are part of the section "Representation". For the modeling of the interactions between the protagonists and the digital twin, sequence diagrams are created. The static system structure is represented by block diagrams which are generated in the software "Enterprise Architect". The third section, "Analysis", includes the related gearbox investigation which is summarized in a simulationmodel that is comprising besides a diagnostics part with load-based (damage accumulation) and vibration-based (IAS signal analysis) approaches, a prognostics part, which is presenting a similarity and degradation estimation. The data input to the simulationmodel is established by HCP-Sense bearings and magnetoresistive sensors which are applied for monitoring the gearbox components, namely the bearings and the gear wheels with their toothing. Based on the data input from the sensors the subsequent information transmission within the system structure is described in the fourth section, "Communication". In this section, interfaces which are categorized by OSI-layers and the specification of objects, transferred between the system elements, are defined. The modularity of the system structure is achieved by the definition of adaption nodes.

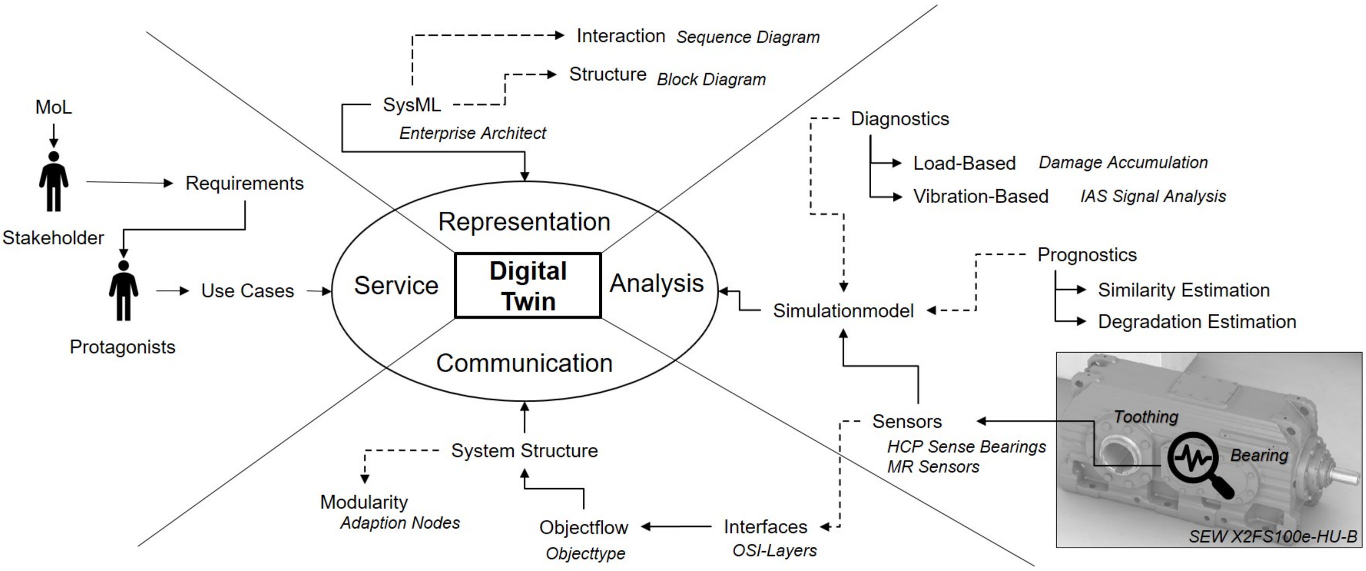


Figure 1.: Schematic Thesis Overview

Contents

List of Figures

List of Tables

Acronyms

AG	Advisory Generation	7
AI	Artificial Intelligence	11
BIM	Building Information Modeling	52
BoL	Begin of Life	52
CBM	Condition-Based Maintenance	7
CI	Condition Indicator	45
CM	Condition Monitoring	1
CPMS	Cyber-Physical Mechatronic System	3
CPS	Cyber-Physical System	3
DA	Data Acquisition	7
DM	Data Manipulation	7
DP	Data Processing	7
DT	Digital Twin	1
EoL	End of Life	1
FVA	Forschungsvereinigung Antriebstechnik	1

HA	Health Assessment	7
HCP	Hertzian Contact Pressure	11
HUMS	Health and Usage Monitoring Systems	7
IAS	Instantaneous Angular Speed	8
IT	Information Technique	1
IoT	Internet of Things	51
LBCM	Load-Based Condition Monitoring	1
LBSD	Load-Based State Diagnostic	9
MARTE	Modeling and Analysis of Real Time Embedded Systems	52
MBSE	Model-Based System Engineering	1
MIMO	Multi Input Multi Output	8
MoL	Middle of Life	1
MR	Magnetoresistive	9
MTTF	Mean Time Till Failure	51
OSI	Open Systems Interconnection	13
PA	Prognostic Assessment	7
PCA	Principle Component Analysis	51
PHM	Prognostics and Health Management	1
PLC	Product Lifecycle	1

pmd	Institute for Product Development and Machine Elements	1
PRM	Predetermined Maintenance	7
PLCM	Product Lifecycle Management	52
REQ-ID	Requirement ID	29
RTES	Real Time and Embedded Systems	52
RUL	Remaining Useful Lifetime	1
SD	State Detection	7
SE	State Estimation	1
SME	Small and Medium-Sized Enterprises	1
SoH	State of Health	7
SYEN	Systems Engineering	15
SysML	Systems Modeling Language	15
TE	Transmission Error	9
UML	Unified Modeling Language	15
VBCM	Vibration-Based Condition Monitoring	1
VBFD	Vibration-Based Failure Detection	8
VBSD	Vibration-Based State Detection	9

1. Introduction

Since the birth of the Digital Twin (DT) idea in 1991 (Moyne et al., 2020) many different definitions were published. One reason for that is the wide applicability of the DT which has lead to extensive research in different fields of proficiency. Another reason is the difference in the definitions' volume: Either completely unspecific or extremley narrow. Therefore, it is crucial to sensefully restrict the context of the thesis to aggregate a clear understanding of the DT. Due to the orientation of the Institute for Product Development and Machine Elements (pmd) a general restriction to drive technology is regarded as appropriate. As stated in the work packages of the assignment, the thesis is based on a Forschungsvereinigung Antriebstechnik (FVA) trend survey (Wilking, 2021) and therefore allows to reasonably narrow the definition further to industrial drive technology. With regards to the implementation example (gearbox test rig) a focus on Middle of Life (MoL) and partly End of Life (EoL) applications allows to categorize the DT on the basis of the Product Lifecycle (PLC).

Due to the complexity of the DT, arising through the engagement of different engineering disciplines, a lucid form of the concept presentation is mandatory. It is for that reason that elements of Model-Based System Engineering (MBSE) are used to express the concept of the DT. This modeling approach has to be accompanied by clearly defined terms which are the basis for an unambiguous development process. As a consequence, the *ISO 13372:2012*, 2012 is used as a guideline.

Through the FVA context the conceptional design of the DT is oriented to the requirements of Small and Medium-Sized Enterprises (SME) situated in the industrial drive technology branch. The focus on SME entails a limited knowledge in the software development area as well as limited financial opportunities for the development of new digital products like DTs. Nevertheless the digitization of the SME' products is essential to maintain competiteveness and to secure future growth. The DT can be regarded as a key element of the digitization process and therefore the FVA aims to support their members via providing guidelines for the development of DT applications. This thesis aims at supporting the guideline identification process via an extensive documentation during the conception and the recording of upcoming questions that are likely to be relevant for the SME.

In order to fulfill as many requirements of the FVA members as possible, the conceptional design of the DT is modularly built. Due to the connection between mechanical elements, electronic components and Information Technique (IT) infrastructure the interface definition is the basis for achieving modularity. To guarantee the interoperability between the DT system elements, adaption nodes which describe the interplay of interfaces and DT system elements are described.

One of the major functionalities that the assignment implies for DTs is the possibility for Condition Monitoring (CM). While aspects of the Prognostics and Health Management (PHM) are part of the mechanical engineering and especially the drive technology branch ever since, the usage of DTs in this context promises new potential. Besides the popular Vibration-Based Condition Monitoring (VBCM) procedures for the State Estimation (SE) of bearings and toothings, new aspects like Load-Based Condition Monitoring (LBCM) for the Remaining Useful Lifetime (RUL) estimation are current issues of research. Both aspects of CM are discussed for bearings and toothings in the context of an exemplarly implementation to a gearbox test rig at the pmd.

2. State of Research

This chapter covers the current state of research, relevant for the allocation of the manifold terms and topics related to the DT. It describes the general DT idea in section 2.1 and provides a short overview on the prognostics and health management approaches referred to in the context of DTs in section 2.2. In section 2.3 and section 2.4 the presented PHM approaches are detailed. The general basics for the enacted development procedure are described in section 2.6 after current modularity approaches are detailed in section 2.5.

2.1. Digital Twin

In order to develop a clear concept structure the DT has to be allocated in the context of the current state of research. Therefore, literature reviews about the DT topic (Juarez et al., 2021; Kritzinger et al., 2018; Negri et al., 2017) aswell as encyclopedic elaborations (R. Stark and Damerau, 2019) were used for a research orientation. The following subsections present relevant elements of the DT, like its' definitions, subsection 2.1.1, essential DT components, subsection 2.1.2, different integration levels, subsection 2.1.3, generic categorization approaches, subsection 2.1.4, and universal classification efforts, subsection 2.1.5. The subsection structure is partly adopted from R. Stark and Damerau, 2019 and Juarez et al., 2021.

Fundamental Idea

The following three major issues of NASA, presented in Grieves and Vickers, 2016, with their engineered products are: Tremendous system costs, low production volume and highly innovative technology. These three aspects are the motivation for the twinning idea and resulted in the DT definition stated in Shafto et al., 2010, 2012. There the DT is defined as "[...] an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. It is ultra-realistic and may consider one or more important and interdependent vehicle systems [...]". This basic idea is the starting point for the following definitions.

2.1.1. Definition

According to Juarez et al., 2021, Negri et al. collected most of the definitions for the DT from 2010 to 2016 in Negri et al., 2017. Juarez et al. concluded that these definitions have in common, that they use "[...]physical, electronic and structural models to simulate the life cycle of the element of interest." Juarez et al., 2021. Further findings in the context of DT definitions of Juaerz et al. are the intelligence integration (Schluse and Rossmann, 2016), the cloud platform execution of DT simulation models (Lee et al., 2013), Cyber-Physical System (CPS) inclusion (Schroeder et al., 2016) and the structural model definition for the work with quantitative data (Majumdar et al., 2013). As the origin for the most accepted definition Juarez et al. identified, in accordance with Negri et al., 2017, Kraft, 2016: “An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by digital thread that uses the best available models, sensor information and input data to mirror and predict activities/ performance over the life of its corresponding physical twin[...]”. This definition’s general character, reflected in the inclusion of the PLC, makes it applicable for this thesis. The mentioned multi-physics, multi-scale and probabilistic simulation refers to the aspects of the in section 2.2 presented CM approaches. The digital thread can be regarded as a synonym for the digital shadow, explained in subsection 2.1.3. Due to the fact that the definition of a generally valid DT description is problematic the following subsections present further description elements for DTs which cannot necessarily be described as “definitions” but help to clear the picture of the current research understanding of the DT.

2.1.2. Components

Juarez et al. identify three main components by the analysis of Grieves, 2015 and Răileanu et al., 2019 in Juarez et al., 2021. These components are the physical world, the digital world and the connection between them. The physical world is understood as the real physical entity that is to be monitored. This can be a process, a technical device or any physical element that is measureable. The digital world comprises the aspects of the virtual world and is represented via data manipulated in any kind of software application. The element that links both worlds can be described as the connector and can be realized via a sensor or the physical model on which the sensing principle is based on. A more detailed description of the components can be found in Y. He et al., 2018.

2.1.3. Integration Level

Kritzinger et al. distinguish in Kritzinger et al., 2018 different elements of DTs categorized by their level of autonomy in information interchange. The elements are the digital model, the digital shadow and, as the most sophisticated element, the DT itself. This categorization can be related to other works like Sjarov et al., 2020; R. Stark et al., 2020; R. Stark et al., 2019 and R. Stark and Halstenberg, 2018, where the digital model is referred to as digital master. The digital model/master comprises all the technical specifications necessary to evaluate the data collected about the unique physical entity in the digital shadow. The separation of both data sets enables the efficient design of different DT variants which comprise both aspects, the digital shadow and the digital model/master. Furthermore, this approach allows the integration of other influencing factors such as manufacturing data or the usage of the DT in prototyping. By the integration of the physical entity in the digital model/master with the digital shadow, the DT can be described as a CPS (Czwick and Anderl, 2020; Czwick et al., 2020; Monostori, 2018) or as a Cyber-Physical Mechatronic System (CPMS) (*VDI/VDE 2206*, 2021).

2.1.4. Categorization Approaches

As stated in the assignment, the work of Wilking in Wilking, 2021 is used as the basis for this thesis. Wilking presents in addition to the general DT structure proposal, see subsection 2.1.5, a generic categorization approach which uses three categories to classify the DT according to its degree of activity autonomy, also presented in Wilking et al., 2021. The categories are: Informational, supporting and autonomous DT. The informational DT serves the purpose of monitoring the physical entity which comprises the data gathering and the transformation in human readable information. Further sophisticated is the supporting DT which is able to suggest system adaptions or other relevant recommendations based on the gathered system information. If the system adaption is not only suggested but directly applied, the DT is categorized as autonomous which represents due to its bidirectional communication capability (sensor - actuator) the most sophisticated DT category. A more detailed explanation of the generic categories can be found in Wilking, 2021.

In Juarez et al., 2021 a subsection called “terms” is used for summarizing further categorization approaches which are commonly used in the context of DTs. These are the digital twin prototype, the digital twin instance and the digital twin aggregate. This classification is based on Răileanu et al., 2019 and Grieves and Vickers, 2016 who explained the differentiation procedure in detail. For this thesis it is sufficient to refer to these categories as detailing categorizations along the PLC.

2.1.5. Universal Classification Efforts

While the mentioned subsections above describe approaches for defining DT elements in detail, some authors published more holistic classification models like the “8-dim model” from R. Stark et al., 2019, the 13 characteristics of DTs according to the review of Jones et al., 2020, and the DT framework of Wilking, 2021. The DT application dimensioning in Wellsandt et al., 2019 is not presented, because the aspects are widely covered in the subsequently depicted approaches.

FVA Framework for Digital Twins

During a FVA trend survey (Wilking, 2021) a DT framework was defined. This framework is portrayed in figure 2.1. As declared in the assignment and previous sections, this framework builds the theoretical basis of this thesis. The generic requirements cover the "Data Transmission" from the "Operational Data" to the DT, the establishment of "Decisionmodels" for the response behavior of the DT and the evaluation of the "Operational Data" in the "Simulationmodel". In order to understand the interplay of the system components a "Systemmodel" is defined which together with the "Framework" describes the FVA framework for DTs.

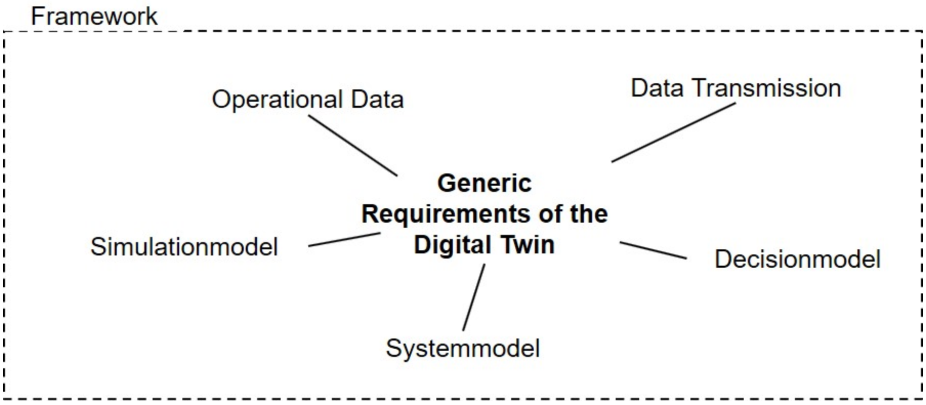
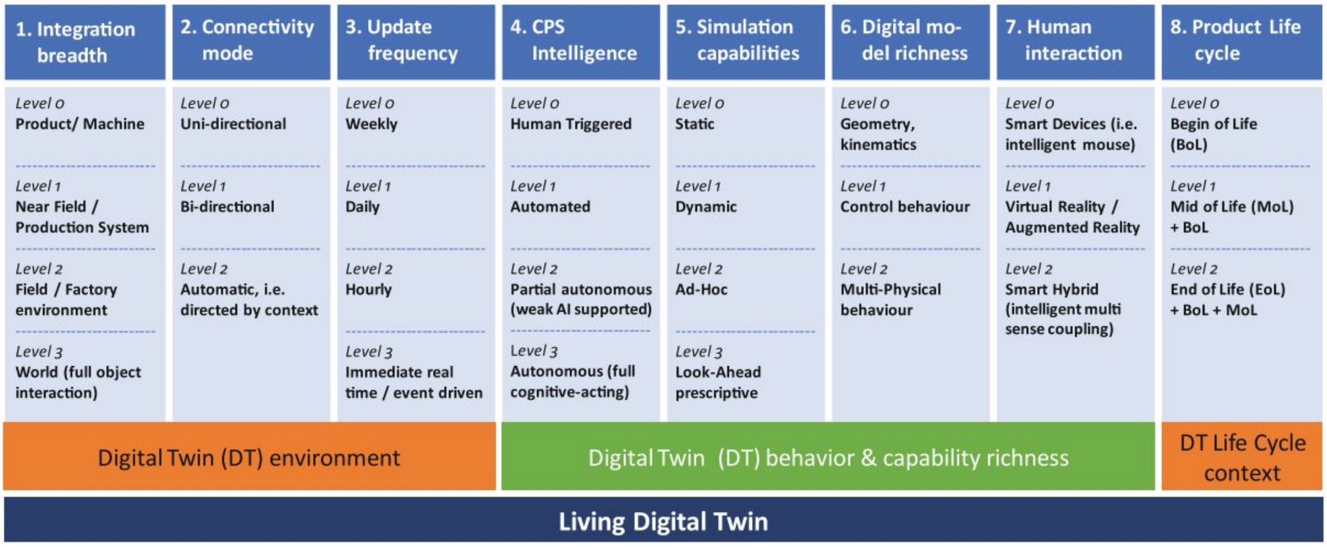


Figure 2.1.: FVA Framework for Digital Twins (Wilking, 2021)

Digital Twin 8-Dimension Model

In R. Stark et al., 2019 the different elements of DTs are categorized in eight main aspects named "dimensions". In R. Stark and Damerau, 2019 the dimensions with their related elaboration are presented, depicted in 2.2.



1. Integration breadth	2. Connectivity mode	3. Update frequency	4. CPS Intelligence	5. Simulation capabilities	6. Digital model richness	7. Human interaction	8. Product Life cycle
Level 0 Product/ Machine	*Level 0* Uni-directional	*Level 0* Weekly	*Level 0* Human Triggered	*Level 0* Static	*Level 0* Geometry, kinematics	*Level 0* Smart Devices (i.e. intelligent mouse)	*Level 0* Begin of Life (BoL)
Level 1 Near Field / Production System	*Level 1* Bi-directional	*Level 1* Daily	*Level 1* Automated	*Level 1* Dynamic	*Level 1* Control behaviour	*Level 1* Virtual Reality / Augmented Reality	*Level 1* Mid of Life (MoL) + BoL
Level 2 Field / Factory environment	*Level 2* Automatic, i.e. directed by context	*Level 2* Hourly	*Level 2* Partial autonomous (weak AI supported)	*Level 2* Ad-Hoc	*Level 2* Multi-Physical behaviour	*Level 2* Smart Hybrid (intelligent multi sense coupling)	*Level 2* End of Life (EoL) + BoL + MoL
Level 3 World (full object interaction)		*Level 3* Immediate real time / event driven	*Level 3* Autonomous (full cognitive-acting)	*Level 3* Look-Ahead prescriptive			
Digital Twin (DT) environment			Digital Twin (DT) behavior & capability richness				DT Life Cycle context
Living Digital Twin							

Figure 2.2.: DT 8-Dimension Model (R. Stark and Damerau, 2019)

13 Characteristics of Digital Twins

On the basis of a systematic literature review Jones et al. isolated 13 characteristics of DTs in Jones et al., 2020. This approach can be regarded as a categorziation approach and is listed in table 2.1.

No.	Characteristic	Description
1	Physical Entity/ Twin	The physical entity/twin that exists in the physical environment
2	Virtual Entity/Twin	The virtual entity/twin that exists in the virtual environment
3	Physical Environment	The environment within which the physical entity/twin exists
4	Virtual Environment	The environment within which the virtual entity/twin exists
5	State	The measured values for all parameters corresponding to the physical/virtual entity/twin and its environment
6	Metrology	The act of measuring the state of the physical/virtual entity/twin
7	Realisation	The act of changing the state of the physical/virtual entity/twin
8	Twinning	The act of synchronising the states of the physical and virtual entity/twin
9	Twinning Rate	The rate at which twinning occurs
10	Physical-to-Virtual Connection/ Twinning	The data connections/process of measuring the state of the physical entity/twin/environment and realising that state in the virtual entity/twin/environment
11	Virtual-to-Physical Connection/ Twinning	The data connections/process of measuring the state of the virtual entity/twin/environment and realising that state in the physical entity/twin/environment
12	Physical Processes	The processes within which the physical entity/twin is engaged, and/or the processes acting with or upon the physical entity/twin
13	Virtual Processes	The processes within which the virtual entity/twin is engaged, and/or the processes acting with or upon the virtual entity/twin

Table 2.1.: DT Characteristics (Jones et al., 2020)

2.2. Prognostics and Health Management

This section aims at the categorization of terms which are often related to the DT in the context of CM. The designation "PHM" is selected according to the elaborations of Zonta et al., 2020 who review the terms for prognostics in relation to Condition-Based Maintenance (CBM), RUL, Predetermined Maintenance (PRM) and State of Health (SoH). The presented categorization approach is dedicated to the context of this thesis and does not satisfy the requirements of generalization. Therefore, the in figure 2.3 presented classification overview is exclusively valid for this thesis. Considering the context, the origins of PHM can be traced back to Health and Usage Monitoring Systems (HUMS), which were established in the service management for helicopter drive systems in the 1990s. On the basis of HUMS different enrichment approaches, for instance Wurzel, 2011, were developed with the goal of establishing a general procedure for monitoring technical systems. The approaches comprise elements of disciplines like “[. . .]sensing technologies, failure physics, machine learning, modern statistics, and reliability engineering [. . .]” (Kim et al., 2017). Including these aspects, PHM can be regarded as the basis for every CM process and therefore also as the basis for every maintenance approach. Todays maintenance strategies can be assigend to two main pillars: Preventive and corrective maintenance. While corrective maintenance can be described as breakdown maintenance, preventive maintenance can be divided in two subpillars: Time-based and condition-based maintenance (Dietrich et al., 2018). The focus of the research is set on CBM because it offers the best relation of prevention and repair cost which was already stated in 1995 in Toms, 1995. According to Jardine et al., 2006, the major elements of CBM are Data Acquisition (DA), Data Processing (DP), diagnostics and prognostics. This categorization can be further detailed with the in *ISO 13374-1:2003*, 2003 defined data assessment blocks. There DP is included in DA, which can be put together with Data Manipulation (DM) and State Detection (SD) to diagnostics. Elements of prognostics can be further categorized by Health Assessment (HA), Prognostic Assessment (PA) and Advisory Generation (AG). Prognostics and diagnostics cannot be regarded as standalone procedures because detailed diagnostics are the basis for every prognostics approach. The following subsections go into more detail with the mentioned elements of PHM.

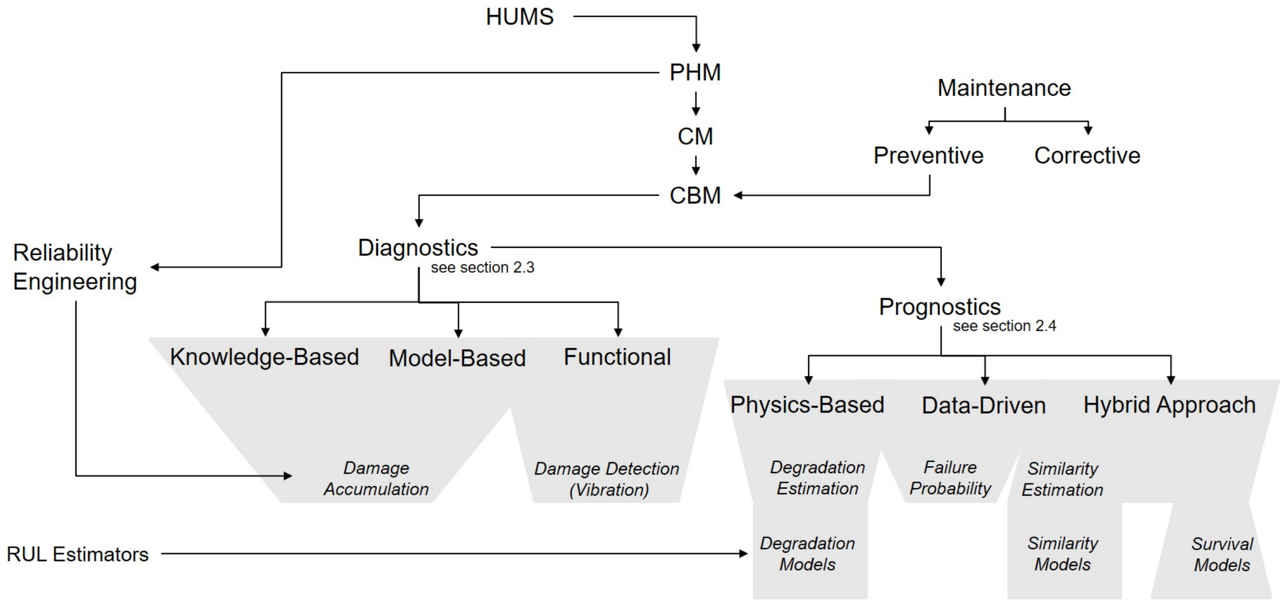


Figure 2.3.: PHM Classification Overview

2.3. Diagnostics

According to *VDI 2888*, 1999 diagnostics can be categorized in knowledge-based, model-based and functional diagnostics, presented in figure 2.4. The direct linkage between a measured symptom and a fault can be established within a rule-based diagnostics procedure. Contrary to the pattern recognition which relies on methods like neural networks or fuzzy logic to detect features of processes that are complexely linked, the rule-based diagnostic is based on empirical knowledge about the relevant system or process. The analysis of failure probabilities and influence on the diagnosed system is comprised in the fault tree procedure. The concrete knowledge about the physical correlation of detected effects enables the modeling of the relation in analytical models. Petri's networks provide analytical models focused on predefined event characteristics (*VDI 2888*, 1999). The subsequent subsections are generally categorized in failure detection, which details the signal analysis, subsection 2.3.1, and the state detection, which presents a hybrid approach, damage accumulation, consisting of rule-based and analytical model approaches, subsection 2.3.2.

