Technische Universität München
TUM School of Engineering and Design

On the Conception and Implementation of Digital Twins – Supporting Companies in the Development of Digital Twins

Jakob Benjamin Trauer

Vollständiger Abdruck der von der TUM School of Engineering and Design der Technischen Universität München zur Erlangung eines

Doktors der Ingenieurwissenschaften (Dr.-Ing)

genehmigten Dissertation.

Vorsitz: Prof. Dr.-Ing Johannes Fottner

Prüfende der Dissertation:

1. Prof. Dr. Markus Zimmermann
2. Prof. Dr.-Ing. Kilian Gericke

Die Dissertation wurde am 17.11.2023 bei der Technischen Universität München eingereicht und durch die TUM School of Engineering and Design am 22.03.2024 angenommen.

ACKNOWLEDGMENTS

The last five years have been the most challenging time of my life. Full of grief, anger, doubts and ever-lasting fights. The only way to make it through is with as much fun as possible and close friendships. Therfore I would like to thank all of you who made this journey possible and – more importantly – somewhat enjoyable! I will not be able to mention all of you here but be assured I am most thankful for all your support.

First, I would like to thank Prof. Markus Zimmermann for giving me the opportunity to graduate. I would like to thank Prof. Kilian Gericke for the continuous and valuable input throughout the years and our fruitful collaboration in the Design Society SIG. Further, I am very thankful for Prof. Johannes Fottner, who did an outstanding job as a chairman of the examination board.

The laboratory would be nothing without two extraordinary people – Dr.-Ing. Markus Mörtl and Katja Zajicek. You are the backbone, the soul, the heart, and the brain of the laboratory. Thank you for your support in all kinds of matters – I am deeply thankful for that.

My work greatly benefited from the many inputs I received from all the previous PE members. Special thanks to my mentor Dr.-Ing. Christoph Hollauer and Dr.-Ing. Julian Wilberg. Further, I am grateful for Dr.-Ing Matthias Gürtler who made a research stay in Sydney, Australia possible. Especially during Covid the “Stamtafel Eindhoven” with Dr. Sjoerd Knippenberg and Dr.-Ing. Sebastian Schweigert Recksiek was a constant source of joy and laughter. And it is Sebastian who has probably shaped my personal and professional career the most. Thank you for your supervision, for the many successful research projects, for being a good colleague and a close friend – on many years to come!

As mentioned before, friendships are key to making it through. I am blessed to have met some of the smartest and funniest people I know, and to call them my friends. Julian, Sebi, Simon, Miguel – thank you! But most of all I need to thank Dr.-Ing. Lukas Kirscher. I would not be here without you.

It is good to see that this spirit of support and friendship continues at the laboratory, and it was an absolute pleasure to work with the “next generation”. Thank you, Akhil, Phil, Klara, Johannes, Klemens, Felix, and Philipp for all the fun and the distractions from everyday problems.

Many aspects of my work were developed in collaboration with students. And my work greatly benefited from their outstanding motivation and inspiration. Among others, special thanks to David, Johannes, Louis, Markus, Michael, Nickcole, and Phat. Additionally, I would like to thank all industry partners who made my case studies possible.

Finally, I need to thank my network outside university. Thank you, Hraban, Paul, Philipp, and Timo, for believing in me and supporting me. To my entire familiy, thank you for your continuous support. Last but not least, thank you, Sarah. Thank you for your support, your patience, resillience, and for turning dull moments into memorable ones.

Munich, July 2024 Jakob Trauer

"I put my heart and my soul into my work and

have lost my mind in the process."

(Vincent van Gogh)

Prior Publications

The following (peer-reviewed) publications are part of the results presented in this thesis (alphabetical order):

Piccolo, S. A., Trauer, J., Wilberg, J., & Maier, A. M. (2018). Understanding Task Execution Time in Relation to the Multilayer Project Structure: Empirical Evidence. In 20th International Dependency and Structure Modelling Conference (DSM 2018). https://www.designsociety.org/publication/40982/understanding+task+execution+time+in+relation+to+the+multilayer+project+structure%3a+empirical+evidence

Schweigert-Recksiek, S., Trauer, J., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). Conception of a Digital Twin in Mechanical Engineering – A Case Study in Technical Product Development. Proceedings of the Design Society: DESIGN Conference, 1, 383–392. https://doi.org/10.1017/dsd.2020.23

Schweigert-Recksiek, S., Trauer, J., Wilberg, J., Stöhr, B. , Mahlau, L., Saygin, M., Spreitzer K., Engel C., Mörtl, M., & Zimmermann, M. (2022). Einführung eines digitalen Zwillings in die technische Produktentwicklung. https://doi.org/10.13140/RG.2.2.34190.23365

Trauer, J., Mac, D. P., Mörtl, M., & Zimmermann, M. (2023). A Digital Twin Business Modelling Approach. In 24th International Conference on Engineering Design.

Trauer, J., Mutschler, M., Mörtl, M., & Zimmermann, M. (2022). Challenges in Implementing Digital Twins – a Survey. In Volume 2: 42nd Computers and Information in Engineering Conference (CIE). American Society of Mechanical Engineers. https://doi.org/10.1115/detc2022-88786

Trauer, J., Pfingstl, S., Finsterer, M., & Zimmermann, M. (2021). Improving Production Efficiency with a Digital Twin Based on Anomaly Detection. Sustainability, 13(18), 10155. https://doi.org/10.3390/su131810155

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). What Is A Digital Twin? – Definitions and Insights from an Industrial Case Study in Technical Product Development. Proceedings of the Design Society: DESIGN Conference, 1, 757–766. https://doi.org/10.1017/dsd.2020.15

Trauer, J., Schweigert-Recksiek, S., Onuma Okamoto, L., Spreitzer, K., Mörtl, M., & Zimmermann, M. (2020). Data-Driven Engineering – Definitions and Insights from an Industrial Case Study for a New Approach in Technical Product Development. In Balancing Innovation and Operation. The Design Society. https://doi.org/10.35199/NORDDESIGN2020.46