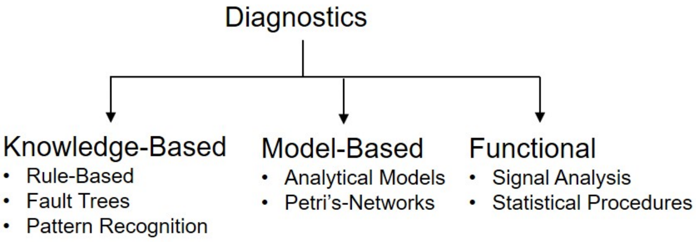


Figure 2.4.: Diagnostics Overview

2.3.1. Failure Detection

The most common method for the failure detection of machines in the industrial drive train domain is the Vibration-Based Failure Detection (VBFD), exemplarily presented in Mohammed et al., 2015. It uses the unique vibration signal characteristics of machines to detect failures and abnormal conditions. There are three types of vibrations: absolute (e.g. housing vibration), relative (e.g. vibration between shaft and housing) and torsional vibrations (e.g. angular velocity fluctuations of a shaft) which are sensed via different sensor concepts. Each concept transforms the measurand into an electrical signal which comprises the effects of the excitation force and the transmission path influence which is characteristic for Multi Input Multi Output (MIMO) constellations. Depending whether the analysis is permanent or intermittent, signal processing techniques, varying in complexity, can be applied. Due to the unique character of the signal, sophisticated predications about the source of the failure can be made (Randall, 2021; Randall and Antoni, 2011). In Roy et al., 2014 the usage of the Instantaneous Angular Speed (IAS) as an analysis signal is described. This approach is applied in this thesis and further elaborated in the subsequent sections. The analysis of the gearbox lubricant, as another common method for failure detection, is not reviewed.

Signal Analysis

As detailed in the work of Li et al., 2016 and Barszcz, 2019 the analysis of the vibration signal can provide detailed information about the failure and state of the gearbox. The general signal processing procedure can be structured in three phases 1. Setting up the sensor signal; 2. Teaching machine characteristic "good" signal; 3. Monitoring signal. The first phase comprises the analysis of best sensor positions (assembly space, signal transmission path), measurement principles (relative, absolute, proximity, velocity, acceleration) and the implementation of data processing techniques. In the second phase the analysis algorithm is trained. Depending on the algorithm specification, different comparison signals need to be recorded and if necessary the machine has to be operated in a reference load cycle. The last phase comprises the actual state supervision. Therefore, two main strategies exist: Permanent and intermittent signal monitoring. Permanent signal monitoring offers the possibility of immediate damage detection, whereas the intermittent signal monitoring allows more sophisticated signal analysis (Randall, 2021; Sharma and Parey, 2016). Further signal analysis methods are the phase demodulation (Transmission Error (TE) detection) (Sweeney and Randall, 1996) and the synchronous averaging (tooth root crack detection)(Ahamed et al., 2014).

2.3.2. State Detection

While the VBFD is predominant in the failure detection, it requires complex algorithms to evaluate the system state further (e.g. Golafshan et al., 2021; Sinha, 2020). The state detection describes the procedure of aggregating detailed information about the system state with or without the presence of a failure. While the SD for the toothing in this thesis is based on the analysis of the IAS signal, in Hu et al., 2016 and Kumar et al., 2020 it is described how a vibration signal can be used for a similar purpose. Additionally, the Load-Based State Diagnostic (LBSD) is detailed, on the basis of elaborations on damage accumulation and bearing dimensioning, for bearings in the subsequent sections.

VBSD of Toothing

The basic information about the Vibration-Based State Detection (VBSD) is presented in subsection 2.3.1. The concrete application to the toothing failure detection comes along with the computational focus on the signal processing, which comprises the transformation of time signals to the frequency range, aswell as filtering of the raw signal. Despite the name "vibration based" the actual measurand is no vibration value, but according to the elaborations of Roy et al., 2014 the IAS. Therefore, the in subsection 4.2.2 presented Magnetoresistive (MR) sensors are mounted to the gearbox. Based on Liang et al., 2019 and Slatter, 2018, the number of counted pulses N_i, the clock signal frequency f_i and the timely resolution $R = \frac{Pulses}{Revolution}$, is calculated to the IAS ($\omega(t)$):

$$\omega(t) = \frac{2\pi \cdot f_i}{R \cdot N_i} \tag{2.1}$$

The signal characteristic is depending on the solid measure which in this gearbox is choosen to be the toothing and a permanent magnet at the end of the output and intermediate shaft. Depending on the type of failure and system state, the signal amplitude values and their sidebands aswell as the amplitude frequency (transformation from time signal to frequency range) can be analyzed and assigned to failure phenomena and current wear states. The establishment of a load based approach (similar to the subsequently presented

LBSD for the bearings) for the toothing is also possible and derived in the appendix E for toothflank pittings and in the appendix F for toothroot failure. The presented realization is based on VBSD because no torque sensor is currently intendend. Furthermore enables the usage of MR sensors a reduction of the signal transmission path which increases the signal to noise ratio and therefore is beneficial for the overall analysis quality (Hausmann et al., 2021).

Damage Accumulation

As in figure 2.5 presented, the procedure of the damage accumulation is based on the measurement of physical processes by sensors. The raw data is transduced and filtered for the aggregation to a stress time function. In order to detract the influence of the stress sequence a counting procedure is applied. The resulting frequency distribution is extrapolated to load spektra which build the basis for the damage accumulation. In alignment with pertinent literature, the linear damage accumulation model according to palmgren-miner original, for the toothing, and palmgren-miner elementary, for the bearings, is applied (Haibach, 2002). According to the elaborations in Köhler et al., 2012, the rainflow counting procedure is regarded as the most appropriate.

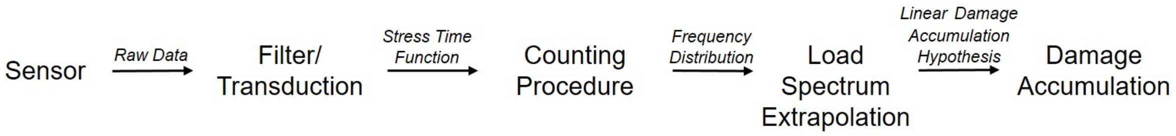


Figure 2.5.: Process Damage Accumulation

LBSD of Bearings

In Schlecht, 2010 the calculated nominal Lifetime L is defined as the number of revolutions in millions or operational hours with constant speed that is reached or exceeded by 90% of a sufficient amount of similar bearings before any degradation signs surface. The nominal lifetime L can be calculated with the dynamical load capacity C, the bearing equivalent load P and the lifetime exponent p, according to Schlecht, 2010, to:

$$L = \left(\frac{C}{P}\right)^p \tag{2.2}$$

In order to relate with the speed n the nominal lifetime can be calculated to:

$$L_{10h} = \left(\frac{C}{P}\right)^p \cdot \frac{10^6}{n \cdot 60} \tag{2.3}$$

The index "10h" relates to the estimated failure propability of 10%, which can be adapted via integrating a factor for considering a different weibull distribution (Bertsche, 2011). The inverse, $\frac{1}{L_{10h}}$, can be interpreted as a momentary damage rate $\delta(t)$. In order to apply the described calculation the acting forces on the bearings need to be measured. On the basis of Martin, 2021; Schirra et al., 2018 and Schirra, 2021 the impedance measurement of roller bearings is used for the measurement of the bearings' equivalent load P. This is enabled via the substitution of the standard bearings with Hertzian Contact Pressure (HCP)-Sense bearings. The measurement principle is explained in subsection 4.2.2. The previously derived momentary damage rate $\delta(t)$ can be integrated over the isolated load spectra to the accumulated damage $D(t)$.

$$D(t) = \int_{\tau=0}^{\tau=t} \delta(t)\, d\tau = \int_{\tau=0}^{\tau=t} \frac{1}{L_{10h}(t)}\, d\tau = \int_{\tau=0}^{\tau=t} \frac{\frac{60min}{h} \cdot n(t)}{10^6} \cdot \left(\frac{P(t)}{C}\right)^p d\tau \tag{2.4}$$

In order to calculate the damage the bearing specifications C and p are essential to know. The equivalent bearing load $P(t)$ as well as the speed $n(t)$ are provided by the sensors and the data preprocessing (DA, DM). For the actual state determination the critical damage D_{lim} has to be defined, either by standard regulations or application experience:

$$\left(\frac{D_{lim} - D(t)}{D_{lim}}\right) \cdot 100 = (State)\% \tag{2.5}$$

The relation of the critical damage to the current, "consumed" damage enables the state detection in form of a relative state estimation.

2.4. Prognostics

Kim et al., 2017 define three different approaches for prognostics. These are: Physics-based, data-driven and hybrid approaches. The physics-based approach uses degradation data and combines it with the current usage conditions. Based on a physical model this approach delivers the highest prediction accuracy and the most information about the monitored process. Data-driven approaches can be subcategorized in Artificial Intelligence (AI) approaches and statistical approaches which are elaborated in Si et al., 2017. In this case the measurement data can be regarded as training data for the related AI approach or the applied statistical method. Via mathematical functions the data-driven prediction outcome is translated into RUL estimations. The accuracy of the prediction can be directly related to the used training data. It can be improved via the backstream of recorded operational data sets which in this thesis is described as operational data iteration. The mentioned hybrid approaches use aspects from both categories and can therefore be adapted according to the given situation (Goebel, 2017; Kim et al., 2017). For the concrete gearbox components the reviews Kumar et al., 2020 and B. He et al., 2021 present an overview of the currently used prognostics (and diagnostics) of gear wheel defects and the review of Xia et al., 2020 presents the current state of RUL prognostics for bearings. The elaborations are comprised in the procedures presented in subsection 2.4.1 and 2.4.2.

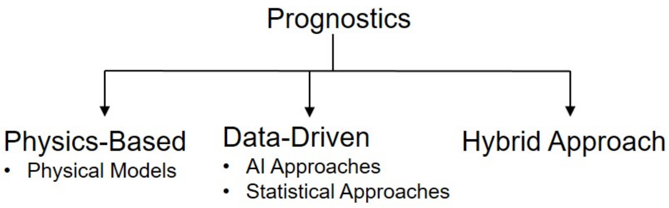


Figure 2.6.: Prognostics Overview

According to the overview given in figure 2.3 the most common realizations of prognostics algorithms are the degradation, subsection 2.4.1, and similarity modeling, subsection 2.4.2. The following descriptions are based on Goebel, 2017, and the RUL estimators from the MathWorks help center (The MathWorks, Inc., 2022a, 2022b).

2.4.1. Degradation Estimation

The CI in the context of the degradation estimation can be regarded as a consumption variable which indicates via the definition of a threshold value the maximum system reserve consumption. The projection of the CI on the operational time enables the aggregation of a degradation progress extrapolation and therefore the prognostic of the estimated system failure.

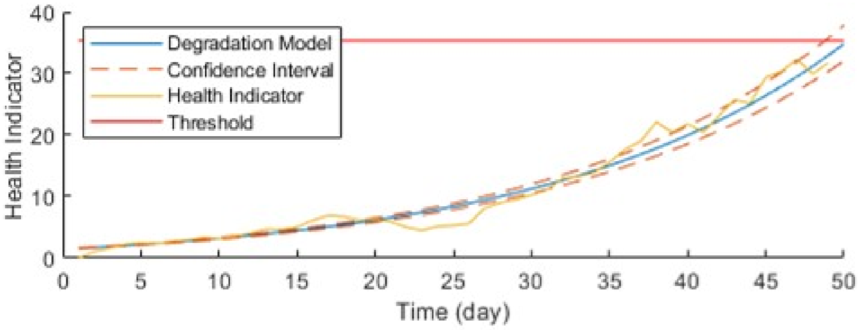


Figure 2.7.: Degradation Estimation (The MathWorks, Inc., 2022a)

The from The MathWorks, Inc., 2022a adopted graph, figure 2.7, presents a "Health Indicator" which describes the mentioned CI variable. Furthermore, the graph indicates besides the blue behavior extrapolation and the red threshold value a confidence interval which indicates the uncertainty of the extrapolation computation. The applicability of this prognostics method depends on the possibility of the CI measurement and the knowledge about the degradation behavior.

2.4.2. Similarity Estimation

This approach relies on data sets aggregated by the analysis of similar systems under similar operational conditions. Therefore, the CI is measured and projected on the operational time or other process relevant lifetime variables like revolutions or load cycles. The quality of the behavior estimation depends on the amount of available data and the similarity degree of the analyzed process. In figure 2.8 an example graph for the similarity estimation adopted from The MathWorks, Inc., 2022b is depicted.

The depicted red line presents the current CI, designated as "Amplitude", and the historical behavior of similar systems in blue lines. The RUL estimation quality can be best expressed via a probability distribution.

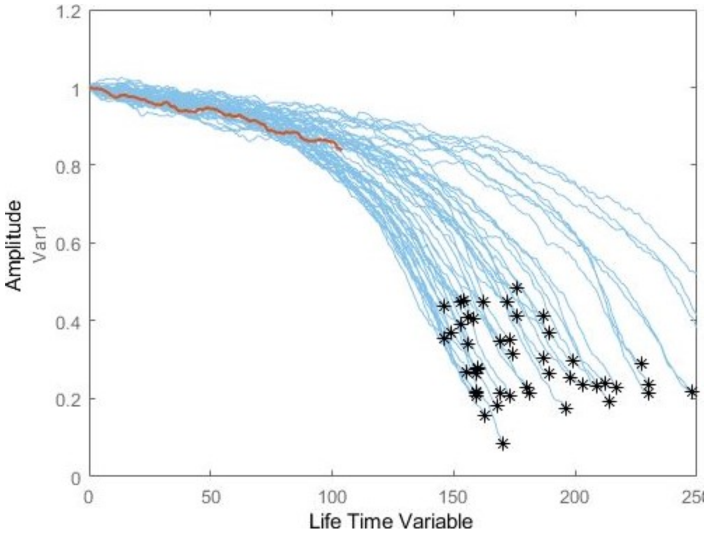


Figure 2.8.: Similarity Estimation (The MathWorks, Inc., 2022b)

2.5. Modularity

The aspired concept architecture objective of modularity is further detailed and motivated in Bi et al., 2002 where it is described that the actual goal of the modular design approach is the achievement of system adaptability. Bi et al. identify two different design approaches to attain adaptability: The first one is characterized as a flexible system which allows the adjustment of system parameters and settings within a defined threshold value. This approach is referred to as "configuration" in *ISO 10007:2017*, 2017 and is exemplarily realized for virtual twins in the context of product development in Abramovici et al., 2018. The second approach intends the creation of modular systems via the design of interchangeable, predefined modules. The understanding of modularity in terms of interchangeable modules is the most common one, also represented in Brancovici and Müller-Schloer, 2007; Mämpel, 2010 and Francalanza et al., 2018. As clearly depicted in Mämpel, 2010 the interchangeability is based on compatible module connections which are described by interfaces. A common approach to maintain interoperability is the definition of interface modules. The description of interfaces in this thesis is based on the assignment to the Open Systems Interconnection (OSI)-layers.

OSI-Layer Reference Model

The OSI-layer reference model is standardized in *ISO/IEC 7498-1:1994*, 1994 and initially created for "[...]providing a common basis for the coordination of standards development for the purpose of systems interconnection, while allowing existing standards to be placed within the overall [reference model][...]" *ISO/IEC 7498-1:1994*, 1994. The related standards (protocols, wire interfaces) are technical realizations which enable the communication among different systems. In table 2.2 the OSI-layers are listed and described on the basis of Luntovskyy and Gütter, 2020 and Meroth and Sora, 2018. Additionally, exemplary protocol and hardware realizations are given.

No.	Designation	PDU	Description	Protocol	Hardware
7	Application Layer	Data	Highlevel application programming interfaces	HTTP	Proxy-Server
6	Presentation Layer	Data	Translating (e.g. encryption, compression) data between networking service and application	MQTT	Proxy-Server
5	Session Layer	Data	Managing communication sessions	HTTPS	Proxy-Server
4	Transport Layer	Segments	Transmission of data segments between network nodes	TCP	Proxy-Server
3	Network Layer	Packets	Addressing, routing and traffic controlling in node network	IP	Router
2	Data Link	Frames	Transmission of data frames between two directly, physically linked nodes	IEEE 802.3	Bridge
1	Physical Layer	Bits	Transmission and reception of unstructured raw data bits over physical medium	ARCNET	Patch Cable

Table 2.2.: OSI-Layer Reference Model (*ISO/IEC 7498-1:1994*, 1994)

2.6. Systems Engineering

Due to the high complexity of the DT concept, resulting from the interdisciplinary development approach, a well guided and defined procedure is mandatory. Following the interdisciplinary concept, a combination of different proven development methods is expedient. While mechanical engineers are well acquainted with the standard V-Model (Bröhl, 1995) and more recently with the V-Model for CPMS (*VDI/VDE 2206*, 2021), software developers complement the development approach by modeling the relationships to break down the complexity of the development process. Aspects of both proficiencies are combined in Systems Engineering (SYEN) which covers with MBSE a method inherent engineering discipline "[...] [that] formalize[s] application of modeling to support system requirements, design analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [...]" (INCOSE, 2007). The communication tool of MBSE is a modeling language named Systems Modeling Language (SysML) which complements the software focused modeling language Unified Modeling Language (UML) with aspects like requirements engineering and system context modeling. Despite the concept verification on the basis of the first order requirements the concept development process can be located on the left branch of the V-Model for CPMS, portrayed in figure 2.9, in the context of the overall DT development. The concretely applied procedural basis is defined by the SYSMOD procedure which is inspired by the work on structured analysis by Tom DeMarco (DeMarco, 1979, 2002). It offers besides a well documented procedure explanation an extensive support via a constantly updated blog (Weilkiens, 2022). In subsection 2.6.2 the original SYSMOD procedure is presented.

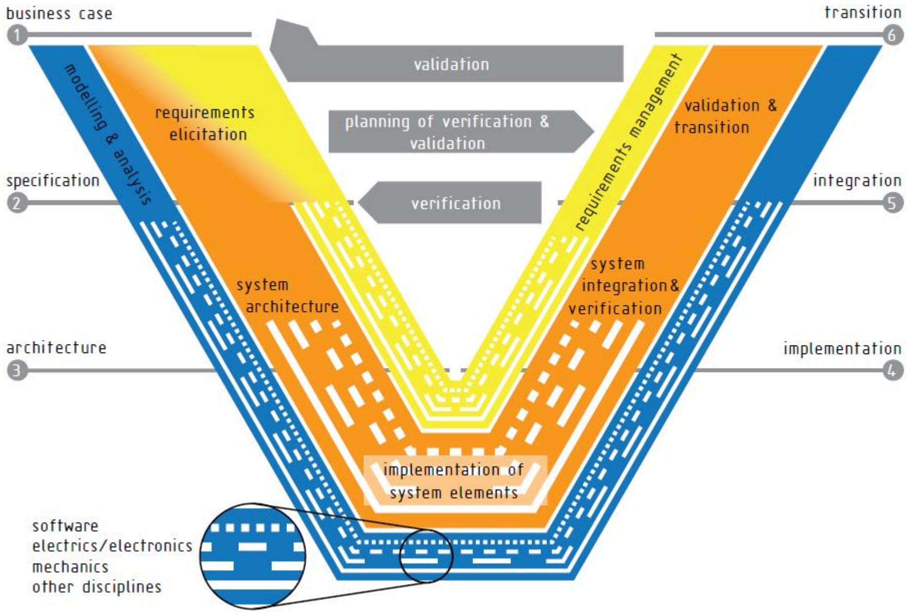


Figure 2.9.: V-Model for CPMS (*VDI/VDE 2206*, 2021)

2.6.1. SysML Modeling

This section presents the modeling features of SysML which are relevant for the comprehension of the created SysML diagrams in this thesis. The descriptions are based on the elaborations of Holt, 2008, and Rupp et al., 2012 for the relation to UML.

Requirements Diagram

In contrast to the collection of requirements in form of lists, the requirements diagram allows a lucid and transparent communication of the relation between the requirements and other system elements. Therefore, the requirements are modeled as diagram elements and related to each other and other system elements, included as blocks (Holt, 2008). In figure 2.10 an exemplarily created requirements diagram is portrayed.

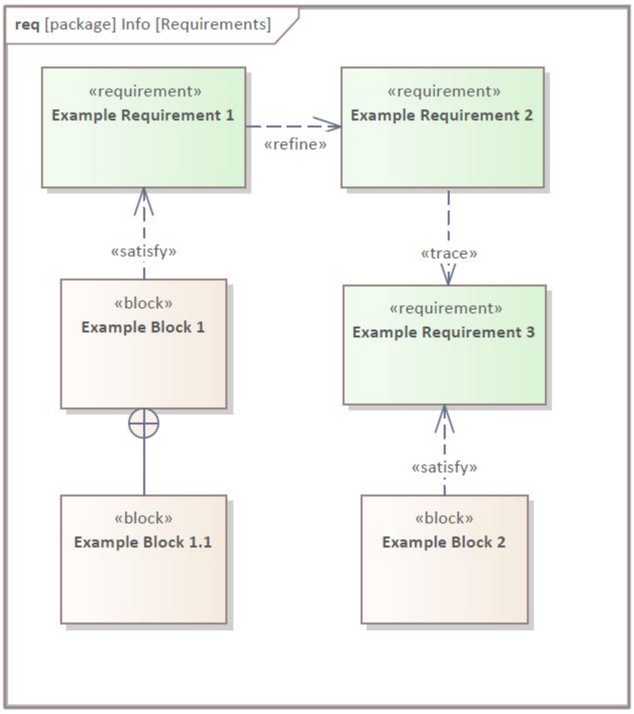


Figure 2.10.: Example Requirements Diagram

The "Example Requirement 1" is fullfilled by the "Example Block 1", which contains the "Example Block 1.1". The "Example Requirement 2" is refined by the "Example Requirement 1" and can be traced to the "Example Requirement 3", which is satisfied by the "Example Block 2". There are further relations definable according to the SysML syntax which are not presented because they are not necessary for the comprehension of the diagrams included in this thesis.

Blockdefinition Diagram

For the representation of static system elements, blocks are used. These comprise certain properties and refer to other system elements via associations. The blockdiagrams originate from the UML classdiagrams in which the blocks are referred to as classes (Rupp et al., 2012). Additionally to the blocks, actors as the representation for humans are included. In figure 2.11 an exemplary blockdefinition diagram is presented.

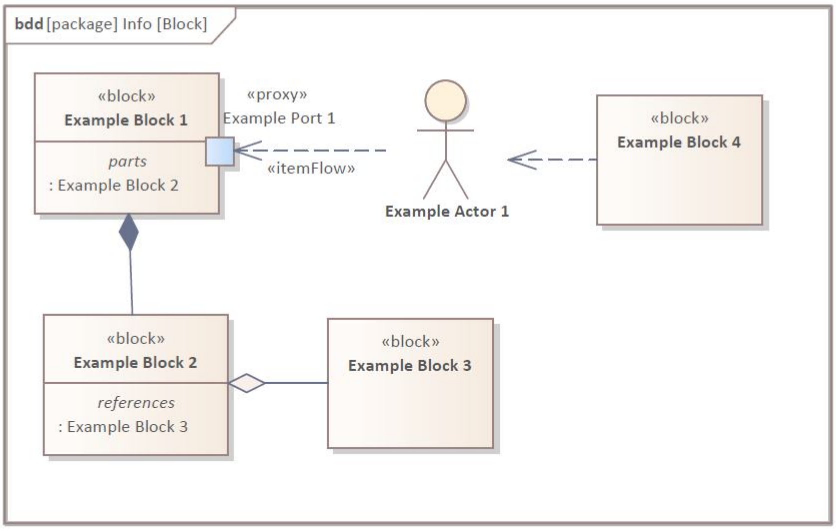


Figure 2.11.: Example Blockdefinition Diagram

The "Example Block 1" is associated to the "Example Block 2" with a "part" association expressed via a filled hash. The part associtaion implies that the "Example Block 2" cannot exist without the "Example Block 1". The "Example Block 3" is related to the "Example Block 2" via a "shared" association, presented via a blank hash. The shared association indicates that the exemplary blocks 2 and 3 are using shared resources but can exist independently from each other. The "Example Actor 1", represented by a stick man, is associated to the "Example Block 1" via the "item flow" connection which allows the object transport over the "Example Port 1". The "Example Block 4" is dependent on the exemplary actor 1, indicated by the association represented by a dashed arrow. Other SysML syntax conform associations exist but are not presented because they are not necessary for the understanding of the SysML diagrams comprised in this thesis.

Internal Blockdiagram

As the diagram frame of figure 2.11 indicates, the diagram itself can be set in the context of the aimed communication goal. While the blockdefinition diagram describes the static elements of the portrayed system, the internal blockdiagram defines the role of the system elements (blocks or actors) in the context of a superordinate system. The associations between the system elements are the same as for the blockdefinition diagram. The superordinate system is defined in the diagram frame. Depending on the modeling package structure the diagram designation can be the same as the superordinate element name (data export strategy). The referred terms are portrayed in figure 2.12.

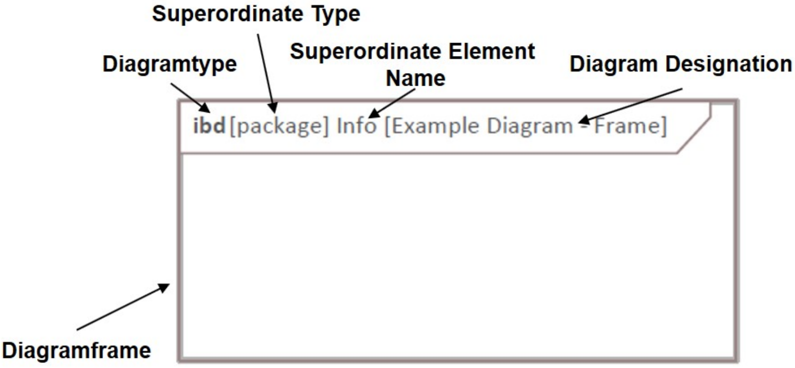


Figure 2.12.: Example Diagram Frame

Sequence Diagram

For the modeling of interactions with a defined order, sequence diagrams, also known in the UML (Rupp et al., 2012), are used in this thesis. The system elements are represented via the in figure 2.13 presented rectangular or stick man elements which are connected to a dashed lifeline. The sequentially arranged messages are expressed via connections between the lifelines. Self-calling messages are described as "Recursion" and refer to the same lifeline they originate from.

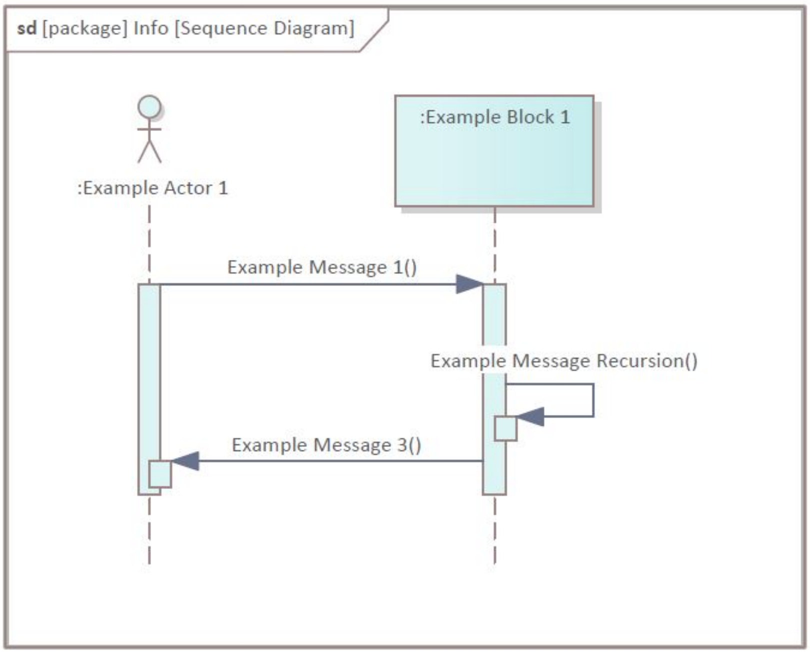


Figure 2.13.: Example Sequence Diagram

The messages are bound to objects which are transferred between the system elements. These objects are indicated by rectangular beams/ squares on the lifelines.

Activity Diagram

If the sequence of the interactions is not defined or necessary to communicate, an activity diagram is preferably used for the modeling of the interaction. It has a defined starting point and elements which are described as "Actions". The interaction between the elements can either comprise objects which are transfered via an "Itemflow", or include control information which is described via a "Controlflow". The object transfer requires the implementation of "Action Pins", connected to the actions. The control flow can be splitted up or joined. Activity diagrams can be linked via calling operations expressed via a fork in the action element, see "Example Action Call". The activity ends with a endpoint. In figure 2.14 an examplary activity diagram, with the mentioned elements is portrayed.

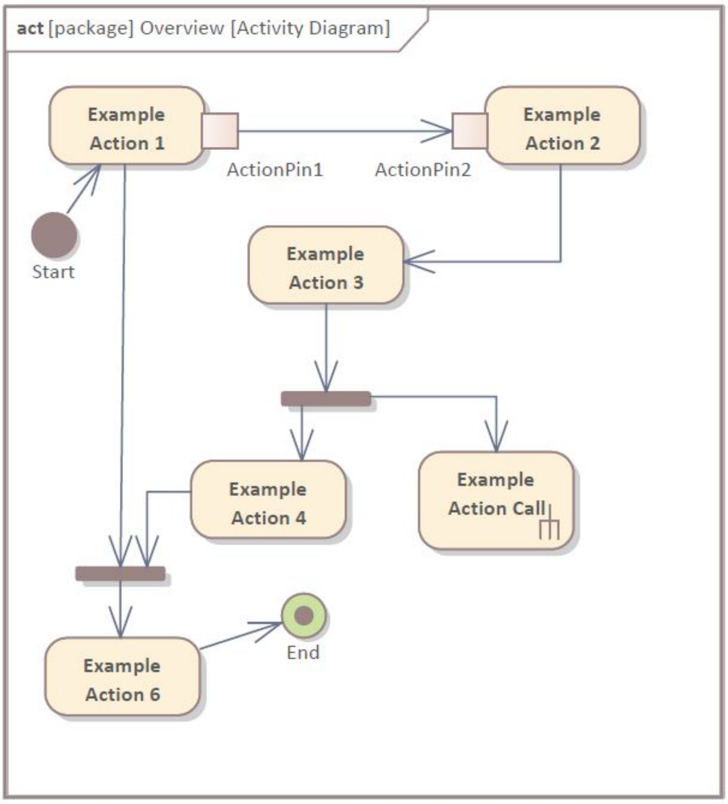


Figure 2.14.: Example Activity Diagram

Port and Interface Modeling

In the generated SysML models, interfaces are indicated by ports, see subsection 3.5.3. According to Weilkiens et al., 2015 there are two major ports used for modeling of SysML diagrams: Proxy ports and full ports. Full ports represent ports which can be defined as independent parts of the system. They have their own characteristics and establish the linkage between the system elements by their unique technical properties. On the other hand, proxy ports describe the necessary presence of a system element's behavior for establishing a communication connection. The proxy port is not part of the item list of the system. The conceptional description and modeling in this thesis relies on the proxy port definition, which is complemented by the OSI categorization via comments.

2.6.2. SYSMOD Procedure Overview

The SYSMOD procedure was developed by Tim Weilkiens and describes a systematic procedure for modeling the requirements and the system architecture of complex systems. It is dedicated to development projects located in the SYEN branch and therefore suitable for trans-technological designs. The integration of the modeling language SysML enables a transparent documentation of the individual development steps. In figure 2.15 an overview of the SYSMOD procedure control flow is depicted. The following subsections go into detail with each step, whereby the paragraphs can be understood as short summaries of the descriptions in Weilkiens et al., 2015 and Weilkiens, 2014.

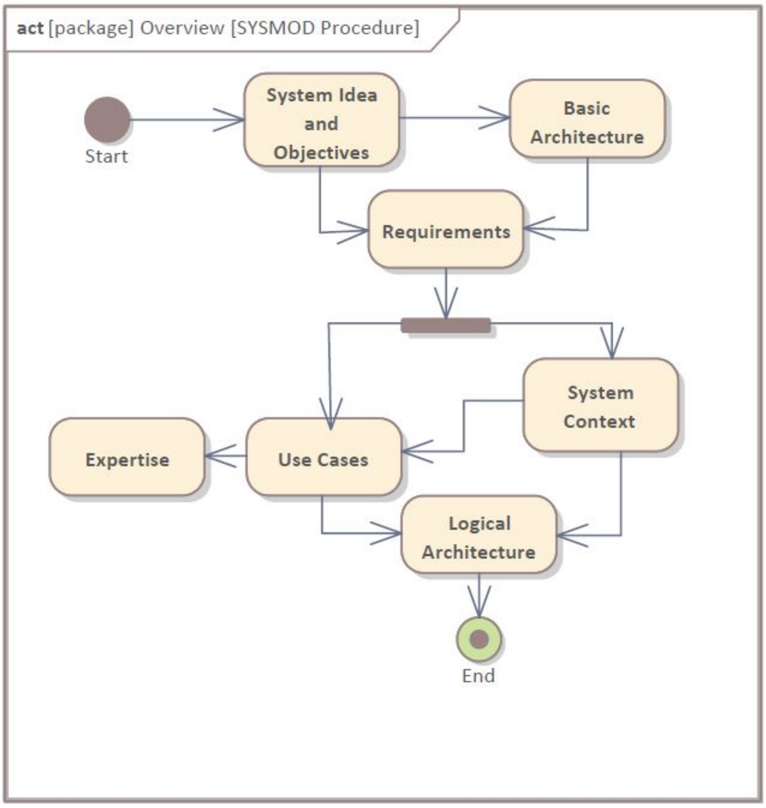


Figure 2.15.: Overview Control Flow SYSMOD Procedure

System Idea and Objectives Description

The procedure starts with the clarification of the system idea and the formulation of the system objectives in order to bring every participant of the development project on the same state of knowledge. The information is collected via brainstorming or workshops with the relevant project participants. In order to support the communication process the ideas and objectives can be organized in a requirements diagram, figure 2.10. This step is the basis for the following steps and in particular the input to the second step: The determination of the basic architecture.

Determination of the Basic Architecture

The basic architecture describes the predefined system architecture and possibly includes technical solutions, degree of innovation and other, to the beginning of the development known, technical restrictions. Moreover that, the basic architecture dictates the abstraction level of the identified requirements.

Identification of the Requirements

In order to compose an exhaustive as possible requirements list, the stakeholders of the system need to be investigated. Therefore, the system idea and objectives togehter with the basic architecture is analyzed and evaluated according to the aimed usage. The analysis of possible impairements through the usage of the system, the failure of the system or the recycling of the system is part of the stakeholder identification process. Subsequent to the stakeholder identification an interview, or alternatively a brainstorming, about their requirements concern can take place. The collected requirements can be organized in a requirements diagram or a requirements list.

System Context Modeling

For making sure that the system has no end in itself, the system context is modeled. Therefore, three steps are necessary. First, the protagonists need to be identified. In contrast to the stakeholder, the protagonists are directly interacting with the system. In the modeling process they represent a certain role in the context of the system functionalities which does not necessarily apply to the stakeholder. Second, interaction points between the protagonists and the system need to be defined. This can be seen as the first step towards an interface description, which is detailed in a later development phase. The third step comprises the description of the objects which are transmitted via the previously described interaction points.

Use Case Identification and Modeling

The use case description comprises, besides the use case identification, five steps. The first step is the technology neutral description of the use cases by so called "essences". Use cases are described by three to eight essences which do not comprise technical details or concrete realization suggestions and therefore allow the technology neutral, functional description of the use cases. As a second step, complex use case sequences are composed to system processes which allows an effective development procedure because functionally close use cases can be developed as one system process. The third step condenses the use case compilation by the elimination of redundant use cases. The fourth step deals with the modeling of the essential use cases and can comprise the usage of SysML use case diagrams. The diagrams clearly depict the use cases and therefore allow a transparent communication. The last step is a refinement of the object description from the system context modeling. By the detailed description of transmitted objects the foundation for an automized consistency check is laid.

Clarification of Expertise

As the system takes shape and more details enter the model a clear terminology is mandatory to avoid ambiguities about the current development progress. Therefore, important terms, described objects, and other relevant expertise is clarified by either using a diagram or a list.

Modeling of Logical Architecture

The logical architecture describes the technical concepts and principles of the system. It is modeled by executing four steps which are built on top of each other. The first step copes with the detailed analysis and modeling of the interaction between system and protagonists. It focuses on the concrete interaction points and therefore lays the foundation for the second step: The interface derivation. Interfaces need to be sophistically described because they build the basis for the interactions of the system. Therefore, so called "ports" are defined. Through the classification of ports the objectflow capability is described and the compatibility of the declared interactions is sufficiently ensured. The third step comprises the concretization of the already implicitly presumed system structure by defining system building blocks which are related to each other by the connection of formerly defined ports. This step is strongly dependent on the description capabilities of the SysML block diagrams. The structuring step is followed by the state modeling which represents the last element of the logical architecture description. In this step the behavior and the exchanged objects of the system building blocks are modeled via SysML state machines or sequence diagrams. The modeling of the logical architecture represents the last relevant concept development step of the SYSMOD procedure.

3. Procedure

This chapter is dedicated to the presentation of the enacted development procedure. It covers the outcome of the pursued development steps which are aligned to the in subsection 2.6.2 described SYSMOD procedure.

3.1. Procedure Overview

The concretely enacted development procedure is presented in the activity diagram portrayed in figure 3.1 and covers the SYSMOD elements as well as the aggregated objects, indicated by blue squares. The missing start and endpoint of the activity diagram expresses the major difference to the SYSMOD procedure: Iterations. Due to the conceptual character of the DT development not all of the information that is needed for the aggregation of the logical architecture can be gathered linearly. Furthermore, the design approaches of intermediate development steps are based on multiple restrictions of previous development steps that in turn are influenced by subsequent development steps which potentially revoke earlier findings. Therefore, no defined starting point of the procedure is indicated, which enables a goal oriented approach.

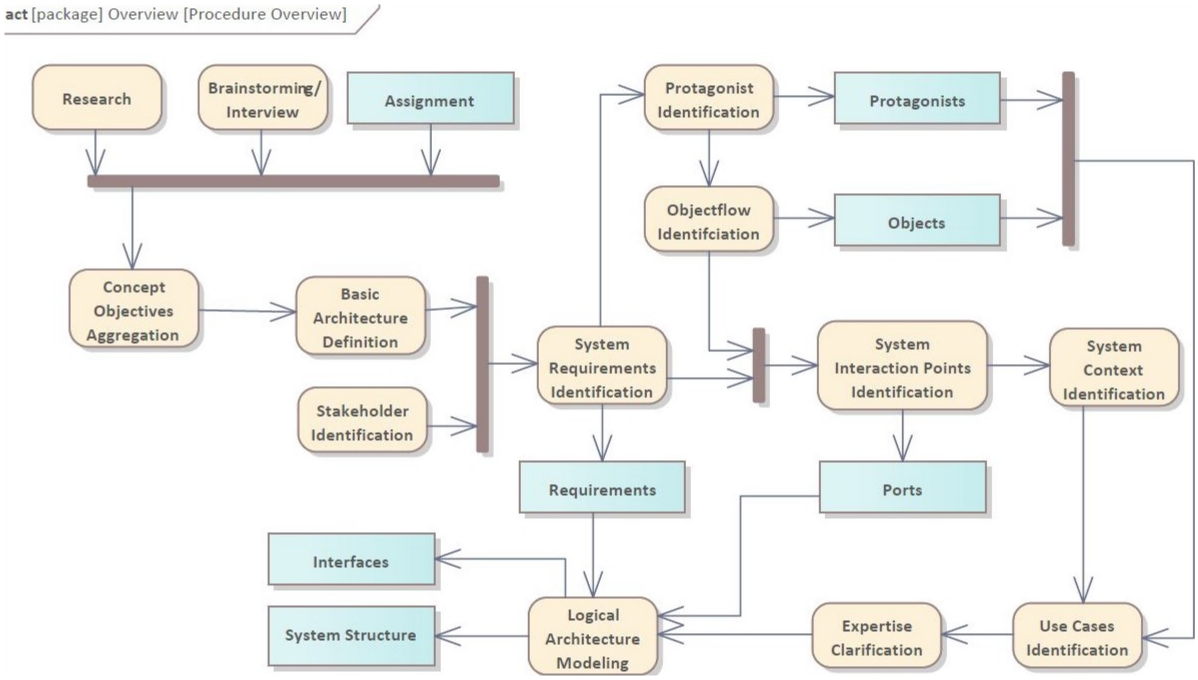


Figure 3.1.: Procedure Overview

3.2. Concept Objectives

This section provides, in addition to chapter 1, an overview of the general concept objectives. The in table 3.1 listed objectives are aggregated on the basis of the assignment, the current state of research and general brainstorming on the DT concept. They build the starting point of the development procedure.

Objective	Description
1	Define a system concept architecture for the data processing of all acquired data related to the DT idea
2	Accompany the derivation process with the formulation of design questions based on SME concerns and record the decision-making process
3	Provide clear interaction definitions and interface elaborations for the system element interplay in order to achieve a modular concept architecture
4	Present the system concept architecture via lucid SysML diagrams
5	Strive for a general DT approach in the context of industrial drive technology

Table 3.1.: Concept Objectives

3.3. Basic Architecture

The definition of a basic architecture in the context of this concept development is to be aggregated with caution because any restrictions to the concept applicability could conflict with the generalization claim, mentioned in table 3.1. For the aggregation, the predefined system objectives in table 3.1, as well as the literature interpretation of DTs, presented in 2.1, and an interview with Fabian Wilking of the KTmfk from the Friedrich-Alexander-University of Erlangen-Nuremberg (Zoom, 10/01/2021) were taken into consideration. As a result, the in figure 3.2 visualized basic architecture was established. It builds the starting point of the actual concept derivation and helps to categorize the detailed findings of the following chapters in a broader context. Therefore, it can also be regarded as a top level view of the DT concept structure.

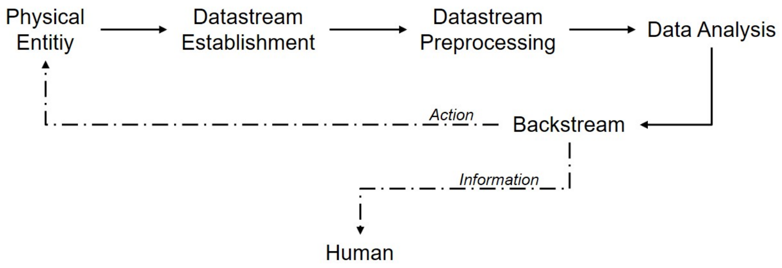


Figure 3.2.: Basic architecture/ Top Level View of the DT Concept Structure

The first block of the DT concept is named "Physical Entity" and represents the element which needs to be monitored by the subsequent DT blocks. In the context of this thesis the physical entity is a drivetrain component or drivetrain assembly. The second block is named "Datastream Establishment" and describes the process of gathering data about the physical entity. It includes the procedure from vital component determination over sensor selection to signal calibration. Bevor the measured data can be analyzed in the "Data Analysis" block it needs to be filtered and potentially smoothed. This happens in the "Datastream Preprocessing" block. The last block, "Backstream", comprises the interface between the technical and software applications itself, in order to directly intervene in the physical process, or inform relevant humans who take up contact with the DT. Additionally, this block includes decision making models for deciding which action needs to be taken based on the outcome of the "Data Analysis" block.

3.4. System Requirements

The most important step of the development procedure is the recording of the system requirements. For a clear expression of the required system functionalities a quantitative formulation should be preferred over a qualitative formulation (Kirchner, 2020). In the context of this thesis the requirements were formulated as quantitative as possible but was due to the conceptional character not completely feasible. The standard approach of collecting requirements in a list also proved to be beneficial in this thesis. The applied changes during the revision of the requirements after a development step are tracked via versioning of the requirements list. In order to trace back design decisions in later development phases the requirements are also represented in SysML. The linkage of the requirements with the relevant element in a SysML diagram enables a quick retrace of the origin of the design element. This facilitates the verification of the concept and increases the informative character of each SysML diagram. In subsection 3.4.1 the identified stakeholder are presented. The stakeholder are together with the basic architecture and the system objectives, aswell as pertinent literature (Carvalho and da Silva, 2021; Durão et al., 2018), the source for the requirements. The section closes with an overview of the first order requirements in subsection 3.4.2, while the complete list is available in the appendix A.

3.4.1. Stakeholder Identification

Stakeholder are the main source of the system requirements and can be a person or a system. The identification process is enacted iteratively and is realized in conjunction with the system context and the use case identification in section 3.5 and section 3.6. The declaration of a system or a person as a stakeholder is depending on the point of view. Therefore, stakeholder can also be regarded as protagonists as long as the description of the system interaction is portrayed and not the requirements determination, see subsection 3.5.1. The identified stakeholder are presented in table 3.2.

Stakeholder	Description
Product Owner	Realization of the DT solution and provision of the IT infrastructure with customer support; Not necessarily the developer of the physical entity
User	Utilisation of the DT service in their daily affairs, processes and businesses; Usually characterized as the customer of the product owner by beeing the owner/user of the physical entity
FVA	Association for drive technology; Represents the interests of the drive technology branch and in particular of related SMEs
Society	Comprises the DT surrounding and covers interests of nontechnical character

Table 3.2.: Stakeholder

3.4.2. Requirements Overview

As indicated in section 3.4 the identification of requirements is an iterative process. With each iteration a refinement of the requirements, originating from the first order requirements, derived from the initial stakeholder identification, takes place. In table 3.3 the first order requirements are portrayed with reference to the related stakeholder. This overview is the starting point of the requirements aggregation and refinement process which is characterized by qualitative formulations of the requirements. In the appendix A the latest version of the requirements list is available. There the requirements are formulated as quantitative as possible in the context of a conceptional development.

Number	Designation	Description	Stakeholder
1	Measurement	Record the operational data of the gearbox components	Product Owner/ User
2	Status	Identify the status of the gearbox components	User
3	Current Health	Analyze the current health of the gearbox components	User
4	Future Health	Determine future health states and RUL predictions for the gearbox components	User
5	End of Life	Enable EoL usage projection for the gearbox recycling	Society
6	Maintenance	Provide actionable information regarding maintenance	User/ FVA
7	System Adaption	Establish a decision algorithm for direct gearbox operation intervention	User/ FVA
8	Data Structure	Provide a save data and IT infrastructure for the interaction with different systems/ users	All stakeholder
9	Modularity	Enable a modular system architecture for maintaining adaptability of the system	All stakeholder

Table 3.3.: First Order Requirements

3.5. System Context Identification

This section presents the system context of the DT. This delimitation is crucial for the understanding of the interaction of the DT and its environment. The system context comprises the protagonists identification in subsection 3.5.1, the object examination between the DT, its' protagonists and other involved systems, subsection 3.5.2, and the system interaction point identification, subsection 3.5.3.

3.5.1. Protagonists Identification

The isolated protagonists have to be understood as elements of the system context which require certain system functionalities expressed by their interaction with the DT. Therefore, a protagonist is not necessarily a human beeing. Also other technical systems can be defined as protagonists in the context of this conceptionalization procedure. In table 3.4 the identified protagonists are listed.

Protagonist	**Description**
Service Worker	Human employee who is responsible for the maintenance of the physical entity. Involved in all physical maintenance processes.
Process Manager	Monitors and optimizes the value creating process in which the physical entity is included.
Designer	Part of the development process of the physical entity. Data provision of the DT is mainly used for the verification of design adaption concepts.
System Engineer	Focused on the merger of physical entity and DT. Engaged with communication and IT infrastructure.
System Administrator	Counterpart of the process manager. Therefore, in the first line of troubleshooting during the operation of the DT. Monitors all functional administration processes of the DT.
Retail User	Special type of customer. Represents the role of individuals who interact with the DT without a commercial background.
Sensor	Prerequisite for the twinning process by providing data about the physical entity. First element of the communication chain.
Researcher	Interested in the DT as a place of data concentration. Interested in the DT system and the physical entity. Data evaluation exceeds standard customer requirements.

Table 3.4.: Protagonists

3.5.2. Objectflow

For a clear elaboration of the interaction between the protagonists and the system, the exchanged objects need to be examined. Therefore, the communication and the service request of each protagonist is analyzed and the related object exchange is described. In table 3.5, the objects with their corresponding datatype are listed. The "General Protagonist" comprises objects which are exchanged by all other protagonists mentionend in subsection 3.5.1. The complete list of exchanged objects, complemented with aspects of subsequent sections, is available in the appendix B.

Protagonist	Object	Datatype	Description
General Protagonist	Query	String	Active data request
	Control Value	Boolean	Signal to enable data presentation
	System Data	Double	Measured data (filtered) from the component condition sensors
	Operational Data	Double	Measuring data (filtered) from sensors or actuators
	Time	Double	Data time stamping
Retail User	GUI sorted Data	Double/ String	Sorted data sets according to GUI
Designer/ System Engineer/ Researcher	Sorted System Data	Double	Sorted data for categorized retrievement
Service Worker	Component State	Double/ String	Current component state information
	Comparison Parameters	Double/ String	Standard system/ component parameters
	Itemlist	String	Maintenance/ replacement itemlist
Process Manager	Critical Component	String	Identified critical component
	Current System State	Double/ String	System state information
	Component Lifespan	Double	RUL of a component
	Critical State	Boolean/ String	Critical component/ system state
Sensors	Measurands	Boolean	Sensor signal
	Measurement Impulse	Double/ Boolean	Measurement initiation signal

Table 3.5.: Objects

3.5.3. System Interaction Points

The interaction points build the first element of the system architecture shaping. It is built on top of the description of the exchanged objects in subsection 3.5.2. By grouping similar objects the basic system communication elements can be identified and characterized as ports. The description of ports allows the establishment of a first overview of the system elements interplay. By further describing the ports in section 4.1 the port description is culminated into the interface definition. The ports are expressed in the SysML diagrams as squares on the diagram and block frame. In figure 4.10 an exemplary SysML blockdiagram, comprising the addressed ports is portrayed. The presented block, "Data Acquisition", is established in detail in the subsequent section 4.1. The focus in this subsection is set on the communication between the system elements which is portrayed by the rudimentary description of ports between the connection lines of the block elements comprised in the "Data Acquisition" block. It is displayed how the port definition fascilitates the understanding of the objectflow and enables a visualization of the relevant input/ output values.

3.6. Use Case Identification

The use cases are aggregated by the analysis of the interactions between the system and the protagonists, which is supported by the system context elaboration presented in section 3.5. The justification of the use case categorization is provided by the refinement of at least one requirement by each use case. In order to gather further information on the interaction, each use case is described by up to 6 essential steps, described in subsection 3.6.1. These essential steps enable the functionally overarching comparison of the use cases and their required system properties. The composition of functionally similar use cases to system processes enables an effective concretization and development process, presented in subsection 3.6.2. This procedure guarantees the conceptional orientation towards a service providing system. In table 3.6 the use cases with their related protagonists are listed. The refined requirements can be tracked via the Requirement ID (REQ-ID) and the latest version of the requirements list, available in the appendix A. In deviation from the in subsection 2.6.2 presented SYSMOD procedure, no further postprocessing steps on the use cases were enacted.