Trauer, J., Schweigert-Recksiek, S., Schenk, T., Baudisch, T., Mörtl, M., & Zimmermann, M. (2022). A Digital Twin Trust Framework for Industrial Application. Proceedings of the Design Society, 2, 293–302. https://doi.org/10.1017/pds.2022.31

Trauer, J., Wöhr, F., Eckert, C., Kannengiesser, U., Knippenberg, S., Sankowski, O., & Zimmermann, M. (2021). Criteria for Selecting Design Process Modelling Approaches. Proceedings of the Design Society, 1, 791–800. https://doi.org/10.1017/pds.2021.79

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	Definition
AI	Artificial Intelligence
AIM-R	Action Innovation Management Research
ALM	Application Lifecycle Management
BOM	Bill of Material
BPMN	Business Process Modelling Notation
DT	Digital Twin
LPL	Laboratory for Product Development and Lightweight Design
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CPS	Cyber-Physical System
CPPS	Cyber-Physical Production System
CRISP-DM	Cross Industry Standard Process for Data Mining
CRM	Customer Relation Management
DDE	Data-Driven Engineering
DMM	Domain Mapping Matrix
DSM	Design Structure Matrix
DTBMA	Digital Twin Business Modelling Approach
DITTID	Digital Twin Toolbox for Implementation and Design
DS	Descriptive Study
DTTF	Digital Twin Trust Framework
EoL	End of Life
ERP	Enterprise Resource Planning
I4.0	The Fourth Industrial Revolution
IoT	Internet of Things
IIoT	Industrial Internet of Things

Abbreviation	Definition
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
OEE	Overall Equipment Efficiency
OEM	Original Equipment Manufacturer
PbL	Project-based Learning
PDM	Product Data Management
PLM	Product Lifecycle Management
PS	Prescriptive Study
PSS	Product Service System
RACI	"Responsible-Accountable-Consulting-Informed" method
RC	Research Clarification
SCM	Supply Chain Management
SDM	Simulation Data Management
sysML	System Modelling Language
TDM	Test Data Management
ZB	zettabyte

1 Introduction

1.1 Initial Situation

In 2020, 64,2 zettabytes[1] (ZB) of data were produced. By 2025 the volume of data is even expected to reach 181 ZB (IDC Research, Inc. & Statista, 2021). According to Ozcan, Mustafa, Bugra et al. (2023), *"193187495 bits of data is created by the time you finish reading this sentence, assuming you really tried to read the exact number."* This is just a reference for the speed of the ongoing digital transformation that affects all aspects of our daily life (Maier et al., 2023). Enabled b y new capabilities of artificial intelligence, ever-increasing computational power, and data analyses of previously unachievable levels of sophistication and accuracy, digital technologies and tools are omnipresent in today's society and industry (Isaksson & Eckert, 2020; Maier et al., 2023; Spath et al., 2023). This transformation is further being accelerated by recent crises. For example, the countermeasures to the outbreak of the coronavirus forced billions of employees to work remotely using digital solutions – leading to a previously unseen acceleration of the digital transformation (LaBerge et al., 2020; Nardelli, 2022). And the climax is not yet reached - according to Isaksson and Eckert (2020), until 2040, "all" products will become smart, interlinked, cyber-physical systems (CPS). Furthermore, the service aspect will become ever more important by turning 'classical' products into product-service systems (PSS)[2].

These trends show that digitalization is a double-edged sword. On the one hand, companies of all sizes are forced to change their way of working and developing. They need to shorten their development times, be able to offer a higher level of individualization, and enable higher overall flexibility in their processes (Lasi et al., 2014). Further, as products become more and more interconnected, and data needs to be exchanged with many different stakeholders' legal issues arise. Entirely new competencies, tools, methods, technologies, IT architectures and processes will be required to succeed in the digital age (Isaksson & Eckert, 2020; Legner et al., 2017; Rosário & Dias, 2023; Trauer, Schweigert-Recksiek, Onuma Okamoto, et al., 2020).

On the other hand, digitalization offers undisputable opportunities for all business sectors. For example, it can significantly increase operational efficiency, sustainability, reduced costs, quality, and customer satisfaction (Neligan et al., 2022; Rosário & Dias, 2023; Wichmann et al., 2019). However, to profit from these benefits, companies have to react (Isaksson & Eckert, 2020; Rosário & Dias, 2023). The reaction of the manufacturing sector is called the fourth

[1] *1 zettabyte equals 1 trillion gigabytes. To put this into perspective – one hour of standard definition video requires approximately one gigabyte of data. One zettabyte would be enough for 36 million years of video.*

[2] *"cyber-physical systems" and "product-service systems" will be introduced in detail in section 2.1.*

industrial revolution, or "Industry 4.0" (Lasi et al., 2014). While this development includes many different approaches and techniques, one of the most proclaimed concepts is the Digital Twin (DT). DTs are virtual dynamic representations of real-world systems that are connected to them for bidirectional data exchange over the entire lifecycle (Trauer, Schweigert-Recksiek, Engel, et al., 2020). For example, in a hydroelectric power station, a DT may be linked to physical sensor data of the turbine and its surrounding components. Based on this sensor data the current stresses at the critical points can be simulated and predicted. Using these insights, the DT can automatically adjust the operation of the turbine to prevent failure, or it can automatically schedule maintenance works, so that downtimes will be reduced (Friederici, 2019). Other examples, such as a DT for improving production efficiency of aluminum extrusion are described in Chapter 4. The underlying concept was developed by NASA in the 1960s as part of the "Apollo" program and was officially published by Michael Grieves and John Vickers in 2002 (Grieves & Vickers, 2017; Jones et al., 2020).

By now, the field of DTs has reached exponential growth (Schmitt & Copps, 2023). Isaksson and Eckert (2020) forecast DTs to become one of the major engineering trends in the next two decades. For example, the BMW Group (2022) recently identified DTs as one of their core trends on which they would like to take action. According to Schmitt and Copps (2023), market research reports estimate an annual market size between \$48B and \$78B for DTs by 2026-2027. With the DT, the company aims for increased process quality and efficiency both in production and development and an improved sustainability. IDC Research, Inc. (2022) forecast, that over the next years, 50 % of consumer goods manufacturers will develop DT ecosystems. In general, the proposed benefits of DTs are manifold – they proved their value for real-time remote monitoring and control, minimizing maintenance costs, reducing product errors, improving time and resource efficiency of engineering and production processes, personalization of products and services, etc. (E.g. Ergün et al., 2023; Jones et al., 2019; Rasheed et al., 2020; Stjepandić et al., 2021a; Stupar et al., 2023; Trauer, Pfingstl, et al., 2021; Tzachor et al., 2022). According to Brossard et al. (2022) DT-technology can increase revenues by up to 10 %, reduce development times by up to 50 %, and improve product quality by up to 25 %. IDC Research, Inc. (2022) expects a reduction of 5 % in quality cost.

Attracted by these promising benefits, DTs were already applied in many different areas ranging from classical mechanical engineering disciplines as manufacturing or aviation, over healthcare use cases to smart cities and human DTs (Barricelli et al., 2019; Ergün et al., 2023; Rasheed et al., 2020). However, most of these applications were academic use cases, or exemplary applications of DTs. According to Trauer, Mutschler, et al. (2022) industry is just at the beginning of adopting DTs and is several years behind research.

1.2 Problem Statement and Motivation

The basic concept of DTs has been known for two decades now – yet, only very few comprehensive industrial implementations are known to date (Sharma et al., 2022). Consequently, there must be some barriers impeding companies in implementing DTs. Previous research has already focused on some of the enablers and challenges of the development of DTs. Most of the identified research focused on technical aspects of the development of DTs (Fuller et al., 2020; Rasheed et al., 2020). This is an important and meaningful contribution – however, with the recent development of new tools, methods and technologies, the implementation of DTs has become more and more feasible. At the same time, many challenges enterprises are facing in the conception and implementation of DTs are non-technical and cannot be fully resolved by these advancements (Trauer, Mutschler, et al., 2022). Based on previous research, these non-technical challenges are related to cultural, legal, methodological, managerial, organizational, and procedural issues (Neto et al., 2020; Perno et al., 2021; Stjepandić et al., 2021b).

Although these challenges are known, existing methodologies mostly focus on technical implementation and neglect the non-technical aspects, e.g., economic benefits of the DT (Alnowaiser & Ahmed, 2023; Bamberg et al., 2021; Fang et al., 2022; VanDerHorn & Mahadevan, 2021). Current implementations are time-consuming and expensive due to a lack of a suitable systematic support (Barricelli et al., 2019; D'Amico et al., 2023; Perno et al., 2021; Tao et al., 2018; Trauer, Mutschler, et al., 2022). In the worst case, this circumstance prevents the introduction of the DT in the company, causing it to miss the opportunity to develop its potential. Here, a systematic methodical approach could lower the efforts in the development[3] of DTs (Lindemann, 2009). As stated before, apart from time and cost effort, there are many other non-technical challenges hindering the development of DTs, which will be discussed in detail in Chapter 3 (Trauer, Mutschler, et al., 2022). For example, challenges in identifying meaningful use cases of DTs, assessing their value and building trust in them. These non-technical challenges are especially relevant in the early phases of a DT project – i.e. the conception and implementation of DTs. In the operation of DTs, technical challenges are more crucial. In the state of the art, non-technical challenges are considered by only few approaches (e.g. Follath et al., 2022; Göbel & Eickhoff, 2020; Heindl & Stary, 2022; Newrzella et al., 2022; Riedelsheimer et al., 2021). These studies already offer some useful elements reducing non-technical challenges. However, they are either too superficial and abstract to be applicable and useful, or they are too application specific and cannot be adopted by different companies for different problems (cf. sections 2.2.2 and 2.3). So far, there is no application-independent and generic, but applicable support available for engineers.

1.3 Research Objective and Scope

As outlined in the previous sections, there is a gap in research and practice on a systematic support[4] for the development of DTs. Despite the undisputed potentials of DTs and the many

[3] *Within this thesis, the "development of DTs" considers their conception and implementation. I.e. the lifecycle phases of a DT up until operation.*

[4] *"The term support is used to cover the possible means, aids and measures that can be used to improve design. This includes strategies, methodologies, procedures, methods, techniques, software tools, guidelines, information sources, etc." (Blessing & Chakrabarti, 2009)*

calls to action, there are only relatively few industrial applications known to date. The challenges in the design and implementation of DTs are known and proven. Especially with respect to non-technical challenges, which are hindering companies. Still there is no suitable support available, neither in industry nor academia, addressing also these non-technical issues. Consequently, research goal of this thesis is to support DT-responsibles[5] of engineering firms in the development of valuable DTs in an efficient way:

> ***Goal*** *of this research is to explore a systematic support for engineering firms including supporting processes & methods to enhance the conception and implementation of Digital Twins.*

As mentioned before, the application areas of DTs are very diverse. Therefore, it is important to narrow down the scope of the current research. Figure 1-1 depicts the area of relevance and contribution (ARC) diagram based on Blessing and Chakrabarti (2009).