3.6.1. Essential Use Case Description

The essential use case description gives a functional overview of the provided DT services and is characterized by a nontechnical formulation. Therefore, each identified use case, presented in table 3.6, is described via up to 6 essential steps. In order to facilitate the understanding of the procedure,, an excerpt of the essential steps identified for the protagonist "Service Worker" is presented in table 3.7. The full list is available in the appendix C.

Protagonist	**Use Case**	**REQ-ID**
Service Worker	Query Maintenance Work	REQ064
	Provide Execution Advice	REQ032
Process Manager	Query Component Status	REQ055
	Query Maintenance Schedule	REQ066
	Warn Against Critical Status	REQ062
	Choose System Adaption Suggestion	REQ067
Designer	Verify Design Approaches	REQ019
	Virtual Product Development	REQ041
System Engineer	Verify Design Approaches	REQ055
	Analyze System Architecture	REQ019
	System Adaption Compatibility Check	REQ011
System Administrator	User Rights Management	REQ011/ REQ027
	Troubleshooting	REQ036
Retail User	System Experience Extension	REQ016
	System Menu Request	REQ034
Sensor	Data provision	REQ043
Researcher	Advanced System Data Access	REQ032
	System Behavior Analysis	REQ019

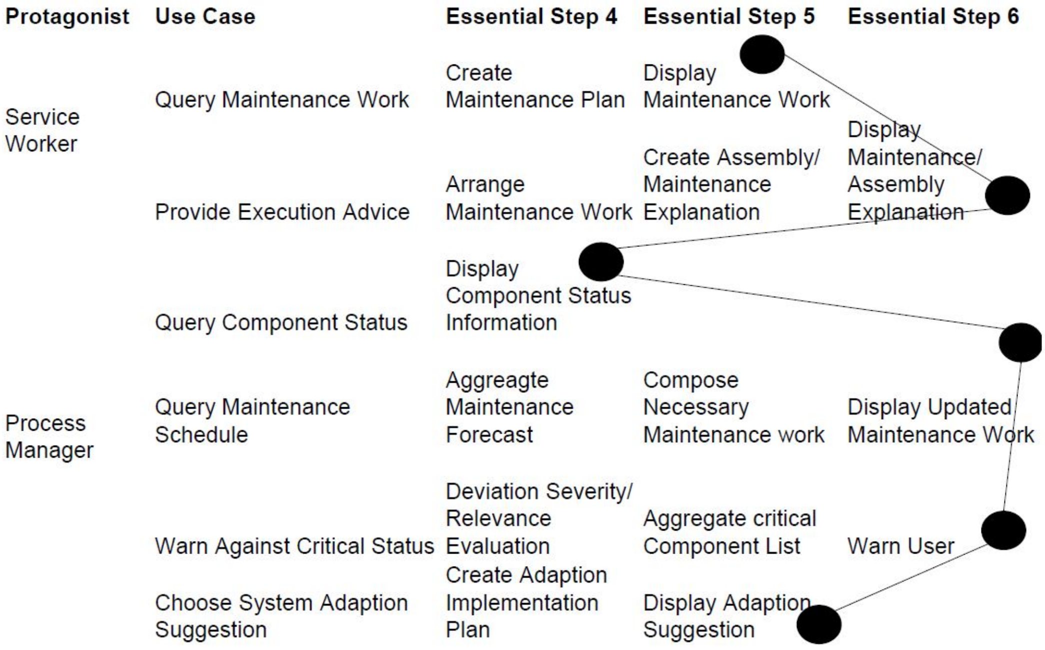
Table 3.6.: Use Cases with Refined Requirements

Use Case **Essential Step**	**Query Maintenance Work**	**Provide Execution Advice**
1	Component Status Determination	Load Component List
2	Maintenance Schedule Comparison	Single Component Query
3	Check Maintenance Necessity	Load Maintenance Manual
4	Create Maintenance Plan	Arrange Maintenance Work
5	Display Maintenance Work	Create Assembly/ Maintenance Explanation
6		Display Maintenance/ Assembly Explanation

Table 3.7.: Essential Steps - Use Cases Service Worker

3.6.2. System Process Description

The description of essential steps enables the functional comparison of the identified use cases. On this basis, complex, use case overarching sequences can be comprised within one system process. By the analysis of pre- and postconditions of the aggregated sequences an effective development of the system processes as elements of the concept can be conducted. In figure 3.3 the system process aggregation is exemplarily portrayed for the system element "Technical Display".



Protagonist	Use Case	Essential Step 4	Essential Step 5	Essential Step 6
Service Worker	Query Maintenance Work	Create Maintenance Plan	Display Maintenance Work	
	Provide Execution Advice	Arrange Maintenance Work	Create Assembly/ Maintenance Explanation	Display Maintenance/ Assembly Explanation
	Query Component Status	Display Component Status Information		
Process Manager	Query Maintenance Schedule	Aggreagte Maintenance Forecast	Compose Necessary Maintenance work	Display Updated Maintenance Work
	Warn Against Critical Status	Deviation Severity/ Relevance Evaluation	Aggregate critical Component List	Warn User
	Choose System Adaption Suggestion	Create Adaption Implementation Plan	Display Adaption Suggestion	

Figure 3.3.: System Process - Technical Display

The connection of the bullets referenced to the essential steps of the listed use cases indicates their similarity with regards to the presentation of relevant information. Therefore, the aggregation of the use cases to a single system process, the displaying of information, can be retraced. This system process is further developed to the system element "Technical Display", realized via the interface description in section 4.1 and detailed via the system-protagonist interaction in subsection 4.1.1.

3.7. Expertise Clarification

The previous sections described the process of shaping a system concept architecture. Therefore, components and terms were used to express the development progress. At some points, e.g. subsection 3.6.2, system elements were anticipated and the explanation was referred to subsequent sections. In order to keep track of the terminology and for the sake of clarity which especially avoids redundancy the used system elements are related to each other in this section. The graphically supported overview presentation, and the relation, aswell as the association between the system elements is modeled in a SysML blockdiagram, presented in figure 3.4.

3.7.1. System Structure Overview

The blockdiagram in figure 3.4 provides an overview of the system structure. The comprised system elements were identified during the development process. The structure is justified via muliple development iterations, which makes use of the knowledge aggregated in subsequent development steps, e.g. section 4.1.

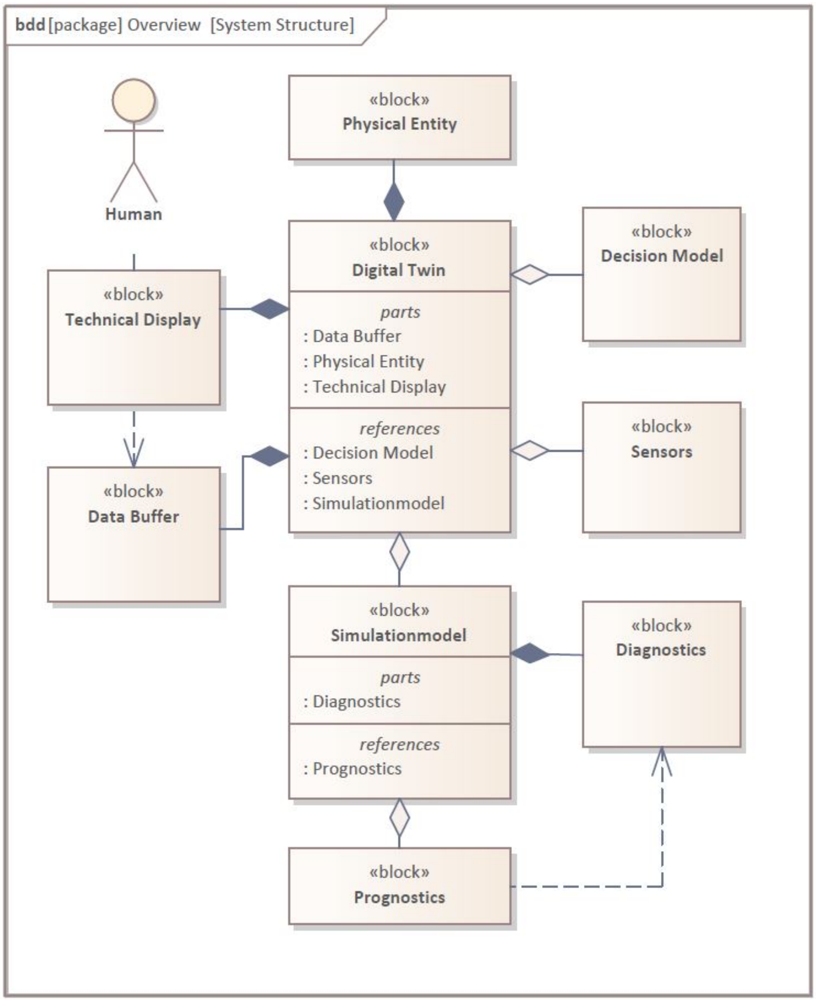


Figure 3.4.: System Structure Overview

The communication between the DT and the protagonists, represented by a stick figure titled "Human", is solely possible via the system element "Technical Display". Therefore, the association between the DT and the "Technical Display" is characterized as a "part" association. The information presented by the technical display is primarily retrieved from the "Data Buffer". The data buffer is feeded from the DT respectively the "Simulationmodel" which comprises in any case a "Diagnostics" element. The potentially included "Prognostics" element depends on diagnostics data. Depending on the DT type, the simulationmodel might be mandatory, resulting in a "shared" association. The same association is expressed between the DT and the "Decision Model", respectively the "Sensors" element. The mandatory "Physical Entity" is included in every DT and therefore associated as a part. In section 4.2 the system elements are described in detail.

4. Results

This chapter presents the concept development outcome and depicts the generally valid DT findings in the context of the test gearbox. The structuring of the subsequent sections follows, slightly adopted, the conducted SYSMOD procedure. The system structure presentation is supported by SysML models that are especially used for clarification and communication reasons. Therefore, model elements that might be required by the SysML syntax are deliberately omitted. The full SysML model is part of the data submission. Besides the logical architecture in section 4.1, the system elements are presented in detail in section 4.2. The chapter closes with the verification of the concept in section 4.3.

4.1. Logical Architecture

Chapter 3 prepared for the design of a logical architecture, which is presented in the subsequent subsections. As the SYSMOD procedure indicates, the logical architecture is the goal of the concept development. It comprises the detailed modeling of the system-protagonist interaction, subsection 4.1.1, and the derivation of interfaces, subsection 4.1.2. The related sequence diagrams are depicted for clarity reasons without their diagram frame, described in subsection 2.6.1.

4.1.1. System-Protagonist Interaction

Based on the use cases presented in section 3.6 and the objectflow identification in subsection 3.5.2 the interactions between the DT and its' protagonists are detailed. Therefore, the interactions are modeled in SysML sequence diagrams which provide besides the exchanged object denotation a chronologically sorted message exchange. In figure 4.1 an overview sequence diagram for the interaction of the protagonists, titled as "Human", and the DT, expressed by the system elements "Technical Display" and "Data Buffer", is portrayed. The exchanged messages are indicated by the connection of the lifelines, referenced to the interacting system element or protagonist. Processes which call for action within the same lifeline are expressed via self referencing messages. The interaction description between the "Human", the "Technical Display" and the "Data Buffer" is valid for every protagonist.

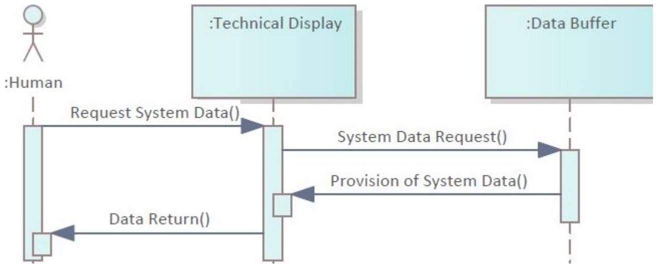


Figure 4.1.: Interaction Overview

Service Worker

As described in subsection 4.1.1, the interaction between the protagonist and the DT is enabled by the "Technical Display". Therefore, the maintenance request is entered here which initiates the calling of information from other system elements. The "Advisory Generation" element executes the maintenance checkup by again calling the system element "State Detection". The output of the initial query to the "Service Worker" is enacted by the "Technical Display". Requests which do not require special information processing can be directly answered by the "Technical Display" via accessing the "Data Buffer". In order to maintain the clarity of the diagram the message exchange between the system elements and the "Data Buffer" is not modeled. Therefore, the analysis of the maintenance work appears as a self referencing message in the lifeline of the "Technical Display", see figure 4.2.

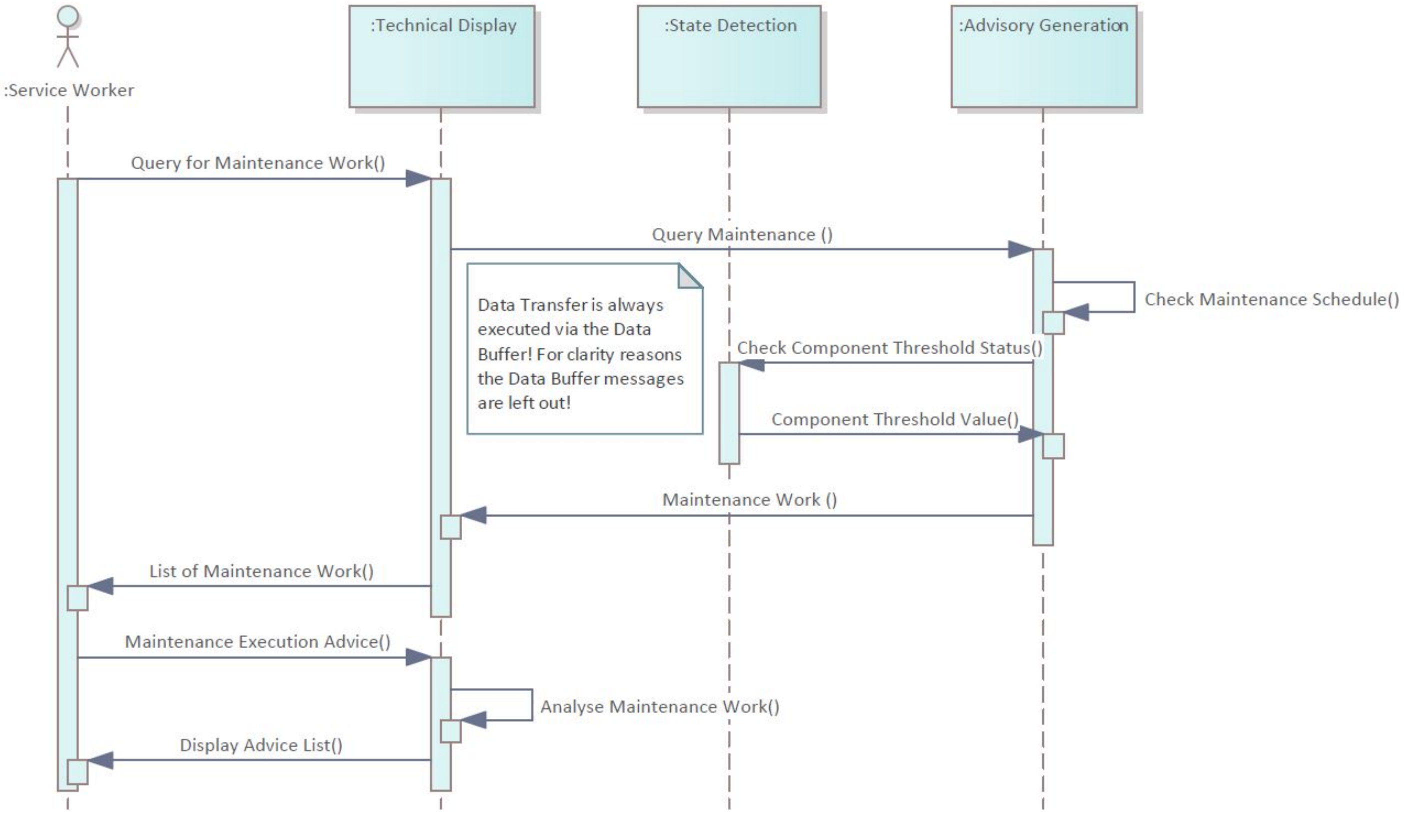


Figure 4.2.: Service Worker Interaction

Process Manager

The requests of the "Process Manager" are similarily to the "Service Worker" processed, via calling of the relevant system elements, in this case: "State Detection" and "Advisory Generation". The message exchange sequences for the "Process Manager"'s requests are depicted in figure 4.3. In contrast to the standard request and response interaction the warning/ alert and adaption suggestion are displayed without request of the protagonist. These messages can be characterized as push notifications.

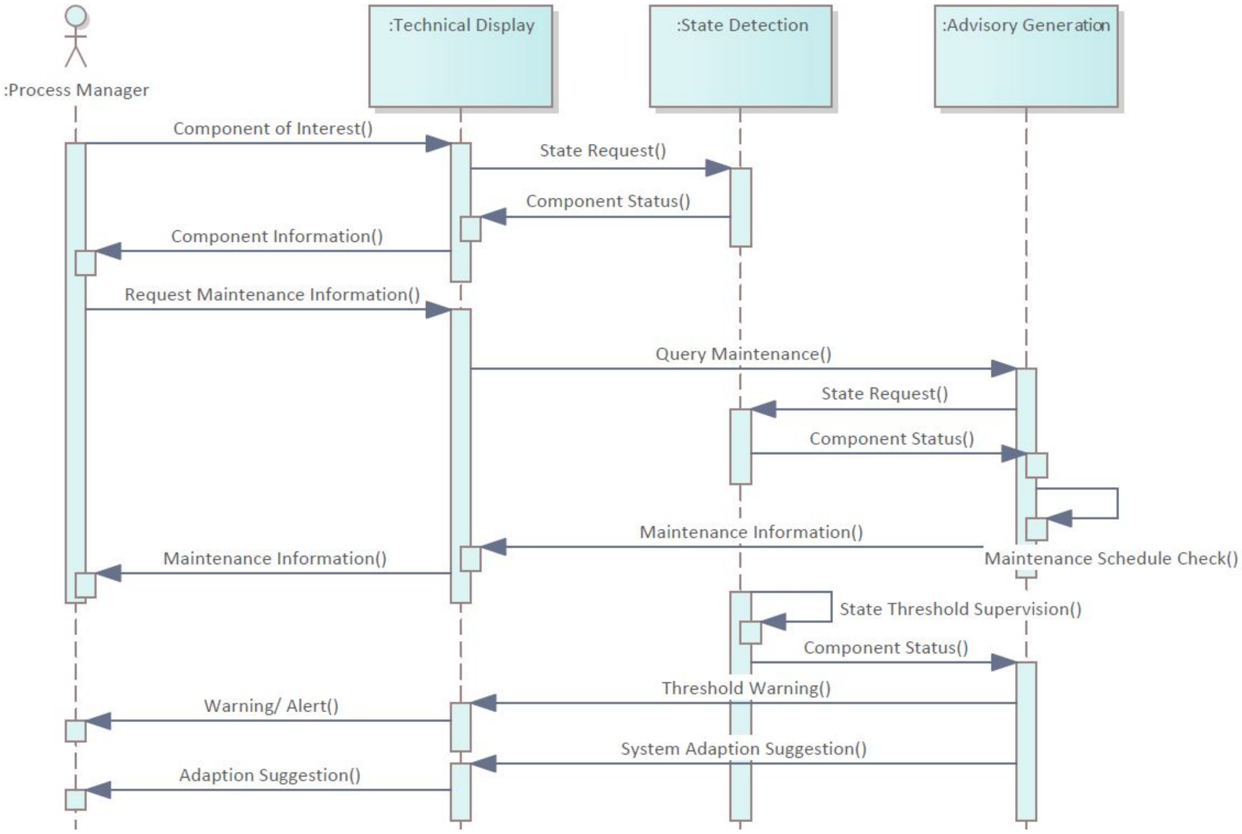


Figure 4.3.: Process Manager Interaction

Sophisticated and Standard Protagonists

Among the in section 3.6 aggregated use cases, related to the in subsection 3.5.1 identified protagonists, some require sophisticated system access which is not reasonably presentable in the full extent via sequence diagrams. Therefore, the description of the relevant system elements in section 4.2 can be used for retracing the interaction possibilities. The affected use cases are related to the protagonists system administrator, system engineer and sensor. Additionally, the system access of the protagonists designer and retail user are reduced to the in subsection 4.1.1 presented standard procedure via requesting the "Technical Display" and the "Data Buffer". Therefore, these interactions are not presented again, but are available in the data submission.

4.1.2. Interfaces Derivation

In order to be able to integrate the system in its environment and to understand the behavior between the system elements, interfaces as the linking element are described. The basis for the interface derivation is the description of the system interaction points, subsection 3.5.3, and the object analysis, subsection 3.5.2. On top of that the interaction modeling between the protagonists and the system via the sequence diagrams in subsection 4.1.1 enables a derivation of services inquired over the interfaces. In order to guarantee a coherent description of the interfaces an established standard for technical communication is used as a guideline. Therefore, the interfaces are described in accordance with the OSI-layers for different levels of communication, assigned to the ports as comments in section 4.2. In addition to the OSI-layer classification of the interfaces which enables a technical description, each OSI-layer is further detailed via the description of its characteristics and properties, known from development methods (Kirchner, 2020). This approach enables a functional clarification of the interfaces and facilitates the comprehension of the concept for non-technicians. Furthermore, the interfaces are essential for the modularity of the system architecture because they enable the interchangeability of the system elements.

OSI-Layer Characteristics and Properties

The categorization of interface features according to their characteristics and properties is expedient to describe interfaces on their functional level. As pointed out in Kirchner, 2020, properties cannot be changed directly, however they represent the features perceptible to the protagonists. The adaption of properties can only be initiated by the change of its characteristics. In table 4.1 characteristics and properties are assigned to each OSI-layer.

Due to the fact that the layers are built on top of each other, the property of the (N-1)-layer defines the characteristic of the (N)-layer whose properties in turn define the characteristics of the (N+1)-layer. Therefore, the description of characteristics and properties might not be compatible with every technical realization.

No.	Designation	Property	Characteristic
7	Application Layer	Interaction between end user and application provided by software	Communicating component software application; Distinction between software-entity and software
6	Presentation Layer	Provide mechanisms for the information exchange between different nodes with different information representation (semantics/ syntax); Compression and encryption	Transformation of presentation protocol data units into session protocol data units; Translation between application and network formats
5	Session Layer	Synchronisation of communication from transport layer and control of dialogues	Safety Points; Arrangement of activities; Processing directions (simplex, half duplex, duplex)
4	Transport Layer	End-to-End layer; virtual transmission connections via the network layer; Flow Control of segments	Fragmentation of packets which are too big for direct transmission: Segments; five classes of connection-mode transport protocols
3	Network Layer	Organise transmission between non-contiguous nodes; connection between heterogenous subnetworks	Packets are transferred in networks via nodes (intermediate nodes) and oriented via addresses
2	Data Link	Guarantee the secure transmission of messages via a channel from the physical layer. Subdivision of the layer in technology dependent and technologyindependent	Frames as universal identification of messages; MAC address and LLC protocol
1	Physical Layer	Transmission/ reception of unstructured raw data between a device and a physical transmission medium: Conversion of digital bits into signals	Layer Specification: Wires, Transceiver, Transmission Safety, Networktopologies, Synchronization

Table 4.1.: OSI-Layer Characteristics and Properties

4.1.3. Adaption Nodes

In addition to the interface definition, explained in subsection 4.1.2, the modularity approach for the concept is achieved via arranging the system elements among system adaption nodes. This enables a compact external appearance of the system's interfaces and subelement requirements and guarantees interoperability by maintaining the established element connections and providing clear adaption guidance if system elements need to be modified, added or removed. As depicted in figure 4.4 the system elements are connected via adaption nodes which comprise besides the interface definition other relevant system element requirements (e.g. min. power supply; max. data rate; max. load), represented by black bullets. The linkage between "Element M-1" and "Element M" is guaranteed via the OSI-layer compatibility and the system element requirements fulfillment. The same applies for the connection of "Element M+1" and "Element M". Due to the compatibility of the adjacent elements, the connection across multiple elements (e.g. "Element M-1" to "Element M+1") is enabled.

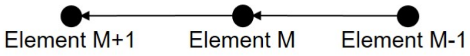


Figure 4.4.: System Element Connection

If the overall system architecture has to be complemented with other system elements or system elements have to be removed, the same compatibility approach remains valid. As depicted in figure 4.5 the "Element M" is removed and "Element M-2" is added. Furthermore, the "Element N" is integrated between the "Element M+1" and "Element M-1". The ensured adjacent compatibility guarantees the connection between all system elements and secures the overall system interoperability.

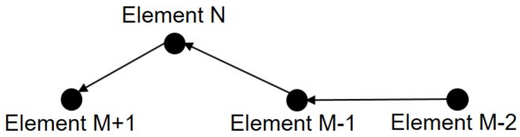


Figure 4.5.: System Architecture Adaption

4.2. System Elements

This section comprises the final description of the system elements, based on the system structure overview in figure 3.4. Beginning with the physical entity in subsection 4.2.1 the selected sensors are presented in subsection 4.2.2. The description includes SysML internal blockdiagrams and the concrete physical realization approaches currently realized at the gearbox testrig. Furthermore, the simulation model with its' subelements diagnostics and prognostics is detailed in subsection 4.2.3. The in figure 3.4 depicted "Technical Display" and the "Decision Model" is not further detailed, because the OSI-layer assignment of the interfaces is sufficient enough for the technical realization of the user communication and the AG assessment block includes the decision making process.

4.2.1. Physical Entity

The context of this thesis allocates the physical entity to the drivetrain domain. Following that, the concrete realization at the test rig is based on a two-stage industrial SEW gearbox type X2FS100e-HU-B, which is portrayed in figure 4.6. The technical specifications are available in the related SEW data sheets.