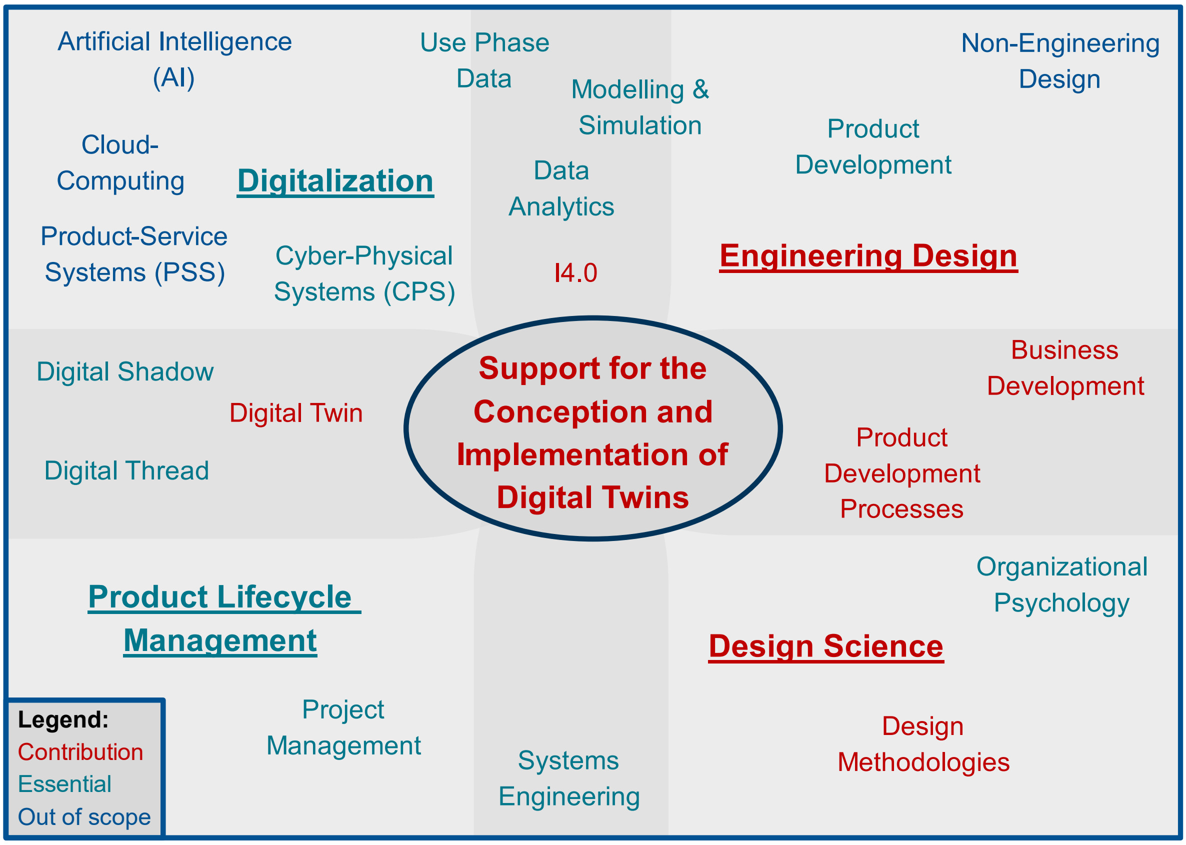


Figure 1-1: Area of Relevance and Contribution (ARC) Diagram (based on Blessing & Chakrabarti, 2009).

[5] *The development of DTs requires experts from many different disciplines - IT, OT, engineering, E-E, etc. have to collaborate in the conception and implementation of DTs. Therefore, the role "DT-responsibles" has been introduced within this thesis to cover all required roles of a team responsible for the development of the DT.*

At the core is the goal of the thesis aiming at providing a systematic support to enhance the design and implementation of DTs. Naturally, the technologies related to DTs are essential. DTs and their precursors, the digital thread and digital shadow stem from the area of product lifecycle management (PLM), intersected with digitalization topics. DTs are closely related to CPS and can often be described as such (cf. section 2.1.3.3). Using use phase data and data analytics, DTs enable new ways of modelling and simulation, which is a core element of today's engineering design[6] practice. While these topics are essential as a basis for this research, they are not at the focus of the contribution. The contribution is related to the field of design science[7] providing suitable design methodologies and product development processes. Whereas here, the scope is on the development of methodologies for the design of DTs. As these approaches are meant to enhance the implementation and applicability of DTs, they are also contributing to the improvement of I4.0 and engineering design practices.

Consequently, the **research scope** of this thesis is on providing a support to engineering companies developing technical products and planning to develop a DT. The development of DTs for other disciplines e.g., smart cities, education, or healthcare, is not within the scope and is therefore not explicitly considered. Within the scope of technical products, the support should be applicable regardless of the lifecycle phase the DT is supposed to operate in, i.e. engineering, production, or operation. To further increase applicability of the support, it should be suitable for different companies. This includes the size of a company, as well as its general field of operation. Consequently, the solution should be designed to be independent of these aspects.

Based on the goal and the scope, two main **research questions** can be formulated, which should be answered within this research. First, a solid understanding of the current situation needs to be created. It is especially important to investigate in detail the challenges companies are facing in the development of DTs and whether nowadays non-technical challenges are indeed more or less crucial than technical challenges. Therefore, the first question (Q1) is:

***Q1:** What are the major impediments in implementing Digital Twins in engineering companies?*

Consequently, the support which is to be developed should overcome the challenges identified in Q1. Focal aspect of the second research question is therefore how these barriers towards the conception and implementation of DTs can be addressed:

***Q2:** How to support DT-responsibles in the conception and implementation of Digital Twins efficiently leading to a high-quality solution?*

[6] *Engineering Design is a discipline in technical product development aiming at developing technical solutions for products. In contrast to non-engineering design, it is not primarily focused on human-centered factors, but on technical feasibility and fulfillment of requirements. (Schweigert-Recksiek, 2022).*

[7] *While Engineering Design describes the activities of engineers needed to develop a technical product, Design Science is the research on the process of Engineering Design and how to improve it.*

1.4 Research Methodology

The present thesis follows the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009). The described methodology is subdivided into the following four stages. Research Clarification (RC), Descriptive Study I (DS-I), Prescriptive Study (PS) and Descriptive Study II (DS-II). Figure 1-2 illustrates the four steps in the standard procedure (solid line) and possible iterations (dashed lines). If necessary, specific steps can be skipped (Blessing & Chakrabarti, 2009).

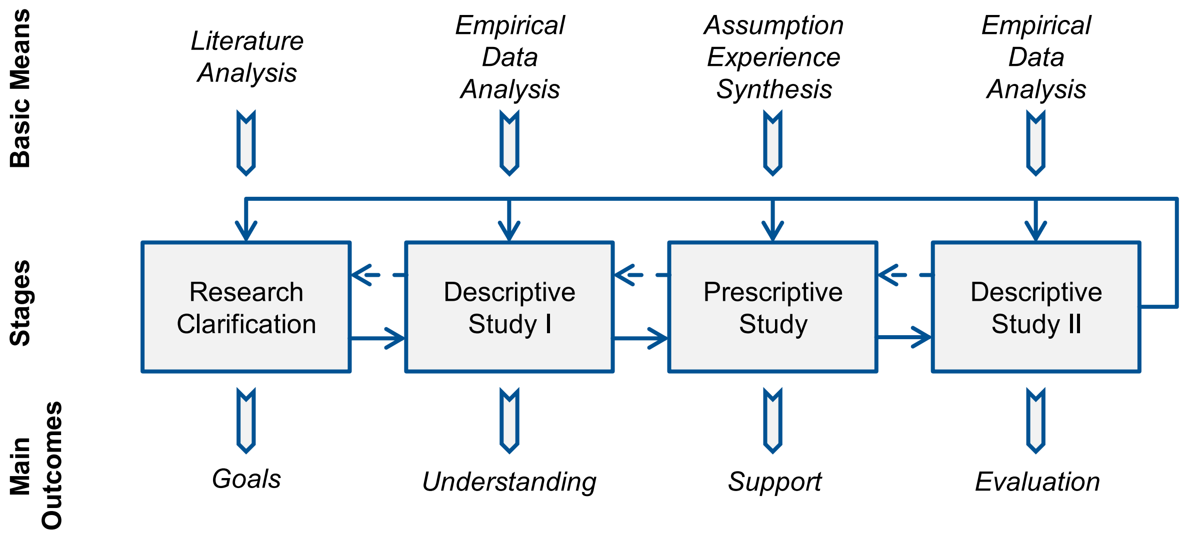


Figure 1-2: DRM-Framework (adapted from Blessing & Chakrabarti, 2009).

Blessing and Chakrabarti (2009) describe seven different paths through this model. The thesis at hand follows a path related to type 5 of the DRM. This type of research is described as the *"development of support based on a comprehensive study of the existing situation"* which suits well the two research questions presented in section 1.3 (Blessing & Chakrabarti, 2009). The goal is to develop a support, but the current situation is not sufficiently investigated by previous research. Therefore, after a review-based RC, a comprehensive DS-I is being conducted to build a sufficient understanding of the current situation. Subsequently, a comprehensive prescriptive study is conducted to develop the required support. At the end of this type of study the developed support is assessed in an initial DS-II. In the following, the application of these steps within this thesis is described.

The primary goal of **research clarification** is to establish a clear research objective and a research goal. For this thesis, a literature review on DTs, industry 4.0 and data-driven engineering was conducted. These results were completed by the experience of the author as well as insights from other projects such as the collaborative research center "SFB768" (http://innovations.sfb768.de/) or KMEAgil (https://www.kme-mittelstand.de/project-pdf/29.pdf).

The purpose of the **descriptive study I** is to gain an in-depth understanding of the current situation and associated issues. Consequently, the results indicate the aspects to be investigated in order to improve the current situation. In the context of the present thesis, several DSs have been conducted. Using a literature review as well as an online survey, the key challenges in implementing DTs were investigated (cf. Chapter 3). This can be considered as the main comprehensive DS-I. Based on this deepened understanding, elements of the support were developed. For each element, an own DS was conducted by reviewing literature and gaining empirical data from industrial and academic case studies (cf. Chapter 4).

According to Yin (2018), a case study refers to a practical investigation that explores a current phenomenon, taking into account its real-world setting. It is particularly useful when the distinction between the phenomenon itself and its context is not clearly defined. The primary objective of conducting case studies is to comprehend complex social phenomena and real-life occurrences, including organizational and managerial processes. The objective of this thesis is to provide a systematic support for the conception and implementation of DTs in industry. Therefore, the support was mainly developed based on case studies and an interview study, considering the interplay with the beforementioned real-life circumstances. Thus, applicability and usefulness for industrial application can be increased.

The insights investigated in the descriptive studies are the starting point for the **prescriptive study**. Here, the systematic support is developed, which is proposed to improve the current situation. This is the main part of the research project. For this thesis, a toolbox for the design and implementation of DTs was developed – including a procedure model, a business modelling approach, a value map, a trust framework, a use case catalogue, and a use case template (cf. Chapter 6). Each part of the developed support was developed in an iterative manner. As described in the previous section, for each element, a subordinate research project was conducted, including a brief DS-I, a PS, and an initial DS-II. The RC for each sub-project was based on the findings of the comprehensive DS-I mentioned in the previous paragraph.

The goal of **descriptive study II** is to implement and assess the effectiveness of the proposed solution. According to Blessing and Chakrabarti (2009), there are two subtypes of evaluation – *"application evaluation"* and *"success evaluation"*. It is used to identify potential areas for improvement and to assess overall success. The application evaluation includes criteria of *applicability* and *usability*. Applicability assesses the extent to which the developed support aligns with the specific context and addresses the given problems. Usability, on the other hand, focuses on evaluating how easily understandable and usable the support is. The success evaluation addresses the usefulness of the support – i.e., whether the application of the developed support yielded the desired success factors.

For the purpose of this thesis each module of the systematic support has been partially applied in industrial case studies. From these applications first indications on further improvement opportunities, as well as applicability, usability and usefulness could be derived. The entire toolbox has been applied only once in an academic practical course. Although this is only an initial evaluation, it was possible to get an indication of applicability, usability, and usefulness of the toolbox as whole (cf. Chapter 7).

1.5 Structure of the Thesis

This thesis is structured in eight Chapters. Figure 1-3 depicts an overview of the structure of the thesis in relation to the previously presented research methodology as well as the main research questions. It also highlights the most important outcomes.

In **Chapter 2** the fundamentals of DTs as well as the context of this research are presented. First, the theoretical background is presented in section 2.1, including a description of related concepts as well as the origin, applications, benefits, challenges, and characteristics of DTs that must be taken into account in their development. Related work is outlined in section 2.2 before the Chapter is concluded in section 2.3, deriving needs, insights, and requirements for a solution approach from the state of the art.