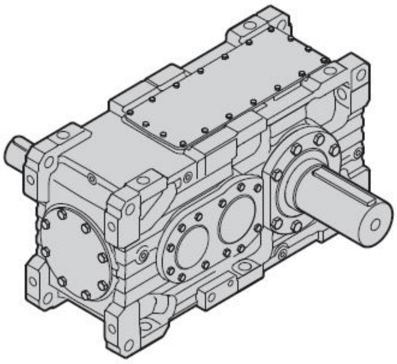


Figure 4.6.: SEW Gearbox (Rendering from SEW data sheet)

4.2.2. Sensors

The sensor selection is based on a previously enacted, internal work of the pmd institute (Schmidt et al., 2021). The allocation to the gearbox components is portrayed in figure 4.7. The depicted element "T" represents a temperature sensor, the "IN" element an inductive sensor and the "PIE" a piezo sensor. These sensors are intended to be included in the gearbox, but not relevant for this thesis. The depicted "MR" and "HCP" elements are briefly explained in this subsection, while the selection reasoning is available in Schmidt et al., 2021.

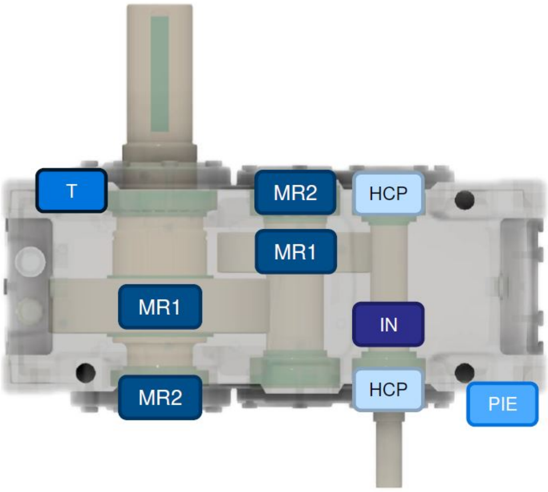


Figure 4.7.: SEW Gearbox Sensor Allocation (Schmidt et al., 2021)

HCP-Sense Bearings

As depicted in figure 4.7 the bearings of the input shaft are replaced by HCP-Sense bearings, which enable the insitu measurement of the effective bearing forces. The measurement is based on the analysis of the electrical impedance between the rolling elements and the roller bearing ring surfaces. Depending on the operational load and speed the contact form and lubrication condition adjusts which is quantifiable by the impedance measurement, which is presented in Martin, 2021. Furthermore, the usage of the HCP-Sense bearings is the precondition for the LBSD presented in section 2.3.

Magnetoresistive Sensors

In order to measure the speed of the intermediate shaft and the output shaft both shafts are equipped with two MR sensors, type SENSITEC TA 903. The sensors are positioned at the gear wheels and at one end of each shaft. The measurement is based on the magnetoresisitve effect which enables the extrapolation of speed from the change in the sensed magnetic field. For the speed measurement at the gear wheel a passive solid measure, the toothing, is used. The magnetic field is provided by a permanent magnet integrated in the sensor itself. At the end of the shafts, permanent magnets are mounted in order to provide the magnetic field. The solid measure is therefore an active solid measure (Hering, 2018). The high resolution of the MR sensors is the basis for the aspired measurement of the IAS which is used as an indicator for gearbox failures, detailed in subsection 4.2.4.

4.2.3. Simulationmodel

As the system structure overview in figure 3.4 indicates, the computational knowledge of the DT is provided by the simulationmodel. In figure 4.8 the relation between the subelements, diagnostics and prognostics, is depicted via a SysML blockdiagram. Furthermore, the in 2.2 introduced assessment blocks, which are described in subsection 4.2.4 respectively subsection 4.2.5, are related to the simulationmodel.

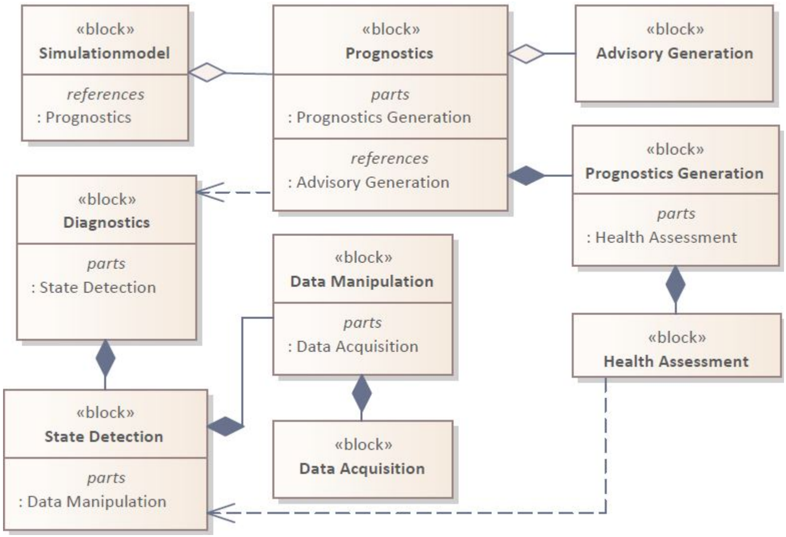


Figure 4.8.: Simulationmodel Overview

The planned software implementations of the DT and the relation between them is depicted in figure 4.9. The computational methods for the simulationmodel are implemented in MatLab and the simulation of the multi-input calculations is realized in Simulink, while the basic data input is managed in Excel. The invocation of the program execution is organized by the SysML modeling tool Enterprise Architect.

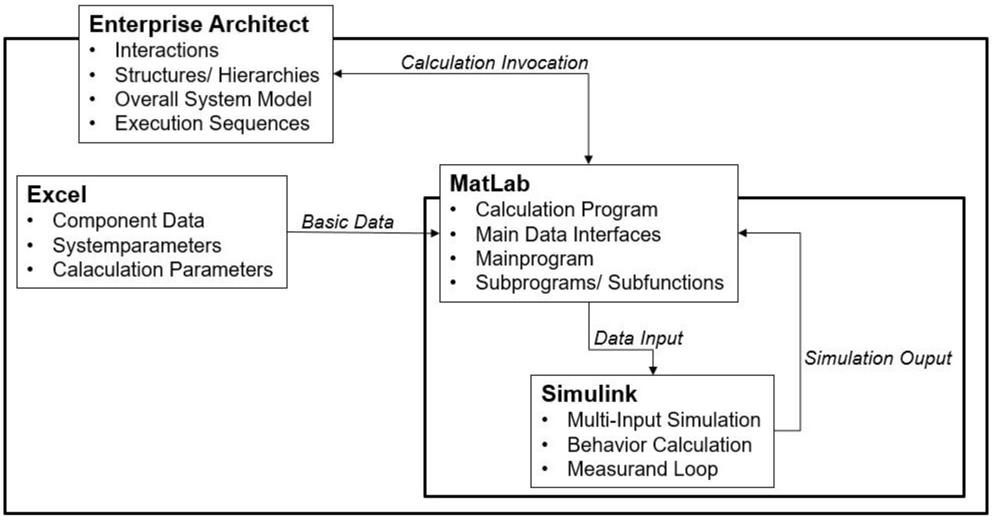


Figure 4.9.: Software Relation

4.2.4. Diagnostics

As depicted in figure 4.8, the simulationmodel subelement "Diagnostics" consists of the assessment blocks DA, DM and SD. The modeled dependencies are partly adopted from *ISO 13374-1:2003*, 2003 and *ISO 13374-2:2007*, 2007. The following internal block diagrams present the assessment blocks in detail and include the definition of the ports, referred to in subsection 3.5.3, with the OSI-layer assignment described in subsection 4.1.2.

Data Acquisition

The DA assessment block is portrayed in figure 4.10. As subelements of DA the "Data Transduction", the "Stamping" and the "Quality Identification" are isolated. The input to the assessment is generated by the data input from the sensors. The analog sensor signal is transmitted via an interface, assigned to OSI-layer 1 to the data transduction which provides the necessary transducer technology for transforming the analog signal to a digital signal. After the digital signal data is stamped with necessary machine data aswell as a timestamp, the quality of the measured and transduced sensor signal is analyzed. The quality identification indicator is complemented to the digital data sets and part of the data output to the buffer, assigned to OSI-layer 2, aswell as part of the direct data transmission to the DM assessment block, identified as "Verified Data", assigned to OSI-layer 2, and in case of direct user request to OSI-layer 7.

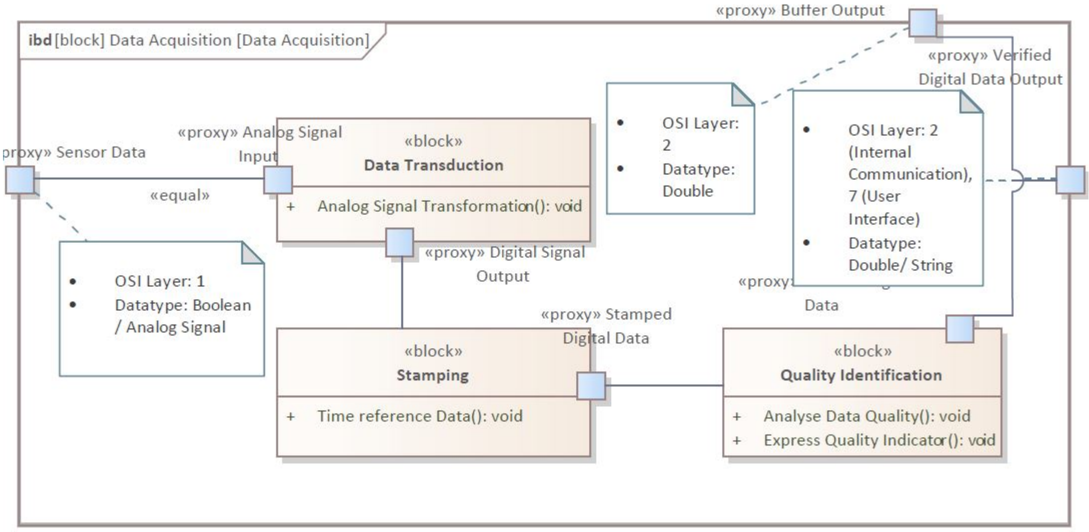


Figure 4.10.: Data Acquisition

Data Manipulation

As in figure 4.11 portrayed, the DM assessment block comprises three subelements: "Signal Processing", "Algorithmic Computation" and "Feature Extraction". The signal processing is the first element that manipulates the verified data, transmitted from the DA block. Via the OSI-layer 2 interface, the raw data is loaded, filterd and transformed. The filtered data sets are further analyzed via computational knowledge, provided in the "Algorithmic Computation". The preanalyzed and algorithmic evaluated data sets are aggregated to features in the "Feature Extraction" which outputs the feature information with the data sets to the buffer, via an OSI-layer 2 interface, and the subsequent assessment block, "State Detection", directly also via an OSI-layer 2 interface or via an user interface, OSI-layer 7, in case the user requests the data directly.

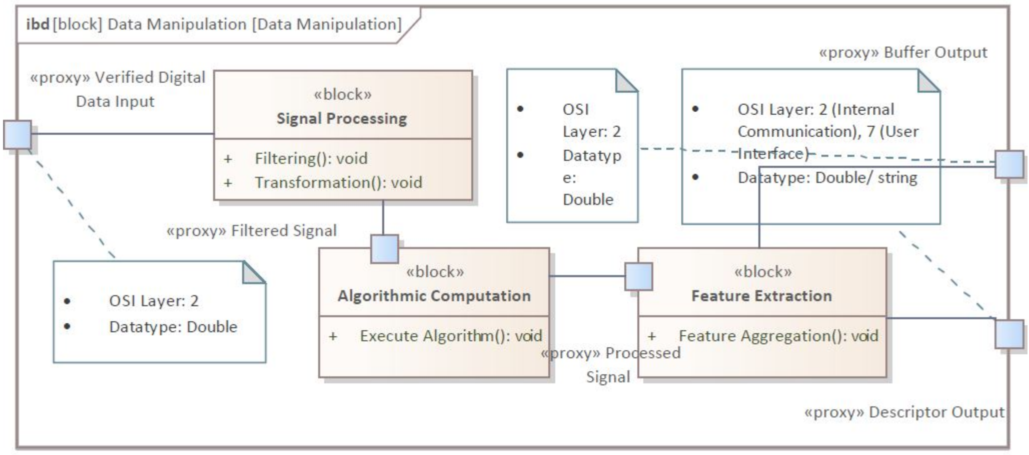


Figure 4.11.: Data Manipulation

State Detection

The assessment block "State Detection" portrayed in figure 4.12 builds the final element of the simulationmodel subelement "Diagnostics". It comprises the subelement "Condition Indicator Determination" which is calculating the aspired CI according to the applied state detection method, based on the descriptor data from the DM block. The "CI evaluation" rates the CI calculation output and analyzes the CI according to relevant threshold values and assesses the state change severity. In case necessary, the state alert is issued via an interface assigned to OSI-layer 5-7. The other data sets are either transmitted to the buffer, OSI-layer 2, or directly to the subsequent assessment block, "Health Assessment".

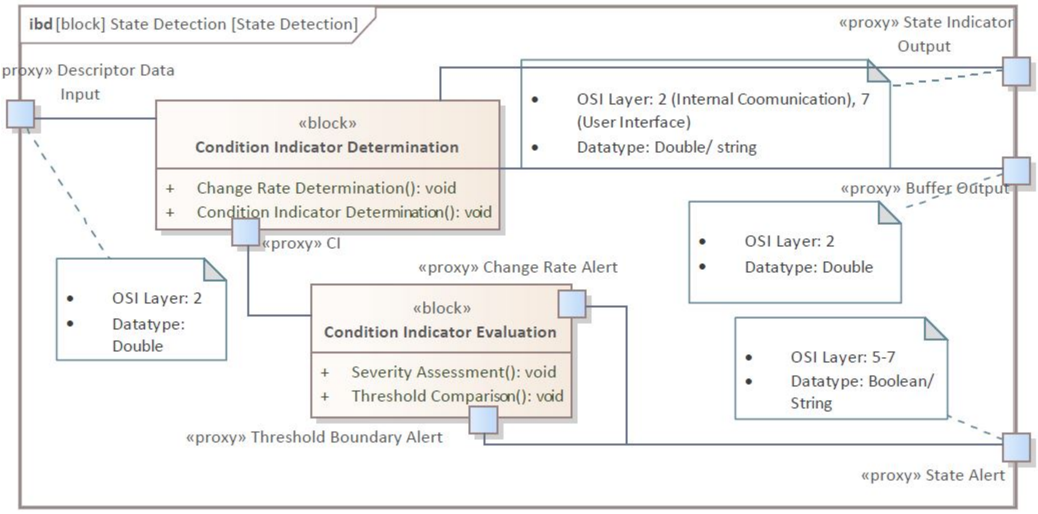


Figure 4.12.: State Detection

4.2.5. Prognostics

As depicted in figure 4.8, the simulationmodel subelement "Prognostics" comprises the assessment blocks "Health Assessment", "Prognostics Generation" and "Advisory Generation". The isolated dependencies are partly adopted from *ISO 13374-1:2003*, 2003 and *ISO 13374-2:2007*, 2007.

Health Assessment

The HA assessment block comprises three subelements. The "Fault/ Failure Diagnosis", the "Health Estimation" and the "Recommendation" element. The general task can be described as a more sophisticated SD which uses the SD data as an input for the fault/ failure diagnosis enhanced with human expertise and additional diagnostics algorithms. In parallel, the buffered historical data sets are used for further enhancing the diagnosis of the faults and failures. Similarily, the "Health Estimation" is relying on the current SD data aswell as the historical buffer data sets to further aggregate information about the gearbox components and the complete system interplay. The subelement output is either directly emitted or further processed in the "Recommendation" which outputs system adaption recommendations limited to possible standard operational setting adaptions. The input and output values are transferred via interfaces assigned to the OSI-layer 2, and in case a direct user interaction is initiated, OSI-layer 7.

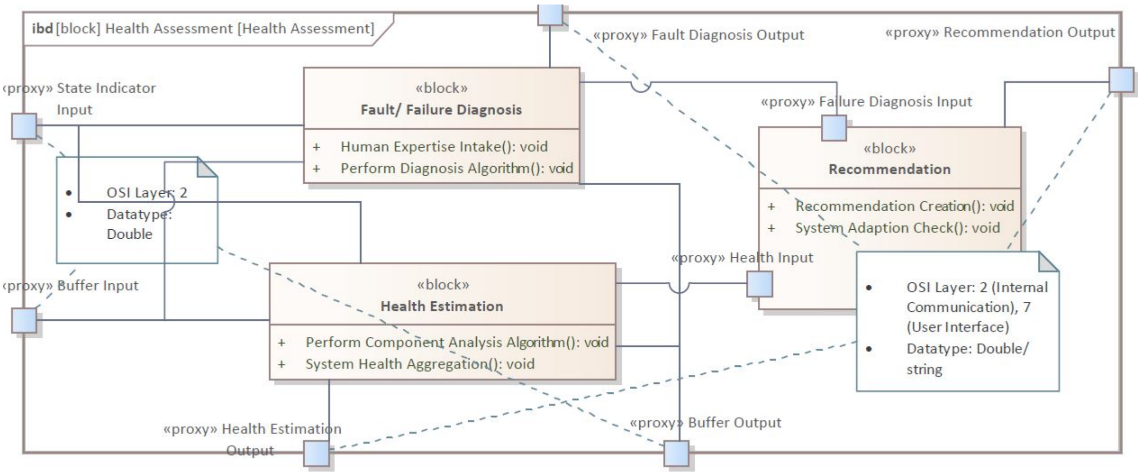


Figure 4.13.: Health Assessment

Prognostics Generation

This assessment block builds the major element of the simulation model subelement prognostics. It comprises the subelement "Prognostics" and "Recommendation". The theoretical background for the prognostics calculation is described in section 2.5. The Input to the prognostics element is similarily designed to the HA block. The current HA data aswell as the historical buffer data is used for the calculation of future states, RUL and future failures. The calculation is used for the recommendation creation which is limited to the creation of system explanations and minor adaption recommendations to the operational settings, and the data input for the subsequent assessment block AG. The concretely applied algorithms for the prognostics calculation can be generally assigned to data driven approaches. Depending on the gearbox component, two different approaches are applied. For the bearings, the similarity estimation, and for the gears the degradation estimation; both theoretically detailed and applied for this thesis in section 2.5. The Output of the PG assessment block is realized via OSI-layer 2 and 7 interfaces, while the input is transferred via an OSI-layer 2 interface.

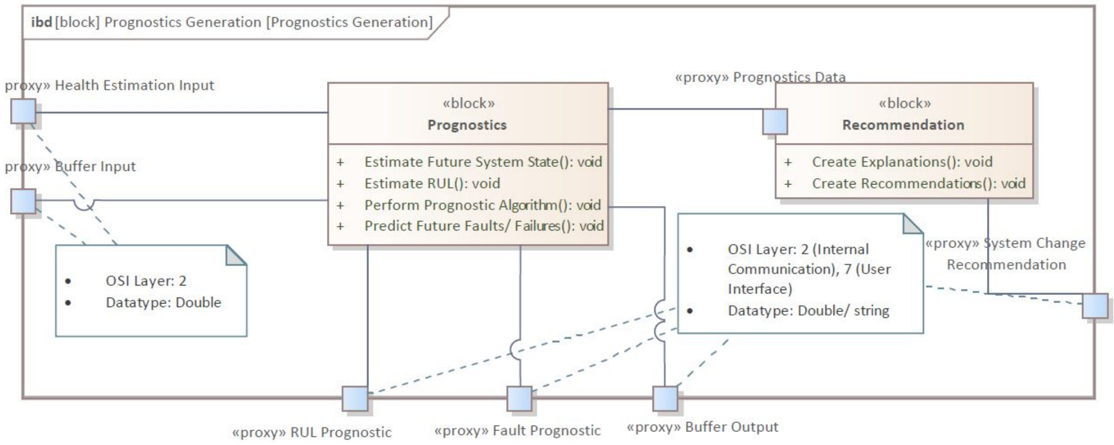


Figure 4.14.: Prognostics Generation

Bearing Similarity Estimation

The in section 2.5.2 explained similarity estimation is applied for the prognostics of the bearings. According to the explanations, the data sets from the previous assessment blocks (DA, DM, SD), bundled in HA are used for aggregating and computing Condition Indicator (CI). The computed CI, in this thesis the accumulated damage, are compared to the similarity data sets which are supplemented with the experience of the user, and complemented with the data iterations of the current operational data. The merger of the data to a characteristic line allows the extrapolation from current state to a future state and represents the actual prognostics generation of the RUL, where the failure possibility is portrayed according to the CI and the operational cycles. In figure 4.15 a qualitative example of the similarity estimation outcome, which is based on the MathWorks Help Desk (The MathWorks, Inc., 2022a) is depicted.

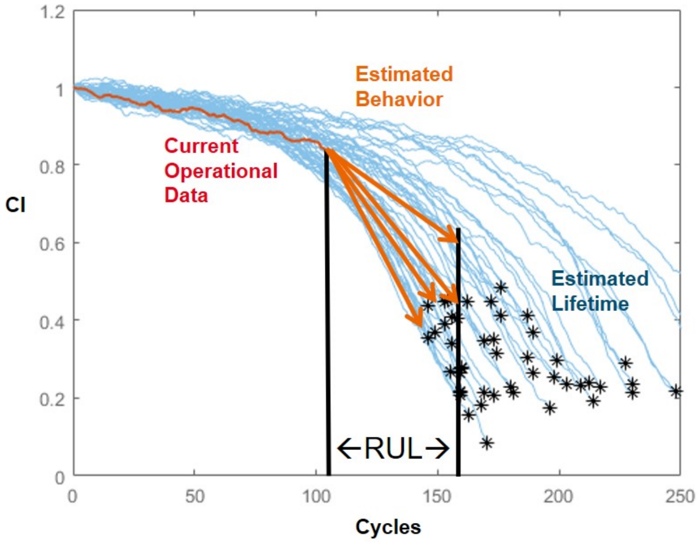


Figure 4.15.: Similarity Estimation Bearing (The MathWorks, Inc., 2022a)

Toothing Degradation Estimation

In accordance with the current research on toothing RUL estimation, partly presented in subsection 2.5.1, the algorithm for the prognostics generation is based on the degradation estimation. To generate a sophisticated estimation the system data from the HA block is used as an input for the CI calculation in the PG block. In this context the amplitude aswell as the signal frequency of the recorded, filtered and preprocessed IAS signal is used as a CI, depending on the monitored failure type (pittings or toothroot failure). The threshold value for the CI is defined by the knowledge, based on historical data, user experience and the operational data iterations. By merging the available data sets, a characteristic line can be aggregated which delivers the estimated RUL from the estimation point by intersecting with the defined threshold value. In figure 4.16 these elements are presented in form of a graphic that is adopted from The MathWorks, Inc., 2022b.

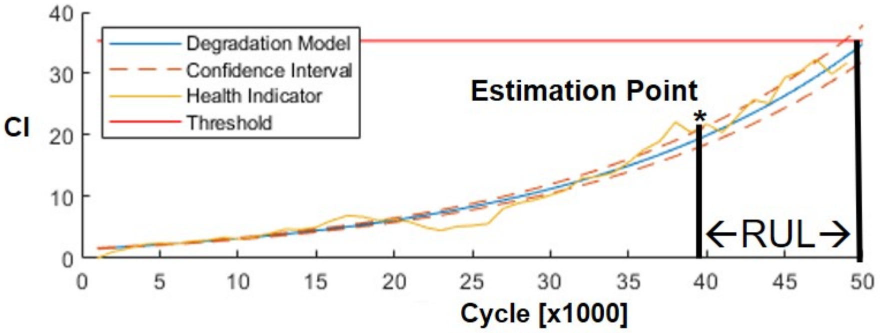


Figure 4.16.: Degradation Model Toothing (The MathWorks, Inc., 2022b)

Advisory Generation

While the previously presented assessment blocks of the prognostics subelement include a recommendation block, the AG is solely dedicated to the generation of "Recommendations". Based on the "Capability Forecast" block which uses the input data from the RUL prognostics of the PG block and the historical data sets from the data buffer to evaluate the current system status and the RUL prognostics for aggregating a maintenance forecast, the recommendations are defined. Typical recommendations refer to the operational settings and the maintenance/ repair advice generation. Additionally, to the data from the capability forecast, external constraints like the sourrounding of the technical application is taken into consideration. According to the implementation type of the DT, the output of the AG is either directly transmitted to a technical system element (OSI-layer 2 interface) or displayed to the user (OSI-layer 7 interface). The input values are transmitted via an OSI-layer 2 interface with a possible additional interface usage of OSI-layer 1 for the external constraints. In figure 4.17 the detailed process is depicted.

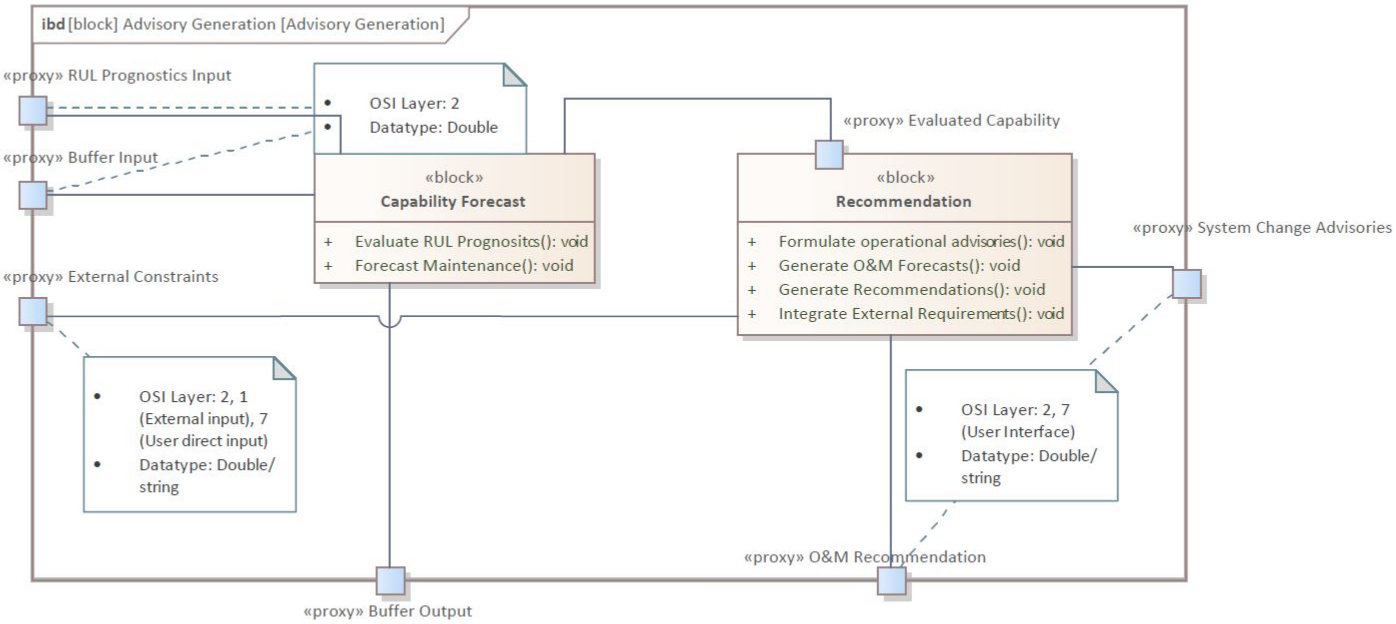


Figure 4.17.: Advisory Generation

4.3. Concept Verification

To conclude the development process the verification of the concept with the comparison to the first order requirements, presented in subsection 3.4.2, is carried out. Therefore, in figure 4.18 the requirements are depicted with the major system elements.

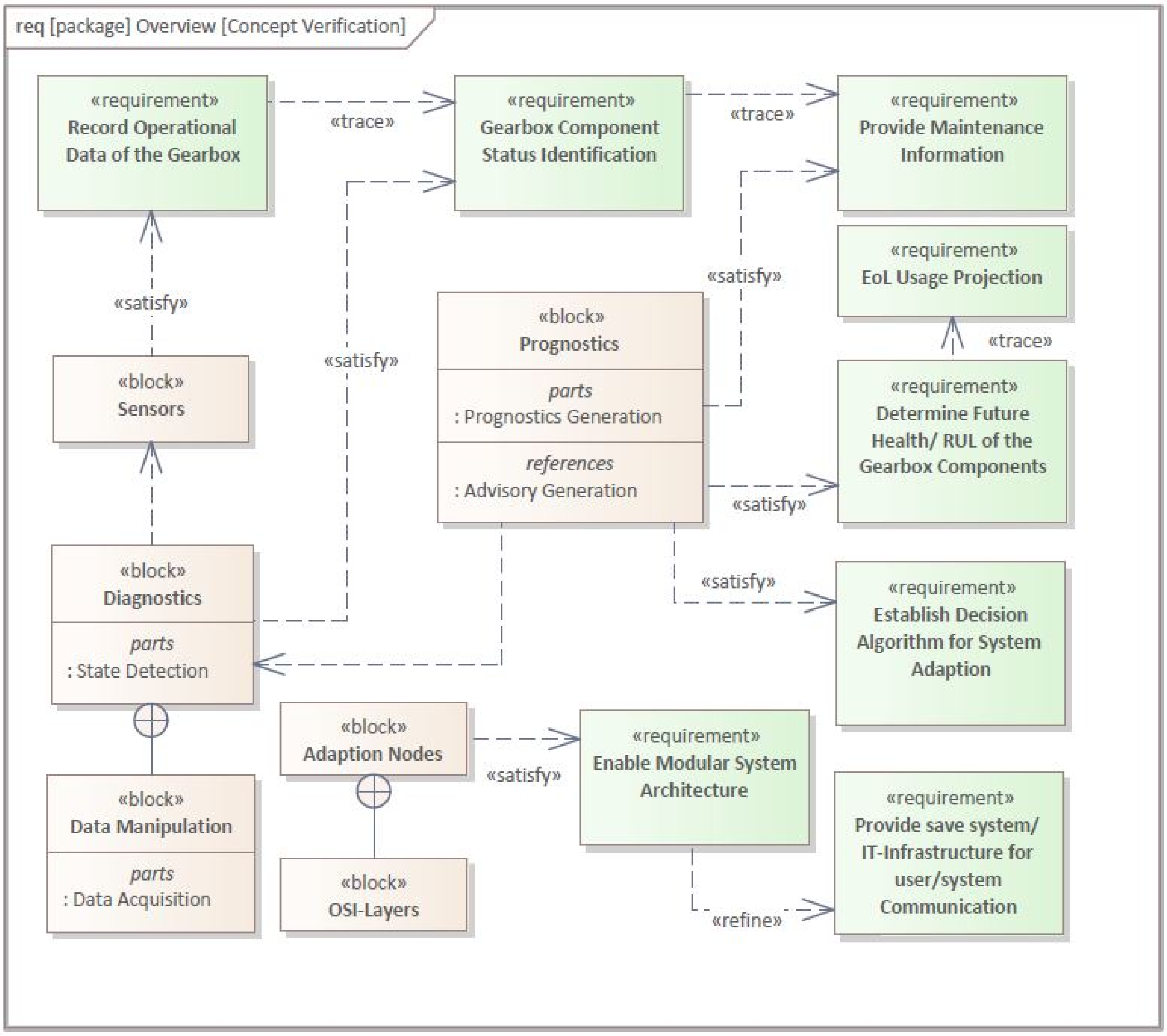


Figure 4.18.: SysML Requirements Diagram

The relation between the requirements and the system elements, represented as blocks, indicate the degree of fullfillment of the requirements. The collection of the operational data is made by the in subsection 4.2.2 presented sensors. The data transformation and data preprocessing is realized by the diagnostics block which is in this concept context dependend on the sensor, because no other instance for the operational data aggregation is realized. To make clear that the raw sensor data needs preprocessing before further information can be aggregated the data manipulation block is connected to the diagnostics block via an containment relation. The diagnostics block with the state detection subelement further statisfies the requirement for the gearbox component status identification which additionally can be traced to the record of operational data. Furthermore, the status identification indicates the maintenance provision, which is noted via the trace connection. The requirements decision algorithm for system adaption, future health and RUL determination of gearbox components and the maintenance information provision can be satisfied via the system element prognostics and its' assessment block parts AG and PG. The requirement for the EoL usage projection can be related to the future health and RUL determination but is not explicitly realized in the concept. The claim for a modular system architecture is satisfied via the establishment of interfaces, described by the OSI-layers and the definition of adaption nodes. The required save system/ and IT infrastructure for the user/ system communication is not explicitly evaluated but can be regarded as a refinement of the modular system architecture requirement.

5. Summary

The general concept elaboration is oriented to the SYSMOD procedure. The first step was the definition of five concept objectives. Together with the state of research aggregation, these were composed to the basic architecture which provided a first idea of the concept structure. On the basis of a stakeholder identification the system requirements were identified. The full list is aggregated as quantitative as possible, whereas six, qulitative, first order requirements were isolated. The subsequent step comprised the identification of system protagonists and their objectflow. The description of the system interaction points resulted in a port definition and completed the system context analysis which categorized the concept in the overall DT context. To further detail the system elements, potential use cases were identified and postprocessed with the aggregation of essential steps for the detailed analysis. With the aggregation of a general system structure overview which comprised the system elements: "Digital Twin", "Physical Entity", "Simulationmodel" with "Diagnostics" and "Prognostics", "Sensors" and "Decision Model", as well as "Technical Display" and "Data Buffer" the procedure explanation was finalized. By the further detailed description of the system protagonist interaction and the interface description via the OSI-layer model, adaption nodes were introduced for the modular system architecture. The aggregated concept structure describes the connection between the system elements which were identified to the SEW gearbox ("Physical Entity") , the HCP and MR sensors ("Sensors"), the "Simulationmodel" with the LBSD for the bearings and the VBSD for the toothing of the gear wheels ("Diagnostics") and the similarity estimation for the bearing and the degradation estimation for the toothing prognostics ("Prognostics"). On the basis of the predefined first order requirements, the concept was verified.

6. Conclusion and Outlook

The elaborated DT concept provides a system architecture for the DT design referred to the industrial drive train domain. The followed generalization efforts resulted in a high abstraction level which makes the concept applicable for different concrete technical realizations. Furthermore, the developed modularity approach provides the necessary guidance and compatibility assurance for future adaption demands. The modeled SysML diagrams of the system elements enable a lucid communication of the architecture decisions and facilitate the concept comprehension. The slightly adapted execution of the SYSMOD procedure proved to be senseful to ensure all potential aspects of the concept requirements are considered. Nevertheless, the pursuit of established design methods according to Lutters, 2018 should be enacted, in order to methodologically back the further development. The following paragraphs detail potential further fields of development aswell as possible concept improvements and outline their suggested extend.

SysML Modeling

The applied SysML modeling resulted in the aggregation of a set of diagrams which are dedicated to the communication of the concept development. The necessary knowledge for the understanding of the diagrams is provided in the thesis and can be regarded as an acceptable effort for the sake of lucid communication. Nevertheless, it is questionable whether the communication benefits justify the diagram creation effort. Therefore, further potential of the SysML modeling in order to reduce the coding effort for the concrete application of the concept should be exploited. The used software, Enterprise Architect, provides the possibility of including parameter diagrams for the inclusion of MatLab, respectively Simulink applications within the SysML environment. Together with a consistent SysML common element designation an automated logic audit could be realized. Furthermore, the strategic organisation of the diagram elements would enable a senseful export of the underlying code. Additionally, the further proceeded development should integrate a clear strategy for the avoidance of redundancy. Especially the transmission of information from one development tool to another, e.g. the transmission of the requirements list (Excel) to the requiremtens diagram (Enterprise Architect), holds the risk of inconsistent data sets.

Uncertainty

A "[...]measurement is only complete when accompanied by a quantitative value of its uncertainty." Rios et al., 2019. Therefore, the described measurements of the gearbox components should be further detailed with their uncertainty estimation in form of a confidence interval. Furthermore, the uncertainty of the data transmission between the system elements should be portrayed (Rios et al., 2019). As a basis for the uncertainty analysis the work of Pelz et al., 2021 could be used. For the sensitivity analysis Marino et al., 2008 and Pianosi et al., 2015 present concrete analysis applications which could be used for the overall system behavior analysis, integrated in the MatLab implementation of the simulationmodel. The outcome of the uncertainty estimation should provide detailed information about the relation between the measurement accuracy and the final confidence of the statistical statement of the gearbox's (component) RUL.

Gearbox Diagnostics and Prognostics

The presented procedure for the diagnostics and prognostics of the gearbox only represents an extract of the possible PHM realizations. Therefore, also other diagnostics and prognostics methods should be reviewed. Especially the sophisticated analysis of the drivetrain by a multi-body simulation with multiple degrees of freedom seems to be promising (Moghadam et al., 2021; Moghadam and Nejad, 2022). Furthermore, other sensor concepts (inductive, temperature, piezoelectric) should be analyzed with regard to their diagnostics potential (Schmidt et al., 2021). Additionally, the description of the aspired estimation approaches should be accompanied by a statistical definition of the used calculation factors. For example could the RUL estimation be further detailed with the statistical clarification of RUL which is corresponding to the statistical expression Mean Time Till Failure (MTTF) (Bertsche, 2011). For the realization of the suggested simulationmodel current approaches of Jablonski, 2021 in MatLab and Laghmouchi, 2017 could be useful. The potentially aggregated large datasets could be handled by the Principle Component Analysis (PCA), described in Jolliffe and Cadima, 2016 and further used for the implementation of neural networks and AI algorithms, presented in Dhamande and Chaudhari, 2016 and Masrour et al., 2021, where the AI approach for industrial applications is outlined. According to the general alignment with the FVA standards the programming of applications should be approached in accordance with the FVA programming guideline (*FVA Richtlinie - Programmierrichtlinie*, 2012) and current releases of the FVA workbench application (FVA Forschungsvereinigung Antriebstechnik e.V., 2022). Further concrete application advices could be drawn from *ISO 17359:2018*, 2018.

IT and Data Infrastructure

The aggregated system structure is defined via the definition of interfaces based on the OSI-layer assignment. This approach allows the lucid communication of the relevant IT technologies but complicates the reflection of the current state of the art IT infrastructure. This is caused by the technical comprehension of multiple OSI-layers in current IT infrastructure technologies which are influenced by the current development approaches in the field of cloud and edge computing as well as Internet of Things (IoT). Therefore, the system concept should be complemented by these aspects. In Obdenbusch, 2017 a DT cloudbased reference architecture is portrayed and could be used as a concrete starting point for the cloud realization. For the selection of an IoT-platform the in Nguyen, 2019 portrayed selection and development method in addition to Lempert, 2021 could be applied. The complementation with the IoT-platform valuation method of Kugler et al., 2019 further details the development procedure suggestion which should be aligned with the common IoT vocabulary, provided by Guizani, 2019. In Borghesi et al., 2021 an IoT-platform for the DT management is described and could be used as a concrete realization guideline. For the technical detailing of the DT realization the knowledge of embedded systems could be helpful which is provided by Marwedel, 2021. The data type organization is closely connected to the applied communication protocol. In Czwick et al., 2019 a communication protocol for the sensor connectivity is presented and could be further detailed for the application in DTs. The concrete communication realization of Zieringer et al., 2020 with the OPC UA standard, provides a promising way of establishing the human-DT communication. Together with the OPC UA design principles of Tantik, 2020 and the continuously updated (companion) specifications from the OPC UA foundation, a data infrastructure, on the basis of OPC UA, could be realized for the in this thesis presented DT concept. In addition to that, the OPC UA standard enables the realization of real-time (hard, firm, soft) applications which could be necessary for some realizations. In Ferrari et al., 2018 a delay analysis of IoT systems with OPC UA is portrayed and could further support the concrete real-time concept implementation. For the modeling of Real Time and Embedded Systems (RTES) a defined UML profile named Modeling and Analysis of Real Time Embedded Systems (MARTE) (The Object Management Group, 2022) could be deployed in Enterprise Architect.

Further General Development Suggestions

The current allocation of the DT to MoL and partly EoL applications is adviseable due to the related gearbox test rig application, but does not make use of the full potential of the DT along the complete PLC which results from the aggregation of all data referred to the physical entity in one place. As already pointed out in Grieves, 2005 the Product Lifecycle Management (PLCM), defined in Herrmann, 2018 and detailed in J. Stark, 2015, is an important element of the future value creation. Therefore, the DT approach should be expanded to Begin of Life (BoL) applications like digital prototypes or experimental DTs, presented in Schluse and Rossmann, 2016. Furthermore, the elaborated EoL procedure could be more detailed by concrete recycling and sustainability endeavours, where the difference between service life and lifetime could be established. The review of Carvalho and da Silva, 2021 could be used as a starting point for the sophisticated requirements aggregation. Additionally, the development procedure should be adapted for an optimized handling and derivation of different DT versions. The further detailing by the essential description of the use cases could be expedient. As a concrete software version management solution GitHub could be used (GitHub, Inc., 2022). The accumulation of data sets by different connected DTs could be further interesting for reproducing the PLCM of a complete product range. In Reiche et al., 2021 this interconnection of DTs is portrayed and could be referred to the described PLCM context. In contrast to the mentionend, mostly mechanical engineering related, approaches, Jones et al., 2020 refer to the Building Information Modeling (BIM) which can be characterized as a DT of a building. During the development different trades work in the same construction drawing organized by a layering system with version control which enables the tracing of changes. The MoL and EoL of the building is also included in BIM by further versioning of changes, sensors in the building and complementing protocols. Due to the high amount of different trades, accompanying the construction process, an analysis of the BIM with special regards to the version control and layering could be senseful. Also the compatibility approach of BIM for high performance software, with large data sets, could be interesting for the DT concept in the industrial drive train context.

A. Appendix A

Version: 4

Requirements DT Concept

State: 2022-03-01

Conceptional Design of a Digital Twin to Predict the Remaining Useful Life Time of a Gearbox

edited by: Michael G. Frank

Part 1 - Requirements for Diagnostics

Nr.	FR, RR, GR, DR	Designation	Description	Source	Date
		1.1. Data Acquisition (DA)	**converts an output from the transducer to a digital parameter representing a physical quantity and related information (such as the time, calibration, data quality, data collector utilized, sensor configuration) (DIN 13374-1:2003-03)**	**Product Owner/ User**	
111	FR	IAS sensing gears	IAS sensing of the gears	RUL calculation/ Vibration analysis	2021-10-28
112	FR	Torque sensing	Torque sensing of output shaft via measuring flange	Tom Gundlach	2021-10-28
113	FR	Oil temperature sensing	Oil temperature sensing in the oil pan at multiple positions	Tom Gundlach	2021-10-28
114	GR	Shear force sensing	Sensing of shear forces in the shaft via eddy current sensor at input shaft	Tom Gundlach	2021-10-28
115	GR	Geometry usage for measurand determination	Usage of Geometrydata for integrated measurement of speed, torque and shearforces	Sensing concept	2021-10-01
116	FR	Vibration measurement	Acceleration sensors via piezo sensors in order to fulfill data requirements of vibration based CM	Randall2021	2021-12-17
117	W	Bearing load measurement	HCP Sense sensor integration at the input shaft bearings	RUL calculation/ Tom Gundlach	2021-12-17
		1.2. Data Manipulation (DM)	**performs signal analysis, computes meaningful descriptors, and derives virtual sensor readings from the raw measurements (DIN 13374-1:2003-03)**		
121	FR	Raw data filtering	Filter measured raw data to eliminate outliers and signal noise	RUL calculation	2021-11-10
122	FR	Condition indicator identification	Identification of CIs for the diagnosis of components	RUL calculation	2021-12-17
123	FR	Quality variable identification	Calculation of QVs for RUL prediction technique	RUL calculation	2021-12-17
124	DR	Preprocessing RUL Algorithm	Preprocess data for the use in the RUL algorithm	Mathworks Support	2022-01-14
		1.3. State Detection (SD)	**facilitates the creation and maintenance of normal baseline “profiles”, searches for abnormalities whenever new data are acquired, and determines in which abnormality zone, if any, the data belong (e.g. “alert” or “alarm”) (DIN 13374-1:2003-03)**	**User**	
131	FF	Diagnose bearing status	Determine the current status of the bearing	RUL calculation	2021-10-28
132	FF	Diagnose toothing status	Determine the current status of the toothing	RUL calculation	2021-10-28
133	FF	Diagnose gear box status	Determine the current status of the gear box	RUL calculation	2021-10-28

134	FF	Design analysis tool	Programming of an analysis tool that combines simulationmodel and sensor data	RUL calculation	2021-10-01

Part 2 - Requirements for Prognostics

		2.1. Health Assessment (HA)	**diagnoses any faults and rates the current health of the equipment or process, considering all state information (DIN 13374-1:2003-03)**		
211	FR	Vibration analysis	Vibration based failure detection	Randall2021	2021-12-17
212	FR	Dammage accumulation	Incrementally update the loading histories	Mars2018; RUL calculation	2021-12-17
213	DR	Multi-body system analysis	Develop a multi-body simulation model of the gearbox	Moghadam2022	2022-01-10
		2.2. Prognostic Assessment (PA)	**determines future health states and failure modes based on the current health assessment and projected usage loads on the equipment and/or process, as well as RUL predictions (DIN 13374-1:2003-03)**		
221	FR	RUL prediction of bearing	Prediction of the RUL of the bearing	Assignment	2021-10-28
222	FR	RUL prediction of toothing	Prediction of the RUL of the toothing	Assignment	2021-10-28
223	FR	RUL prediction of the gear box	Prediction of the RUL of the gear box containing the bearing and the toothing	Assignment	2021-10-28
224	DR	Similarity Curves	Historical analysis data is used for comparison with the current situation	Bertsche2011; Mathworks support	2021-12-17
225	FR	Uncertainty estimation	Provide procedures to estimate the accuracy of the prognostics assessment, adivsory generation and health assessment	Goebel2017	2021-12-17
226	FR	Wear Consideration	CI as a wear factor	Bertsche2011; Mathworks support	2021-12-17
		2.3. Advisory Generation (AG)	**provides actionable information regarding maintenance or operational changes required to optimize the life of the process and/or equipment (DIN 13374-1:2003-03)**		
231	FR	Plan maintenance schedule for system components	Determination of the ideal maintenance timing for the system components, namely bearing and toothing	User/ FVA	2021-10-28
232	DR	Autonomation	System takes direct action	FVA	2021-10-28
233	FR	Implement decision tree	Enable the system to take action or decide on system behavior based on operational data or system calculations		2021-10-30
234	FR	System adaption guideline	Provide a guideline for adapting the system on the basis of operational data or calculated component/ system data		2021-11-21
235	GR	Determination of the maintenance work	Determination of the necessary maintenance work related to system components	User/ FVA	2021-11-16
236	FR	Alarm/ Alert generation	Alarm/ Alert user according to (critical) system status		2021-12-17
		2.4. Data Driven Models Integration			
241	DR	Neural Networks integration	tbd	Goebel2017	2021-11-04
242	DR	Support Vector Machines and Relevance Vector Machines	tbd	Goebel2017	2021-10-01
243	DR	Guassian Process Regression	tbd	Goebel2017	2021-11-10
244	DR	Case-Based Reasoning Systems	tbd	Goebel2017	2021-11-10

245	DR	Bayesian Belief Network	tbd	Goebel2017	2021-11-10

Part 3 - Requirements for Data & IT Infrastructure

		3.1. (HM)Interfaces	**describes the characteristics of certain data formats, interaction points, … to combine systems or components**		
311	FR	Technical displays	Necessary data presentation via a lucid communication platform	DIN 13374-1:2002	2021-12-17
312	FR	Information presentation	Convert the measured, filtered data into pertinent information	DIN 13374-1:2003	2021-12-17
313	GR	Administration interface	Implementation of an administration layer with enhanced access rights for troubleshooting system problems	Product Owner	2022-01-10
314	DR	User Menu	GUI implementation with predefined menu elements with predefined information output	User	2022-01-10
		3.2. Connectivity	**provides information about the possibility of connecting the DT to different users or systems**		
321	FR	Global data access		User/ Product Owner	2021-10-28
322	FR	Enterprise IT network	Integration into enterprise network	User	2021-10-28
323	DR	Plug and Play ready	stable IoT device interface provision for plug and play integration of IoT devices like sensors, actuators or PLCs	User	2021-12-17
		3.3. Data Security	**%Important Topic but very big and not part of the thesis% %!tbd!%**	**General!**	
331	FR	End to End Data encryption	End to End data encryption to guarantee the data security	Frank	2021-10-29
332	FR	User management	Organize user access via user identification processes	Frank	2021-11-04
333	FR	Access rights definition	Definition of the access rights for different users and customers according to the booked DT version	Frank	2022-01-06
		3.4. Data Management			
341	DR	Data logging	Store system raw data for verification and analyzation processes and general system optimization/ development approaches	Frank	2021-01-09
342	FR	Integration of REXS dataformats	Integration of REXS dataformat for automated gearbox data integration and DT variant development	Wilking/ Assignment	2021-10-29
343	W	Integration of CAx dataformats	Geometry/ manufacturing/ assembly automated data integration	Wilking/ Assignment	2021-10-29
344	FR	Database set up	Sort the data stream into a database for ordered access	Wilking	2021-10-01
345	ZF	Data search and filterung	Data sorting algorithm establishment for the data selection according to the system request	Frank	2021-11-10
346	FR	Data storage	Storage of the collected operational data as well as the calculated system/ component data in any desired time horizont	Frank	2021-11-15
347	FF	Data structure	Establish a datastructure valid for edge to cloud communication	Frank	2021-11-16
		3.5. Transferability			
351	DR	FVA concept adaptability	Prepare concept for further FVA use cases	FVA	2021-10-28
352	GR	SysML model of DT	Concept of DT is expressed as a SysML Model for clear communication and seemless extension of the work	Development communication	2021-10-01

353	DR	Virtual protoyp preparation	Transfer the DT concept from MoL only use cases to BoL use cases in the development domain	Product Owner/ FVA	2021-12-29
	3.6. System Support				
361	GR	Troubleshooting self support	Provide list of possible and frequent problem statements with solving procedure	User	2021-12-29
362	GR	Support department	Support provision via phone, mail, chat according to booked service fee	User	2021-12-29
Part 4 - Requirements for Concept Generalization					
	4.1. Modularity		**definition and presentation of a clear concept structure that provides adaption elements in order to extent the concept of the DT**		
411	DR	Version administration	Versioning of softwareupdates and administration of actualization	Product Owner	2021-10-21
412	FR	Definition of adaption nodes	Describe system adaption nodes which include system elements that are directly affected by the change of the system and therefore need adaption in order to maintain interoperability	FVA	2022-01-10
413	DR	Modular System	Keep the system modularily extendable	Assignment	2022-01-10

B. Appendix B

Version: 4
State: 2022-03-09

Objects DT Concept

Conceptional Design of a Digital Twin to Predict the Remaining Useful Life Time of a Gearbox

edited by: Michael G. Frank

Part 1 - Protagonists

Designation	**Description**	**Object**	**Datatype**
General Protagonist	Active data request	Query	string
	Signal to enable data presentation	Control Value	boolean
	Measured data (filtered) from the component condition sensors	System Data	double
	Measuring data (filtered) from sensors or actuators	Operational Data	double
	Data time stamping	Time	double
Retail User	Sorted data sets according to GUI	GUI Sorted Data	double/ string
Designer/ System Engineer/ Researcher	Sorted data for categorized retrievement	Sorted System Data	double
Service Worker	Current component state	Component State	double/ string
	Standard system/ component parameters	Comparison Parameters	double/ string
	Maintenance/ replacement itemlist	Itemlist	string
Process Manager	Identified critical component	Critical Component	string
	System state information	Current System State	double/ string
	RUL of a component	Component Lifespan	double
	Critical component/ system state	Critical State	boolean/ string
Sensors	boolean signal/ sensor specific signal	Measurands	boolean
	Measurement initiation signal	Measurement Impulse	double/ boolean