To complete the comprehensive DS-I, an online survey on challenges in implementing DTs is presented in **Chapter 3**. It includes the study design as well as the results and a short discussion of the outcomes. At the end, a prioritized list of challenges is presented answering Q1 (cf. section 1.3).

Chapter 4 presents the study design, results, and discussions of the four conducted empirical studies of this research project. In collaboration with a company for household climate solutions, a project on engineering twins is presented in section 4.2. In section 4.3, an industrial case study on production twins for aluminum extrusion processes is described. Combining findings from the previous studies, section 4.4 presents the results of the development of a DT demonstrator for an academic practical course, which was also used for the initial evaluation. To develop a framework to create trust in DTs, an interview study has been conducted in collaboration with Siemens AG, which is presented in section 4.5, including study design, results, and discussion. Chapters 3 and 4 show the interplay of the individual DSs and the PS.

All empirical findings are consequently summarized in **Chapter 5**, presenting the relevant insights for designing a systematic support for the conception and implementation of DTs.

The final developed systematic support, i.e., the Digital Twin Toolbox for Implementation and Design (DITTID), is presented in **Chapter 6**. This is the outcome of the PS and the answer to Q2 (cf. section 1.3). After a short overview of its components and their interplay (cf. section 6.1), the modules of the solution approach are described in detail in section 6.2. They consist of the DT procedure model, the DT business modeling approach, the DT value map, the DT use case catalogue, the DT use case template, and the DT trust framework.

The initial DS-II with the evaluation of the developed support is described in **Chapter 7**. First the application of the toolbox in the student course is depicted in section 7.1. Based on these results, the developed solution approach is discussed in section 7.2.

Finally, the content of this dissertation is concluded in **Chapter 8**, including a summary (cf. section 8.1), the contribution to industry and academia (cf. section 8.2), and an outlook for future work (cf. section 8.3).

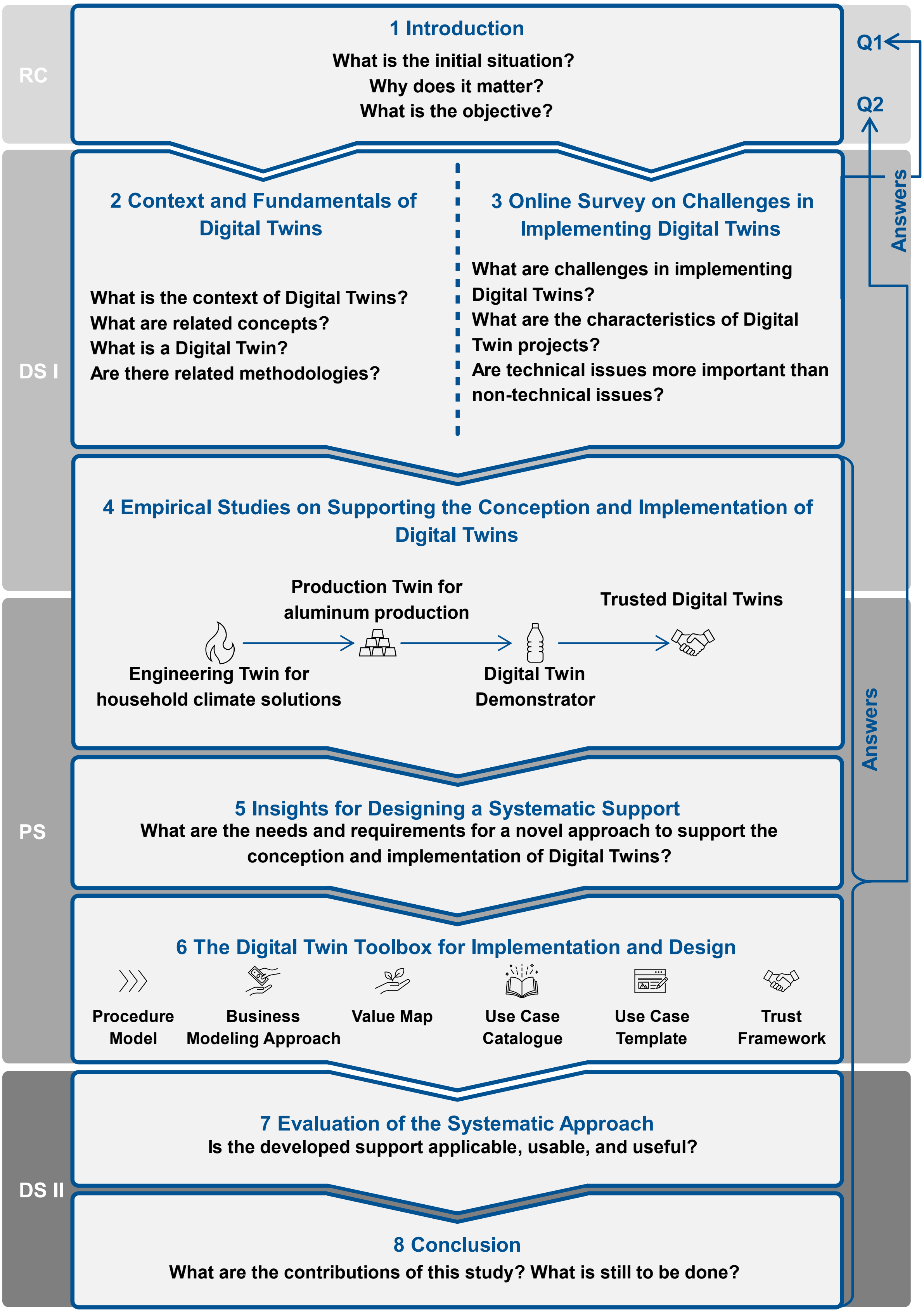


Figure 1-3: Overview of the Structure of the Thesis.

2 Context and Fundamentals of Digital Twins

2.1 Theoretical Background

2.1.1 Digital Transformation, Big Data, Artificial Intelligence, and Industry 4.0

The **digital transformation** is a trend that – by now – affects almost any part of our daily life and business (Maier et al., 2023). According to Gong and Ribiere (2021), digital transformation can be defined as *"A fundamental change process, enabled by the innovative use of digital technologies accompanied by the strategic leverage of key resources and capabilities, aiming to radically improve an entity[1] and redefine its value proposition for its stakeholders."* This transformation emerged from the capabilities developed in the third industrial revolution[2] and is driven by digitization and digitalization (Spath et al., 2023). **Digitization** is understood as the process of turning analogue data into digital data (Schumacher et al., 2016). While this refers predominantly to the digital technologies used, **digitalization** on the other hand describes the sociotechnical effects these digital technologies imply. This covers personal, organizational and social impacts (Legner et al., 2017).

These trends lead to a massive increase in data produced (Wilberg, 2020). This large amount of data is often referred to as **"Big Data"** (Katal et al., 2013; Wilberg et al., 2017). This kind of data is characterized by a great variety of different data, a large volume, high velocity with which data is collected, a high variability in data flows, a large complexity required to handle the data, and value that can be deducted from the data (Katal et al., 2013). Enabled by the big data available, technologies like **artificial intelligence** (AI). This is an intertwined relationship – big data is required to feed AI models, and AI is required to cope with the velocity, volume, variety, and complexity of big data (O'Leary, 2013).

These and many other technologies and trends lead to previously unachievable levels of accuracy and sophistication in data analytics (Isaksson & Eckert, 2020). While, the mere digitization technologies like, electronics, IT, and automation systems marked the beginning of the third industrial revolution, the previously mentioned rapid advancements in digitalization initiated a "second wave of digitalization" and the fourth industrial revolution "**industry 4.0**" (I4.0) (Horváth & Szabó, 2019; Kagermann & Winter, 2018; Vaidya et al., 2018). This I4.0 is mainly driven by three key components – **cyber-physical systems** (CPSs), **internet of things** (IoT), and **smart factories** (Hermann et al., 2016; Wichmann et al., 2019).

---

[1] *An organization, a business network, an industry, or society (Gong & Ribiere, 2021).*

[2] *The third industrial revolution started in the 1970s and according to Spath et al. (2023) "is characterized by the use of electronics and IT in businesses around the world and the progressive standardization and automation of business processes."*

While systems, whose functionality only depends on physical operations are considered physical systems, according to Nardelli (2022), CPS are systems that *"[...] necessarily operate mediated by data processes that determine logical relations directly or indirectly employed in decision-making processes associated with actions to maintain their proper functioning. This constitutive mediation by data processes is what defines the cyber domain of CPSs, and thus, the concept of CPSs as such."* Consequently, CPS are defined by three basic layers – a (1) physical layer, which comprises the physical systems, which deliver data that can be processed in a (2) data layer (this is considered the "cyber" aspect of CPS), and (3) a decision layer referring to the decision-making activities that are initiated based on the insights provided by the data layer (Nardelli, 2022).

With this basic structure – a physical system interlinked with a cyber-system to trigger decisions in the real world – CPS are the overarching framework connecting many different concepts, like IoT, smart factories, and also DTs (cf. section 2.1.3.2). Many different definitions of IoT exist, some focusing more on the technical aspects, some more on the socio-technical impact of IoT (Wilberg, 2020). In the context of this thesis the definition of Rayes and Salam (2019) is used, describing IoT as *"[...] the network of things, with device identification, embedded intelligence, and sensing and acting capabilities, connecting people and things over the Internet."* In other words, this means, that all different types of products or systems are equipped with sensors to collect data, software to process the data, and an interface to communicate among each other and to be accessible (Rayes & Salam, 2019). When "things" refer to industrial products, machines, buildings and processes, rather than consumer products and the associated techniques are applied in an industrial setting, it is called **industrial internet of things** (IIoT) (Boyes et al., 2018). Consequently, while CPS and IoT/IIoT, are very similar, the former focuses more on the framework allowing for data-driven decision-making activities, whereas the latter is more focused on "just" connecting the physical products, without specifying the targeted value. These concepts are all interrelated – according to Rathore et al. (2021), IoT generates Big Data, which is employed in AI and machine learning. AI is used to create DTs, which use the IoT. There are many more related concepts and terminologies. For example, the **smart factory** relates to a factory applying the IIoT concept, connecting machines, processes, people and other domains (Radziwon et al., 2014). In general, these objects, able to communicated are referred to as **connected products** (Wilberg, 2020).

2.1.2 Product Lifecycle Management

DTs stem from the field of **Product[3] Lifecycle Management** (PLM), therefore this concept is highly relevant to understand what a DT is. J. Stark (2022) defines PLM as *"the business activity of managing, in the most effective way, a company's products all the way across their lifecycles; from the very first idea for a product all the way through until it is retired and disposed of."* Originally, PLM emerged at the end of the last century from **Engineering Data**

[3] *Products usually are associated with physical, tangible objects, which can be purchased. However, within this thesis, the term "product" also refers to intangible goods, as service and software.*

Management (EDM) and **Product Data Management** (PDM), which were necessary technologies to handle the suddenly growing amount of data, generated by **Computer Aided Design** (CAD) systems (Grieves, 2005; Saaksvuori & Immonen, 2008). However, by now PLM is much more than just a system to handle CAD data, bills of material (BOM), and version histories – *"PLM is a holistic business concept developed to manage a product and its lifecycle including not only items, documents, and BOM's, but also analysis results, test specifications, environmental component information, quality standards, engineering requirements, change orders, manufacturing procedures, product performance information, component suppliers, and so forth."* (Saaksvuori & Immonen, 2008). Figure 2-1 depicts a general, not extensive, overview of the domains, product lifecycle stages, as well as related concepts and data sources with interfaces to PLM.