Part 2 - System Elements

Data Buffer	Data storage of simulation calculation output	Simulation Data Input	double
	Output of stored data that was requested	Data Output	double
Technical Display	Data received from adjacent elements	Data Input	double
	Data output according to request	Data Output	double
	User request input	Request Input	string
	Request output to other elements in order to gather data according to user request; e.g. data buffer request	Request Output	string/ double
Simulation Model	Historical system and operational data	Historical Data	double/ string
	Health data of components	Component Condition	double/ string
	Health data of system	System Condition	double/ string
	Defined system data or data sets combined to parameters	Comparison Parameters	double/ string
	Component or system state that is critical and the related component is identified	Critical Component	string
	Component Wear is identified	Component Wear	double/ string
	boolean signal/ sensor specific signal	Measureands Input	boolean
	Conversion of boolean sensor signals into human readable information	Data Procession/ Presentation	double/ string
	Output of calculated models	Calculation Outcomes	double/ string

C. Appendix C

Version 4

Use Cases w Essential Steps DT Concept

Edited by: Michael Georg Frank

Protagonist	Use Case	Essential Step 1	Essential Step 2	Essential Step 3	Essential Step 4	Essential Step 5	Essential Step 6
Service Worker	Query Maintenance Work	Component Status Determination	Maintenance Schedule Comparison	Check Maintenance Necessity	Create Maintenance Plan	Display Maintenance Work	
	Provide Execution Advice	Load Component List	Single Component Query	Load Maintenance Manual	Arrange Maintenance Work	Create Assembly/ Maintenance Explanation	Display Maintenance/ Assembly Explanation
Process Manager	Query Component Status	Component of Interest definition	Component Status Information Aggregation	Information Composition	Display Component Status Information		
	Query Maintenance Schedule	Query Maintenance Work	Compare Schedule/ Maintenance List	Condition Based Maintenance Evaluation	Aggreagte Maintenance Forecast	Compose Necessary Maintenance work	Display Updated Maintenance Work
	Warn Against Critical Status	Current Component/ System State Identification	Target Component/ System State Identification	Current/ Target State Comparison	Deviation Severity/ Relevance Evaluation	Aggregate critical Component List	Warn User
	Choose System Adaption Suggestion	Current System State Identification	Adaption Possibility Aggregation	Evaluation of Adaption Possibilities	Create Adaption Implementation Plan	Display Adaption Suggestion	
Designer	Verify Design Approaches	Implement Mechanical Design Changes	Initiate System Test Run	Analyze System Data	Compare System Data to Target Data		
	Virtual Product Development	Implement Design Process Digitally	Apply Operational System Data on Digital Design	Simulate Virtual Product Behavior	Evaluate Behavior	Iterate Design Process	

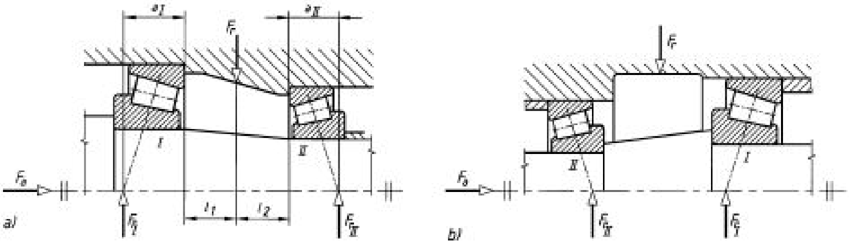
System Engineer	Verify Design Approaches	Implement System Design Changes	Initiate System Test Run	Analyze System Behavior	Compare System Behavior with pursued Design Adaption	Confirm System Design Change Functioning	
	Analyze System Architecture	Create System Architecture Overview	Describe System Element Connections	Analyze Exchanged Objects			
	Compatibility Check of System Adaption	Implement System Element Changes	Initiate System Test Run	Check System Element Functionality	Check System Element Interplay Functioning	Confirm System Design Change Functioning	
System Administrator	User Rights Management	Maintain User List	System Access Permission Description	Relate User ID to Access Permission	Standardize Assignment Process		
	Troubleshooting	Factual Problem Analysis	Read Out Error Code	Root Problem Identification	Remedy Process Initiation		
Retail User	System Extension	Analyse Aspired System Extension Compatibility	Add System Element via Provided Interface				
	Menu System Request	Open Standard GUI	Call Submenu Elements	Provide Standard System Information			
Sensor	Data Provision	Calibrate Sensor	Analog Voltage Signal Creation	Analog to Digital Transduction	Data Quality Indication		
Researcher	Access Advanced System Data	Open Standard GUI	Authorize Deep System Access	Load Advanced System Data			
	Analyze System Behavior	Digital System Data Aggregation	Physical Entity Data Aggregation	Evaluate Datasets			

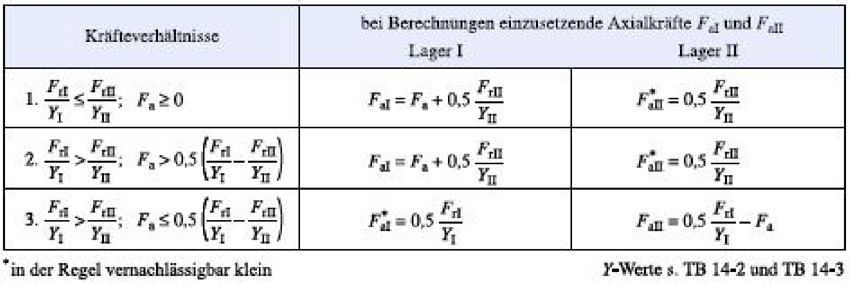
D. Appendix D

Extrapolation of Bearing Forces

Preassumptions

All geometry values are assumed to be known. The related diameters d1, d2, d3, d4 are the pitch cycle diameters. Due to supporting effects resulting from an additional axial load (axial toothing force) between the tapered roller bearings in x-arrangement one bearing caries additional axial load resulting from the counter bearing. Therefore, a case discrimination depicted in D.1 (Wittel et al., 2019) according to the operational loads has to take place. The related Y-factor is mentionend in the shaft (I-III) sections.





Kräfteverhältnisse	bei Berechnungen einzusetzende Axialkräfte F_{aI} und F_{aII} Lager I	Lager II
1. $\frac{F_{rI}}{Y_I} \leq \frac{F_{rII}}{Y_{II}}$; $F_a \geq 0$	$F_{aI} = F_a + 0{,}5\,\frac{F_{rII}}{Y_{II}}$	$F_{aII}^{*} = 0{,}5\,\frac{F_{rII}}{Y_{II}}$
2. $\frac{F_{rI}}{Y_I} > \frac{F_{rII}}{Y_{II}}$; $F_a > 0{,}5\left(\frac{F_{rI}}{Y_I} - \frac{F_{rII}}{Y_{II}}\right)$	$F_{aI} = F_a + 0{,}5\,\frac{F_{rII}}{Y_{II}}$	$F_{aII}^{*} = 0{,}5\,\frac{F_{rII}}{Y_{II}}$
3. $\frac{F_{rI}}{Y_I} > \frac{F_{rII}}{Y_{II}}$; $F_a \leq 0{,}5\left(\frac{F_{rI}}{Y_I} - \frac{F_{rII}}{Y_{II}}\right)$	$F_{aI}^{*} = 0{,}5\,\frac{F_{rI}}{Y_I}$	$F_{aII} = 0{,}5\,\frac{F_{rI}}{Y_I} - F_a$

*in der Regel vernachlässigbar klein

Y-Werte s. TB 14-2 und TB 14-3

Figure D.1.: Tapered Roller Bearings - Case Discrimination (Wittel et al., 2019)

Free Body Diagram SEW Gearbox

The in D.2 depicted toothing forces are categorized in: Fz=radial toothing force; Fy=tangential toothing force; Fx=axial toothing force. The following dependencies, with the flank to normal angle α and the helix anlge β, apply:

$$F_x = F_y * tan(\beta) \tag{D.1}$$

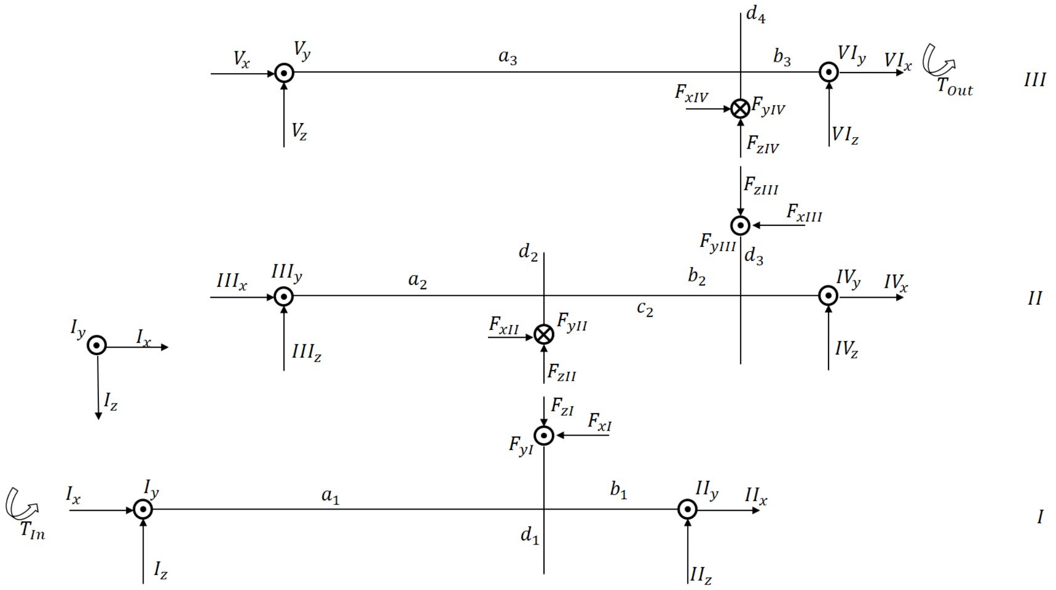


Figure D.2.: Free Body Diagram Two-Stage Gearbox

$$F_z = F_y * (tan(\alpha)/cos(\beta)) \tag{D.2}$$

Balance of Forces Shaft I

$$Z : -I_z - II_z + F_{zI} = 0 \tag{D.3}$$

$$Y : I_y + II_y + F_{yI} = 0 \tag{D.4}$$

$$X : I_x - F_{xI} + II_x = 0 \tag{D.5}$$

$$T1 : F_{xI} = F_{yI} * tan(\beta_1) \tag{D.6}$$

$$T1 : F_{zI} = F_{yI} * (tan(\alpha_1)/cos(\beta_1)) \tag{D.7}$$

Balance of Moments Shaft I, Bearing I

$$Z : a_1 * F_{yI} + (a_1 + b_1) * II_y = 0 \tag{D.8}$$

$$Y : -a_1 * F_{zI} + d_1/2 * F_{x1} + (a_1 + b_1) * II_z = 0 \tag{D.9}$$

$$X : T_{In} + (d_1/2) * F_{yI} = 0 \tag{D.10}$$

Balance of Forces Shaft II

$$Z : -IV_z - III_Z + F_{zIII} - F_{zII} = 0 \tag{D.11}$$

$$Y : IV_y + III_y - F_{yII} + F_{yIII} = 0 \tag{D.12}$$

$$X : III_x + F_{xII} - F_{xIII} + IV_x = 0 \tag{D.13}$$

$$T2 : F_{xII} = F_{yII} * tan(\beta_2) \tag{D.14}$$

$$T2 : F_{zII} = F_{yII} * (tan(\alpha_2)/cos(\beta_2)) \tag{D.15}$$

Balance of Moments Shaft II, Bearing III

$$Z : -a_2 * F_{yII} + (a_2 + b_2) * IV_y + (a_2 + c_2) * F_{yIII} = 0 \tag{D.16}$$

$$Y : a_2 * F_{zII} - (a_2 + c_2) * F_{zIII} + (a_2 + b_2) * IV_z + (d_2/2) * F_{xII} + (d_3/2) * FxIII = 0 \tag{D.17}$$

$$X : (d_2/2) * F_{yII} + (d_3/2) * F_{yIII} = 0 \tag{D.18}$$

Balance of Forces Shaft III

$$Z : -V_z - VI_z - F_{zIV} = 0 \tag{D.19}$$

$$Y : V_y - F_{yIV} + VI_y = 0 \tag{D.20}$$

$$X : V_x + F_{xIV} + VI_x = 0 \tag{D.21}$$

$$T3 : F_{xIV} = F_{yIV} * tan(\beta_3) \tag{D.22}$$

$$T3 : F_{zIV} = F_{yIV} * (tan(\alpha_3)/cos(\beta_3)) \tag{D.23}$$

Balance of Moments Shaft III, Bearing V

$$Z : -a_3 * F_{yIV} + (a_3 + b_3) * VI_y = 0 \tag{D.24}$$

$$Y : a_3 * F_{zIV} + (d_4/2) * F_{xIV} + (a_3 + b_3) * VI_z = 0 \tag{D.25}$$

$$X : (d_4/2) * F_{yIV} + T_{Out} = 0 \tag{D.26}$$

Variable Dependencies

Interlocking Forces

$$F_{yIV} = F_{yIII} \tag{D.27}$$

$$F_{yII} = F_{yI} \tag{D.28}$$

$$F_{zI} = F_{zII} \tag{D.29}$$

$$F_{xII} = F_{xI} \tag{D.30}$$

$$F_{xIV} = F_{xIII} \tag{D.31}$$

$$F_{zIII} = F_{zIV} \tag{D.32}$$

Equation Reforming Bearing Forces Extrapolation

Known Values

Geometry Values: a1, a2, a3; b1, b2, b3; c2; d1, d2, d3; $\alpha_1, \alpha_2, \alpha_3; \beta_1, \beta_2, \beta_3$
Bearing Forces Shaft I: Ix, Iy, Iz; IIy, IIz, IIx
Torque: TIn; TOut

Shaft I

$$F_{zI} = I_z + II_z = F_{zII} \tag{D.33}$$

$$F_{yI} = -I_y - II_y = F_{yII} \tag{D.34}$$

$$F_{xI} = I_x - II_x = F_{xII} \tag{D.35}$$

Shaft II

With:

$$F_{yIV} = (-T_{Out} * 2)/d_4 = F_{yIII} \tag{D.36}$$

Results:

$$T3 : F_{xIII} = F_{yIII} * tan(\beta_3) \tag{D.37}$$

$$T3 : F_{zIII} = F_{yIII} * (tan(\alpha_3)/cos(\beta_3)) \tag{D.38}$$

With:

$$IV_y = (-(a_2 + c_2) * F_{yIII} + a_2 * F_{yII})/(a_2 + b_2) \tag{D.39}$$

$$III_y = F_{yII} - F_{yIII} - IV_y \tag{D.40}$$

$$IV_z = (-(d_2/2) * F_{xII} - (d_3/2) * FxIII + (a_2 + c_2) * F_{zIII} - a_2 * F_{zII})/(a_2 + b_2) \tag{D.41}$$

Results:

$$D7 : III_Z + = IV_z - F_{zIII} + F_{zII} \tag{D.42}$$

$$F_{yIII} = ((d_2/2) * F_{yII})/(d_3/2) \tag{D.43}$$

With:

$$III_x = -F_{xII} + F_{xIII} + IV_x = 0 \tag{D.44}$$

The necessity for the case discrimination is pointed out. According to Hauptverwaltung der SKF Gruppe, 2022c the Y-factor for the equivalent bearing force calculation is: $Y_{II} = Y_{III}$=1.7. With this factor and the absolute operational loads the concrete axial bearing forces can be calculated according to D.1.

Shaft III

With:

$$F_{yIV} = F_{yIII} \tag{D.45}$$

Results:

$$VI_y = a_3 * F_{yIV}/(a_3 + b_3) \tag{D.46}$$

$$V_y = +F_{yIV} - VI_y \tag{D.47}$$

With:

$$T3 : F_{xIV} = F_{yIV} * tan(\beta_3) \tag{D.48}$$

$$T3 : F_{zIV} = F_{yIV} * (tan(\alpha_3)/cos(\beta_3)) \tag{D.49}$$

Results:

$$VI_z = (-a_3 * F_{zIV} - (d_4/2) * F_{xIV})/(a_3 + b_3) \tag{D.50}$$

$$V_z = -V_I z - F_{zIV} \tag{D.51}$$

With:

$$V_x = -F_{xIV} + VI_x \tag{D.52}$$

The necessity for the case discrimination is pointed out. According to Hauptverwaltung der SKF Gruppe, 2022a, 2022b the Y-factor for the equivalent bearing force calculation is: Y_V=1.5 and Y_{VI}=1.4. With these factors and the absolute operational loads the concrete axial bearing forces can be calculated according to D.1.

SEW Gearbox Dimensions

In D.3 the dimensions of the SEW gearbox are depicted (Measurement by Tom Gundlach). With these and the in appendix G provided geometrical gearbox data the concrete bearing forces can be calculated.

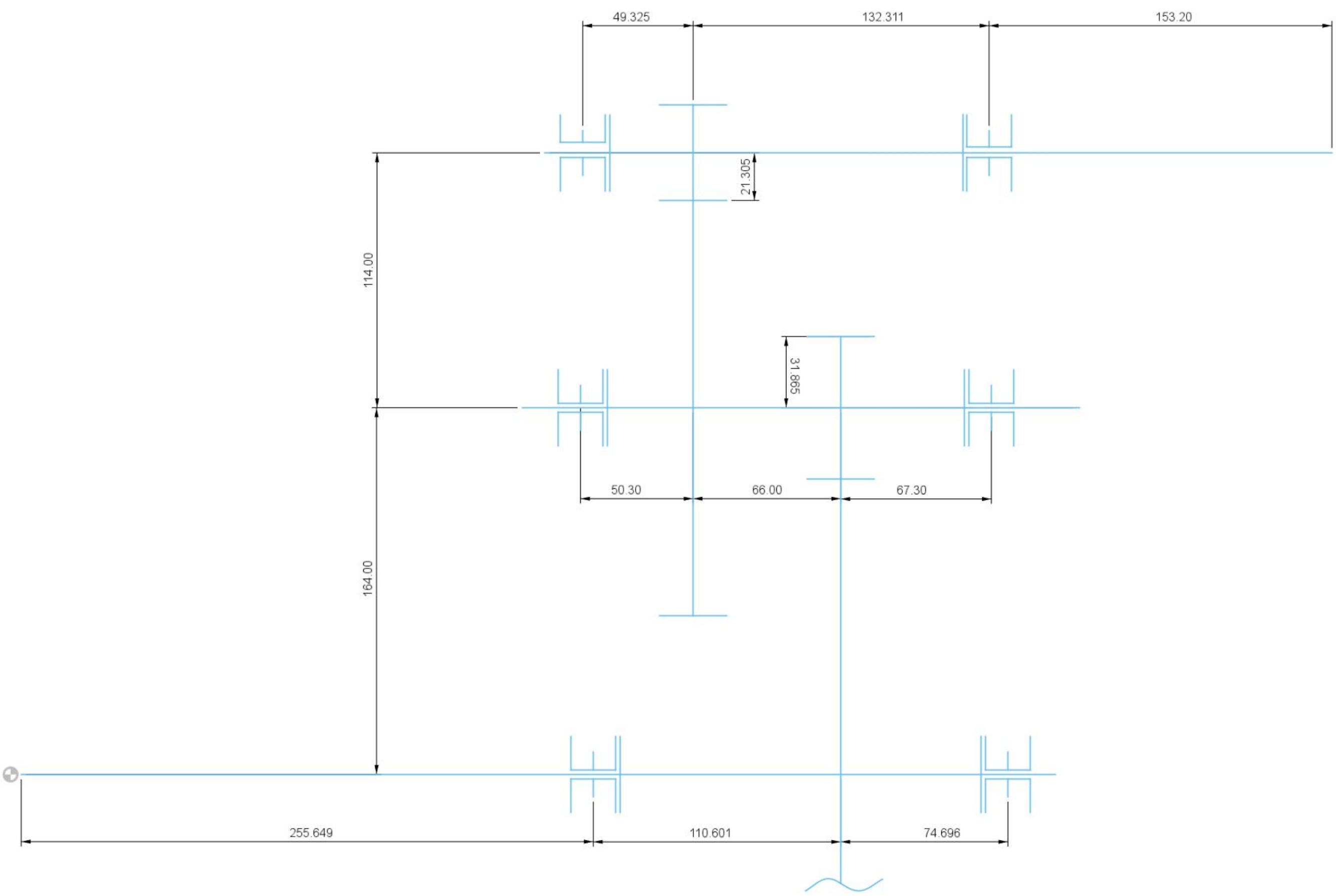


Figure D.3.: Gearbox Dimensions Typ SEW X2FS100e-H-B (Constructed by Tom Gundlach)

E. Appendix E

Damage Accumulation Toothflank Pittings

With the nominal Stress of the toothflank σ_{H0}:

$$\sigma_{H0} = Z_H * Z_E * Z_\epsilon * Z_\beta * \sqrt{\frac{F_t}{b * d} * \frac{u+1}{u}} \tag{E.1}$$

The effective stress of the toothflank σ_H can be calculated:

$$\sigma_H = \sqrt{K_A * K_V * K_{H\alpha} * K_{H\beta}} * Z_{B,D} * \sigma_{H0} \tag{E.2}$$

With the permitted stress of the toothflank σ_{HP}:

$$\sigma_{HP} = Z_L * Z_V * Z_R * Z_W * Z_X * \frac{\sigma_{Hlim} * Z_{NT}}{S_{Hmin}} \tag{E.3}$$

And the adaption of the lifetime factor Z_{NT}:

$$Z_{NT} = \sqrt[k_H]{\frac{N_{Hlim}}{N_L}} \tag{E.4}$$

Where the inclination paramter k_h of the S-N curve, the number of current cycles N_L and the number of cycles of the kink point from fatigue strength to endurance strength (double logarithmic plot) N_{Hlim} can be extracted from the S-N curve for hertzian contact pressure according to the used toothing material, exemplarily depicted in E.1. Note that if no special S-N curve for the gear is available $N_{Hlim} = N_A$.

Results the accumulated damage according to:

$$D(t) = \int_{\tau=0}^{\tau=t} \frac{n(t)}{N_A} * \left(\frac{\sigma_{HP}}{\sigma_H}\right)^{-k_H} d\tau \tag{E.5}$$

The load based approach is based on measurement of the speed $n(t)$ and the tangential tooth force F_t which can be measured via a torque measurement at the shaft. The used toothing factors Z_x and K_x have to be determined according to the used toothing. Note that the accumulated damage integral has to be calculated for each time period depending on the constant phase of the effective stress of the toothflank (load spectra aggregation). The calculations and equations are based on the elaborations in the lecture Innovative Machine Elements 1 and partly adopted from Schlecht, 2010 respecitvely *ISO 6336-2:2019*, 2019.

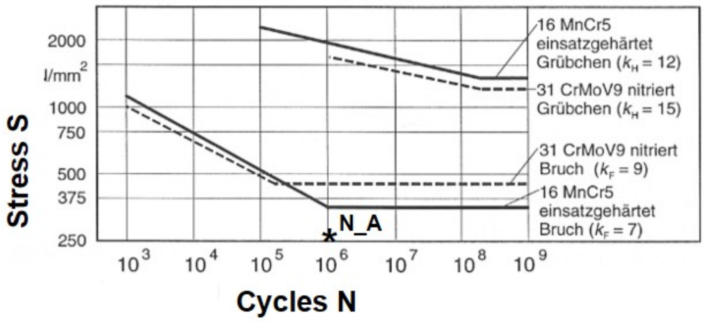


Figure E.1.: Examplary S-N Curve Hertzian Contact Pressure/ Bending Stress (based on Kirchner, 2007)

F. Appendix F

Damage Accumulation Toothroot Failure

Estimation for tooth root crack at tensile side; Cracking at pressure side is not decisive (=bending load).

With the nominal Stress of the tooth root σ_{F0}:

$$\sigma_{F0} = \frac{F_t}{b * m_n} * Y_S * Y_F * Y_\beta \tag{F.1}$$

The effective stress of the tooth root σ_F can be calculated:

$$\sigma_F = K_A * K_V * K_{F\beta} * K_{F\alpha} * \sigma_{F0} \tag{F.2}$$

With the permitted stress of the tooth root σ_{FP}:

$$\sigma_{FP} = \frac{\sigma_{Flim} * Y_{ST} * Y_{NT}}{S_{Fmin}} * Y_{\delta relT} * Y_{RrelT} * Y_X \tag{F.3}$$

And the adaption of the lifetime factor Y_{NT}:

$$Y_{NT} = \sqrt[k_F]{\frac{N_{Flim}}{N_L}} \tag{F.4}$$

Where the inclination paramter k_F of the S-N curve, the number of current cycles N_L and the number of cycles of the kink point from fatigue strength to endurance strength (double logarithmic plot) N_{Hlim} can be extracted from the S-N curve for bending stress according to the used toothing material, exemplarily depicted in E.1. Note that if no special S-N curve for the gear is available $N_{Flim} = N_A$.

Results the accumulated damage according to:

$$D(t) = \int_{\tau=0}^{\tau=t} \frac{n(t)}{N_A} * \left(\frac{\sigma_{FP}}{\sigma_H}\right)^{-k_F} d\tau \tag{F.5}$$

The load based approach is based on measurement of the speed $n(t)$ and the tangential tooth force F_t which can be measured via a torque measurement at the shaft. The used toothing factors Y_x and K_x have to be determined according to the used toothing. Note that the accumulated damage integral has to be calculated for each time period depending on the constant phase of the effective stress of the toothflank (load spectra aggregation). The calculations and equations are based on the elaborations in the lecture

Innovative Machine Elements 1 and partly adopted from Schlecht, 2010 respectively *ISO 6336-3:2019*, 2019.

Bibliography

Abramovici, M., Savarino, P., Göbel, J. C., Adwernat, S., & Gebus, P. (2018). Systematization of virtual product twin models in the context of smart product reconfiguration during the product use phase. *Procedia CIRP*, *69*, 734–739. https://doi.org/10.1016/j.procir.2017.11.025

Ahamed, N., Pandya, Y., & Parey, A. (2014). Spur gear tooth root crack detection using time synchronous averaging under fluctuating speed. *Measurement*, *52*, 1–11. https://doi.org/10.1016/j.measurement.2014.02.029

Barszcz, T. (2019, January 19). *Vibration-based condition monitoring of wind turbines*. Springer-Verlag GmbH. https://www.ebook.de/de/product/34865860/tomasz_barszcz_vibration_based_condition_monitoring_of_wind_turbines.html

Bertsche, B. (2011). *Reliability in automotive and mechanical engineering*. Springer Berlin Heidelberg. https://www.ebook.de/de/product/14809840/bernd_bertsche_reliability_in_automotive_and_mechanical_engineering.html

Bi, Z., Zhang, W., & Lang, S. (2002). Modular robot system architecture. *7th International Conference on Control, Automation, Robotics and Vision, 2002. ICARCV 2002.* https://doi.org/10.1109/icarcv.2002.1238569

Borghesi, A., Modica, G. D., Bellavista, P., Gowtham, V., Willner, A., Nehls, D., Kintzler, F., Cejka, S., Tisbeni, S. R., Costantini, A., Galletti, M., Antonacci, M., & Ahouangonou, J. C. (2021). IoTwins: Design and implementation of a platform for the management of digital twins in industrial scenarios. *2021 IEEE/ACM 21st International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*. https://doi.org/10.1109/ccgrid51090.2021.00075

Brancovici, G., & Müller-Schloer, C. (2007). A generic and modular system architecture for trustworthy, autonomous applications. In *Lecture notes in computer science* (pp. 169–178). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-73547-2_19

Bröhl. (1995). *Das v-modell der standard für die softwareentwicklung mit praxisleitfaden*. Oldenbourg.

Carvalho, R., & da Silva, A. R. (2021). Sustainability requirements of digital twin-based systems: A meta systematic literature review. *Applied Sciences*, *11*(12), 5519. https://doi.org/10.3390/app11125519

Czwick, C., & Anderl, R. (2020). Cyber-physical twins - definition, conception and benefit. *Procedia CIRP*, *90*, 584–588. https://doi.org/10.1016/j.procir.2020.01.070

Czwick, C., Kugler, S., Greven, J., & Anderl, R. (2019). Communication protocol application for enhanced connectivity of sensors, machines and systems in additive manufacturing and production networks. In *IFIP advances in information and communication technology* (pp. 136–145). Springer International Publishing. https://doi.org/10.1007/978-3-030-42250-9_13

Czwick, C., Martin, G., Anderl, R., & Kirchner, E. (2020). Cyber-physische zwillinge. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *115*(s1), 90–93. https://doi.org/10.3139/104.112310

DeMarco, T. (1979). *Structured analysis and system specification*. Prentice-Hall.

DeMarco, T. (2002). Structured analysis and system specification. In *Software pioneers* (pp. 529–560). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-59412-0_33

Dhamande, L. S., & Chaudhari, M. B. (2016). Detection of combined gear-bearing fault in single stage spur gear box using artificial neural network. *Procedia Engineering*, *144*, 759–766. https://doi.org/10.1016/j.proeng.2016.05.082

Dietrich, F., Thiede, S., & Seliger, G. (2018). Maintenance. In *CIRP encyclopedia of production engineering* (pp. 1–5). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_12-3

Durão, L. F. C. S., Haag, S., Anderl, R., Schützer, K., & Zancul, E. (2018). Digital twin requirements in the context of industry 4.0. In *Product lifecycle management to support industry 4.0* (pp. 204–214). Springer International Publishing. https://doi.org/10.1007/978-3-030-01614-2_19

Ferrari, P., Flammini, A., Rinaldi, S., Sisinni, E., Maffei, D., & Malara, M. (2018). Evaluation of communication delay in IOT applications based on OPCUA. *2018 Workshop on Metrology for Industry 4.0 and IoT*. https://doi.org/10.1109/metroi4.2018.8428346

Francalanza, E., Mercieca, M., & Fenech, A. (2018). Modular system design approach for cyber physical production systems. *Procedia CIRP*, *72*, 486–491. https://doi.org/10.1016/j.procir.2018.03.090

FVA Forschungsvereinigung Antriebstechnik e.V. (Ed.). (2022, March 18). *Our Software - The FVA Workbench: Leading drive design software*. https://www.fva-service.de/en/software/

FVA Richtlinie - Programmierrichtlinie. (2012, January 9). FVA Forschungsvereinigung Antriebstechnik e.V.

GitHub, Inc. (Ed.). (2022, March 18). *Where the world builds software: Millions of developers and companies build, ship, and maintain their software on github—the largest and most advanced development platform in the world.* https://github.com/

Goebel, K. (2017). *Prognostics : The science of making predictions*. CreateSpace Independent Publishing Platform.

Golafshan, R., Dascaliuc, C., Jacobs, G., Roth, D. J., Berroth, J. K., & Neumann, S. (2021). Damage diagnosis of cardan shafts in mobile mining machines using vibration analysis. *19th Drive Train Technology Conference (ATK 2021) 9th-11th March 2021, Aachen*, 1–12 (2021). doi:10.1088/1757. https://doi.org/10.18154/RWTH-2021-04403

Grieves, M. (2005). Product lifecycle management: The new paradigm for enterprises. *International Journal of Product Development*, *2*(1/2), 71. https://doi.org/10.1504/ijpd.2005.006669

Grieves, M. (2015). Digital twin: Manufacturing excellence through virtual factory replication.

Grieves, M., & Vickers, J. (2016). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary perspectives on complex systems* (pp. 85–113). Springer International Publishing. https://doi.org/10.1007/978-3-319-38756-7_4

Guizani, M. (2019). The industrial internet of things vocabulary (Industrial Internet Consortium, Ed.). *IEEE Network*, *33*(5), 4–4. https://doi.org/10.1109/mnet.2019.8863716

Haibach, E. (2002). Experimentelle grundlagen der betriebsfestigkeit. In *Betriebsfestigkeit* (pp. 21–149). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-06038-4_2

Hauptverwaltung der SKF Gruppe (Ed.). (2022a, March 13). *30213 - kegelrollenlager einreihig*. https://www.skf.com/de/products/rolling-bearings/roller-bearings/tapered-roller-bearings/single-row-tapered-roller-bearings/productid-30213

Hauptverwaltung der SKF Gruppe (Ed.). (2022b, March 13). *32018 x - kegelrollenlager einreihig*. https://www.skf.com/de/products/rolling-bearings/roller-bearings/tapered-roller-bearings/single-row-tapered-roller-bearings/productid-32018%20X

Hauptverwaltung der SKF Gruppe (Ed.). (2022c, March 13). *32310 - kegelrollenlager einreihig*. https://www.skf.com/de/products/rolling-bearings/roller-bearings/tapered-roller-bearings/single-row-tapered-roller-bearings/productid-32310

Hausmann, M., Koch, Y., & Kirchner, E. (2021). Managing the uncertainty in data-acquisition by in situ measurements: A review and evaluation of sensing machine element-approaches in the context of digital twins. *International Journal of Product Lifecycle Management*, *13*(1), 48. https://doi.org/10.1504/ijplm.2021.115700

He, B., Liu, L., & Zhang, D. (2021). Digital twin-driven remaining useful life prediction for gear performance degradation: A review. *Journal of Computing and Information Science in Engineering*, *21*(3). https://doi.org/10.1115/1.4049537

He, Y., Guo, J., & Zheng, X. (2018). From surveillance to digital twin: Challenges and recent advances of signal processing for industrial internet of things. *IEEE Signal Processing Magazine*, *35*(5), 120–129. https://doi.org/10.1109/msp.2018.2842228

Hering, E. (2018). *Sensoren in wissenschaft und technik funktionsweise und einsatzgebiete*. Springer Vieweg.

Herrmann, C. (2018). Product life cycle management. In *CIRP encyclopedia of production engineering* (pp. 1–4). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_6610-3

Holt, J. (2008). *Sysml for systems engineering*. Institution of Engineering; Technology.

Hu, C., Smith, W. A., Randall, R. B., & Peng, Z. (2016). Development of a gear vibration indicator and its application in gear wear monitoring. *Mechanical Systems and Signal Processing*, *76-77*, 319–336. https://doi.org/10.1016/j.ymssp.2016.01.018

INCOSE. (2007). *Systems engineering vision 2020* (tech. rep. INCOSE-TP-2004-004-02). Technical Operations International Council on Systems Engineering (INCOSE).

ISO 10007:2017: Quality management — guidelines for configuration management (Standard). (2017, March). Internatinal Organization of Standardization - ISO/TC 176/SC 2Quality systems.

ISO 13372:2012: Condition monitoring and diagnostics of machines - vocabulary (Standard). (2012, September 15). International Organization of Standardization - ISO/TC 108/SC 5 Condition monitoring and diagnostics of machine systems.

ISO 13374-1:2003: Condition monitoring and diagnostics of machines - data processing, communication and presentation part 1: General guidelines (Standard). (2003, March 15). International Organization of Standardization - ISO/TC 108/SC 5 Condition monitoring and diagnostics of machine systems.

ISO 13374-2:2007: Condition monitoring and diagnostics of machines — data processing, communication and presentation — part 2: Data processing (tech. rep.). (2007, July 15). Internatinal Organization of Standardization - ISO/TC 108/SC 5Condition monitoring and diagnostics of machine systems.

ISO 17359:2018: Condition monitoring and diagnostics of machines — general guidelines (Standard). (2018, January). Internatinal Organization of Standardization - ISO/TC 108/SC 5Condition monitoring and diagnostics of machine systems.

ISO 6336-2:2019: Calculation of load capacity of spur and helical gears — part 2: Calculation of surface durability (pitting) (Standard). (2019, November). Internatinal Organization of Standardization - ISO/TC 60/SC 2Gear capacity calculation.

ISO 6336-3:2019: Calculation of load capacity of spur and helical gears — part 3: Calculation of tooth bending strength (Standard). (2019, November). Internatinal Organization of Standardization -.

ISO/IEC 7498-1:1994: Information technology — open systems interconnection — basic reference model: The basic model (Standard). (1994). International Organization of Standardization -ISO/IEC JTC 1 Information technology.

Jablonski, A. (2021). *Condition monitoring algorithms in matlab®*. Springer International Publishing. https://www.ebook.de/de/product/41248732/adam_jablonski_condition_monitoring_algorithms_in_matlab.html

Jardine, A. K., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, *20*(7), 1483–1510. https://doi.org/10.1016/j.ymssp.2005.09.012

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: A review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2065), 20150202. https://doi.org/10.1098/rsta.2015.0202

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the digital twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, *29*, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

Juarez, M. G., Botti, V. J., & Giret, A. S. (2021). Digital twins: Review and challenges. *Journal of Computing and Information Science in Engineering*, *21*(3). https://doi.org/10.1115/1.4050244

Kim, N.-H., An, D., & Choi, J.-H. (2017). *Prognostics and health management of engineering systems*. Springer International Publishing. https://doi.org/10.1007/978-3-319-44742-1

Kirchner, E. (Ed.). (2007). *Leistungsübertragung in fahrzeuggetrieben*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-35292-1

Kirchner, E. (2020). *Werkzeuge und methoden der produktentwicklung*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-61762-5

Köhler, M., Jenne, S., Pötter, K., & Zenner, H. (2012). *Zählverfahren und lastannahme in der betriebsfestigkeit*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-13164-6

Kraft, E. M. (2016). The air force digital thread/digital twin - life cycle integration and use of computational and experimental knowledge. *54th AIAA Aerospace Sciences Meeting*. https://doi.org/10.2514/6.2016-0897

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, *51*(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Kugler, S., Czwick, C., & Anderl, R. (2019). Development of a valuation method for IoT-platforms. In *IFIP advances in information and communication technology* (pp. 293–301). Springer International Publishing. https://doi.org/10.1007/978-3-030-42250-9_28

Kumar, A., Gandhi, C., Zhou, Y., Kumar, R., & Xiang, J. (2020). Latest developments in gear defect diagnosis and prognosis: A review. *Measurement*, *158*, 107735. https://doi.org/10.1016/j.measurement.2020.107735

Laghmouchi, A. (2017). *Adaptives entwicklungstool zur intelligenten konfigurierung von condition-monitoring-algorithmen*. Fraunhofer Verlag.

Lee, J., Lapira, E., Bagheri, B., & Kao, H.-a. (2013). Recent advances and trends in predictive manufacturing systems in big data environment. *Manufacturing Letters*, *1*(1), 38–41. https://doi.org/10.1016/j.mfglet.2013.09.005

Lempert, S. (2021, September 16). *Iot-software-plattformen*. Springer Fachmedien Wiesbaden. https://www.ebook.de/de/product/41504105/sebastian_lempert_iot_software_plattformen.html

Li, Z., Jiang, Y., Hu, C., & Peng, Z. (2016). Recent progress on decoupling diagnosis of hybrid failures in gear transmission systems using vibration sensor signal: A review. *Measurement*, *90*, 4–19. https://doi.org/10.1016/j.measurement.2016.04.036

Liang, L., Liu, F., Kong, X., Li, M., & Xu, G. (2019). Application of instantaneous rotational speed to detect gearbox faults based on double encoders. *Chinese Journal of Mechanical Engineering*, *32*(1). https://doi.org/10.1186/s10033-019-0324-z

Luntovskyy, A., & Gütter, D. (2020). *Moderne rechnernetze*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-25617-3

Lutters, E. (2018). Design methodology. In *CIRP encyclopedia of production engineering* (pp. 1–3). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_6449-3

Majumdar, P., Haider, M. F., & Reifsnider, K. (2013). Multi-physics response of structural composites and framework for modeling using material geometry. *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. https://doi.org/10.2514/6.2013-1577

Mämpel, J. (2010). *Definition und exemplarische realisation eines modularen systems für die kletterrobotik*. Univ.-BibliothekUniv.-Verl. Ilmenau.

Marino, S., Hogue, I. B., Ray, C. J., & Kirschner, D. E. (2008). A methodology for performing global uncertainty and sensitivity analysis in systems biology. *Journal of Theoretical Biology*, *254*(1), 178–196. https://doi.org/10.1016/j.jtbi.2008.04.011

Martin, G. (2021). *Die wälzlagerimpedanz als werkzeug zur untersuchung von oberflächenabweichungen in wälzlagern*. https://d-nb.info/124552920X/34

Marwedel, P. (2021). *Eingebettete systeme*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-33437-6

Masrour, T., Hassani, I. E., & Cherrafi, A. (Eds.). (2021). *Artificial intelligence and industrial applications*. Springer International Publishing. https://doi.org/10.1007/978-3-030-53970-2

Meroth, A., & Sora, P. (2018). *Sensornetzwerke in theorie und praxis*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-18386-8

Moghadam, F. K., de S. Rebouças, G. F., & Nejad, A. R. (2021). Digital twin modeling for predictive maintenance of gearboxes in floating offshore wind turbine drivetrains. *Forschung im Ingenieurwesen*, *85*(2), 273–286. https://doi.org/10.1007/s10010-021-00468-9

Moghadam, F. K., & Nejad, A. R. (2022). Online condition monitoring of floating wind turbines drivetrain by means of digital twin. *Mechanical Systems and Signal Processing*, *162*, 108087. https://doi.org/10.1016/j.ymssp.2021.108087

Mohammed, O. D., Rantatalo, M., & Aidanpää, J.-O. (2015). Dynamic modelling of a one-stage spur gear system and vibration-based tooth crack detection analysis. *Mechanical Systems and Signal Processing*, *54-55*, 293–305. https://doi.org/10.1016/j.ymssp.2014.09.001

Monostori, L. (2018). Cyber-physical systems. In *CIRP encyclopedia of production engineering* (pp. 1–8). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_16790-1

Moyne, J., Qamsane, Y., Balta, E. C., Kovalenko, I., Faris, J., Barton, K., & Tilbury, D. M. (2020). A requirements driven digital twin framework: Specification and opportunities. *IEEE Access*, *8*, 107781–107801. https://doi.org/10.1109/access.2020.3000437

Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. *Procedia Manufacturing*, *11*, 939–948. https://doi.org/10.1016/j.promfg.2017.07.198

Nguyen, H. P. L. (2019, September 29). *Entwicklung einer methode zur zielgerichteten auswahl und aufbau einer iot-plattform* (Masterthesis). Technical University Darmstadt.

Obdenbusch, M. (2017). *Referenzarchitektur für cloudbasiertes condition monitoring am beispiel von verpackungsmaschinen = reference architecture for cloud-based condition monitoring using the example of packaging machines*. Apprimus Verlag.

Pelz, P. F., Groche, P., Pfetsch, M. E., & Schaeffner, M. (Eds.). (2021). *Mastering uncertainty in mechanical engineering*. Springer International Publishing. https://doi.org/10.1007/978-3-030-78354-9

Pianosi, F., Sarrazin, F., & Wagener, T. (2015). A matlab toolbox for global sensitivity analysis. *Environmental Modelling & Software*, *70*, 80–85. https://doi.org/10.1016/j.envsoft.2015.04.009

Răileanu, S., Borangiu, T., Ivănescu, N., Morariu, O., & Anton, F. (2019). Integrating the digital twin of a shop floor conveyor in the manufacturing control system. In *Service oriented, holonic and multi-agent manufacturing systems for industry of the future* (pp. 134–145). Springer International Publishing. https://doi.org/10.1007/978-3-030-27477-1_10

Randall, R. B. (2021). *Vibration-based condition monitoring : Industrial, automotive and aerospace applications*. Wiley.

Randall, R. B., & Antoni, J. (2011). Rolling element bearing diagnostics—a tutorial. *Mechanical Systems and Signal Processing*, *25*(2), 485–520. https://doi.org/10.1016/j.ymssp.2010.07.017

Reiche, L. T., Gundlach, C. S., Mewes, G. F., & Fay, A. (2021). The digital twin of a system: A structure for networks of digital twins. *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. https://doi.org/10.1109/etfa45728.2021.9613594

Rios, J., Staudter, G., Weber, M., & Anderl, R. (2019). A review, focused on data transfer standards, of the uncertainty representation in the digital twin context. In *IFIP advances in information and communication technology* (pp. 24–33). Springer International Publishing. https://doi.org/10.1007/978-3-030-42250-9_3

Roy, S. K., Mohanty, A. R., & Kumar, C. S. (2014). Fault detection in a multistage gearbox by time synchronous averaging of the instantaneous angular speed. *Journal of Vibration and Control*, *22*(2), 468–480. https://doi.org/10.1177/1077546314533582

Rupp, C., Queins, S., & SOPHISTen, D. (2012, April 3). *Uml 2 glasklar*. Hanser Fachbuchverlag. https://www.ebook.de/de/product/18112464/christine_rupp_stefan_queins_die_sophisten_uml_2_glasklar.html

Schirra, T. (2021). *Phänomenologische betrachtung der sensorisch nutzbaren effekte am wälzlager – einfluss unbelasteter wälzkörper auf die elektrische impedanz* (Doctoral dissertation). Darmstadt. https://d-nb.info/1233429493/34

Schirra, T., Martin, G., Vogel, S., & Kirchner, E. (2018). Ball bearings as sensors for systematical combination of load and failure monitoring. *Proceedings of the DESIGN 2018 15th International Design Conference*. https://doi.org/10.21278/idc.2018.0306

Schlecht, B. (2010). *Maschinenelemente 2 - getriebe verzahnungen lagerungen: 2. getriebe - verzahnung - lagerungen*. Pearson Studium.

Schluse, M., & Rossmann, J. (2016). From simulation to experimentable digital twins: Simulation-based development and operation of complex technical systems. *2016 IEEE International Symposium on Systems Engineering (ISSE)*. https://doi.org/10.1109/syseng.2016.7753162

Schmidt, F., Schuhmann, A., Stein, L., & Zotz, A. (2021, April 19). Advanced design project - conceptual design of a testing facility to validate sensor integration in heavy duty gear units.

Schroeder, G. N., Steinmetz, C., Pereira, C. E., & Espindola, D. B. (2016). Digital twin data modeling with AutomationML and a communication methodology for data exchange. *IFAC-PapersOnLine*, *49*(30), 12–17. https://doi.org/10.1016/j.ifacol.2016.11.115

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., & Wang, L. (2010). *Draft modeling, simulation, informationtechnology and processing roadmap*. National Academies Press.

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., & Wang, L. (2012). NASA space technology roadmaps and priorities. National Academies Press. https://doi.org/10.17226/13354

Sharma, V., & Parey, A. (2016). A review of gear fault diagnosis using various condition indicators. *Procedia Engineering*, *144*, 253–263. https://doi.org/10.1016/j.proeng.2016.05.131

Si, X.-S., Zhang, Z.-X., & Hu, C.-H. (2017, February 9). *Data-driven remaining useful life prognosis techniques*. Springer Berlin Heidelberg. https://www.ebook.de/de/product/27810066/xiao_sheng_si_zheng_xin_zhang_chang_hua_hu_data_driven_remaining_useful_life_prognosis_techniques.html

Sinha, J. K. (2020, January). *Industrial approaches in vibration-based condition monitoring*. CRC Press. https://doi.org/10.1201/9781315147222

Sjarov, M., Lechler, T., Fuchs, J., Brossog, M., Selmaier, A., Faltus, F., Donhauser, T., & Franke, J. (2020). The digital twin concept in industry – a review and systematization. *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. https://doi.org/10.1109/etfa46521.2020.9212089

Slatter, R. (2018). Low power miniaturized tunnel magnetoresistive (tmr) sensors for in-dustry 4.0 applications. In *Micro-nano-integration ; 7th gmm-workshop : 22-23 oct. 2018*. VDE Verlag.

Stark, J. (2015). *Product lifecycle management*. Springer.

Stark, R., Anderl, R., Thoben, K.-D., & Wartzack, S. (2020). WiGeP-positionspapier: „digitaler zwilling“. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *115*(s1), 47–50. https://doi.org/10.3139/104.112311

Stark, R., & Damerau, T. (2019). Digital twin. In *CIRP encyclopedia of production engineering* (pp. 1–8). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_16870-1

Stark, R., Fresemann, C., & Lindow, K. (2019). Development and operation of digital twins for technical systems and services. *CIRP Annals*, *68*(1), 129–132. https://doi.org/10.1016/j.cirp.2019.04.024

Stark, R., & Halstenberg, F. (2018). Digitale zwillinge - entwicklungen im maschinenbau, *66*(3/4-2018). https://unternehmermedien.de/Flipping-Books/2018/UMAG-03-04-2018/

Sweeney, P. J., & Randall, R. B. (1996). Gear transmission error measurement using phase demodulation. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *210*(3), 201–213. https://doi.org/10.1243/pime_proc_1996_210_190_02

Tantik, E. (2020). *Gestaltungsprinzipien für opc ua-applikationen* (Doctoral dissertation). Düren, Shaker Verlag.

The MathWorks, Inc. (Ed.). (2022a, March 7). *Similarity-based remaining useful life estimation*. https://www.mathworks.com/help/predmaint/ug/similarity-based-remaining-useful-life-estimation.html

The MathWorks, Inc. (Ed.). (2022b, March 7). *Wind turbine high-speed bearing prognosis*. https://de.mathworks.com/help/predmaint/ug/wind-turbine-high-speed-bearing-prognosis.html

The Object Management Group (Ed.). (2022, March 22). *About the UML Profile for MARTE Specification Version 1.2*. https://www.omg.org/spec/MARTE/1.2/About-MARTE/

Toms, L. A. (1995). *Machinery oil analysis : Methods, automation and benefits : A guide for maintenance managers and supervisors* (1st ed.).

VDI 2888: Maintenance condition monitoring (Guideline). (1999). Verein Deutscher Ingenieure - VDI-Fachbereich Fabrikplanung und -betrieb; VDI-Gesellschaft Produktion und Logistik.

VDI/VDE 2206: Entwicklung cyber-physischer mechatronischer systeme (cpms) (Guideline). (2021). Verein Deutscher Ingenieure - VDI/VDE-Fachbereich Autonome Systeme u. Mechatronik; VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik.

Weilkiens, T. (2014). *Systems engineering mit sysml, uml : Anforderungen, analyse, architektur* (3., überarb. und aktualisierte Aufl.). http://d-nb.info/1047160625/04

Weilkiens, T. (2022, February 22). *Mbse4u model based systems engineering - knowledge, practice, and more*. https://mbse4u.com/

Weilkiens, T., Lamm, J. G., & Roth, S. (2015). *Model-based system architecture*. Wiley John + Sons. https://www.ebook.de/de/product/24176524/tim_weilkiens_jesko_g_lamm_stephan_roth_model_based_system_architecture.html

Wellsandt, S., Thoben, K.-D., Uhlenkamp, J.-F., & Hribernik, K. (2019). Digital twin applications - a first systemization of their dimensions. *Proceedings, 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) : Sophia Antipolis Innovation Park, France, 17-19 June 2019*.

Wilking, F. (2021). Digitaler zwilliing - trendstudie "digitaler zwilling". *Abschlussbericht Forschungsvorhaben Nr. 889*, (1419).

Wilking, F., Schleich, B., & Wartzack, S. (2021). Digital twins - definitions, classes and business scenarios for different industry sectors. *Proceedings of the Design Society*, *1*, 1293–1302. https://doi.org/10.1017/pds.2021.129

Wittel, H., Jannasch, D., Voßiek, J., & Spura, C. (2019). *Roloff/matek maschinenelemente*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-26280-8

Wurzel, G. D. (2011). *Development of a condition-based maintenance concept for helicopter drive systems* (Doctoral dissertation). https://catalogplus.tuwien.at/permalink/f/8j3js/UTW_al

Xia, Z., Guan, Q., Gao, Y., Chen, X., & Zhai, X. (2020). Review on remaining useful life prediction methods of bearing. *2020 11th International Conference on Prognostics and System Health Management (PHM-2020 Jinan)*. https://doi.org/10.1109/phm-jinan48558.2020.00083

Zieringer, C., Bauer, B., Stache, N. C., & Wittenberg, C. (2020). Human-robot interaction via a virtual twin and OPC UA. In *Advances in intelligent systems and computing* (pp. 101–107). Springer International Publishing. https://doi.org/10.1007/978-3-030-51758-8_14

Zonta, T., da Costa, C. A., da Rosa Righi, R., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). Predictive maintenance in the industry 4.0: A systematic literature review. *Computers & Industrial Engineering*, *150*, 106889. https://doi.org/10.1016/j.cie.2020.106889