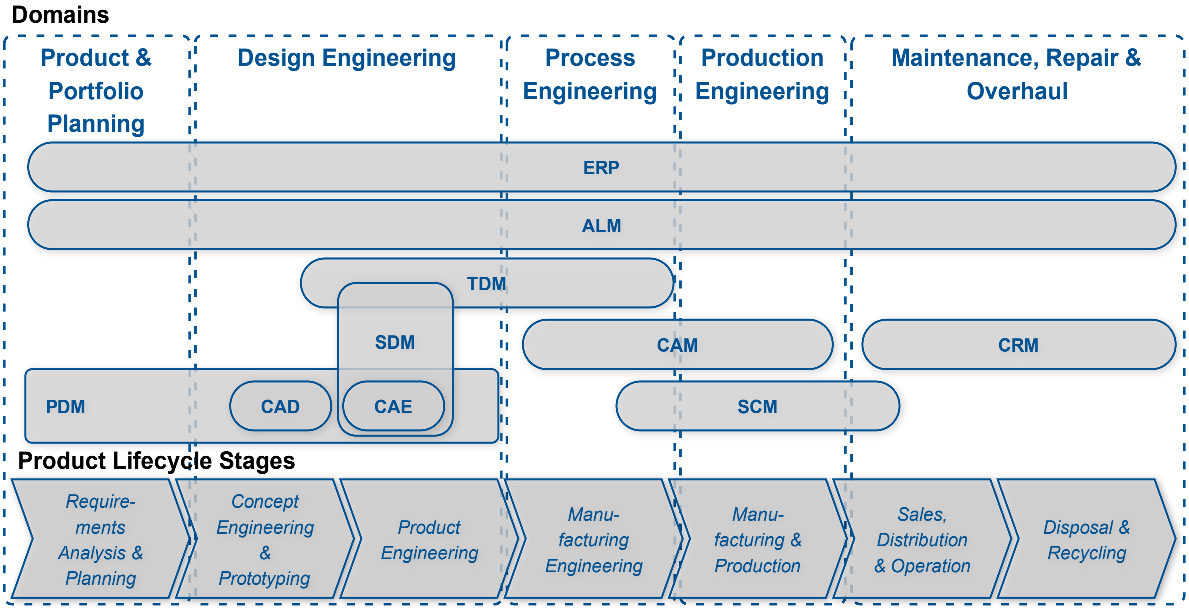


Figure 2-1: Overview of the Lifecycle Stages, Domains, and Related Concepts in the Context of PLM[5] (based on Eigner, 2021; Grieves, 2005).

The lifecycle includes all phases from the requirements analysis, over product engineering and manufacturing, to the operation phase and also disposal and recycling (Eigner, 2021). This coverage of the entire lifespan of a product enables knowledge exchange between product generations as well as holistic assessment of the product. Thus, data from previous product lifecycles can be used e.g., to optimize product development processes (Piccolo et al., 2018), or to enable data-driven engineering[4] (Trauer, Schweigert-Recksiek, Onuma Okamoto, et al., 2020). To the potential of PLM, the paradigm should cover interfaces to the most important

[4] *"Data-driven engineering is a framework for technical product development in which the use case-oriented collection and utilization of sufficiently connected product lifecycle data guides and drives decisions and applications in the product development process."* (Trauer, Schweigert-Recksiek, Onuma Okamoto, et al., 2020)

related concepts and technologies, like PDM, SDM, TDM, or ERP[5] (cf. Figure 2-1). For the development of DTs, CPS or PSS, it is essential to combine PLM with Application Lifecycle Management (ALM). ALM is the counterpart to PLM, focusing on the software development of applications for the product (Eigner, 2021). As this is often a continuous integration process, it extends over all phases of the product's lifecycle.

2.1.3 Digital Twins

2.1.3.1 Origins of Digital Twins

As described earlier, DTs stem from PLM[6] – The first concept of a DT was introduced during a presentation by the University of Michigan in 2002 titled "Conceptual Ideal for PLM" (Grieves, 2023; Grieves & Vickers, 2017). In this initial concept, it was portrayed as the ideal representation of a PLM system (Barricelli et al., 2019; Grieves & Vickers, 2017; Minerva et al., 2020). Thus, the DT serves as a mirror image of a physical product existing in the real world, with the potential for data exchange between the virtual and physical counterparts (Grieves & Vickers, 2017). Often, DTs are traced back to the Apollo missions, where NASA built the spacecraft twice – to shoot one in space and to use the other as a "physical twin" or simulation on the ground (Boschert & Rosen, 2016). However, as Grieves (2022) stated, physical twins have been used since a long time in human history, whether it be models of buildings or prototypes of cars. The only difference with the NASA mission was to build a model at scale. While originally associated with PLM, the concept presented in the early 2000s already embodied fundamental attributes of DTs that have remained relatively consistent over time: the interconnection of a "real space" and a "virtual space" facilitated by data and information exchange (Grieves & Vickers, 2017), Several years later, in 2010, NASA provided a widely accepted definition of a DT as an *"integrated multi-physics, multiscale, 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 corresponding flying twin"* (Shafto et al., 2010). In the context of modern manufacturing, a more contemporary definition characterizes a DT as *"a digital representation of an active unique product [...] or unique product-service system [...] that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases"* (R. Stark & Damerau, 2019). Since then, an exponential growth of publications appeared, which relates to the growing interest in DTs (Jones et al., 2020). However, as Trauer, Mutschler, et al. (2022) showed, it also led to a growing ambiguity in the definition of a DT, which is still present.

---

[5] *Enterprise Resource Planning (ERP), Application Lifecycle Management (ALM), Test Data Management (TDM), Simulation Data Management (SDM), Product Data Management (PDM), Computer Aided Design (CAD), Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), Supply Chain Management (SCM), and Customer Relation Management (CRM).*

[6] *Parts of this section are based on and have already been published by Trauer, Schweigert-Recksiek, Engel, et al. (2020).*

2.1.3.2 Definition of Digital Twins

As mentioned before, there is no common definition of what a DT is – which is not a major issue if the basic concept and the characteristic of a DT are clear. Within an industrial case study, Trauer, Schweigert-Recksiek, Engel, et al. (2020) identified the following three basic characteristics of a DT:

1. A DT is a virtual dynamic representation of a physical system.
2. Real space and virtual space are connected for automatic and bidirectional data exchange, and
3. The DT covers all phases of the product lifecycle.

These basic characteristics lead to the definition, which is referred to throughout this thesis (Trauer, Schweigert-Recksiek, Engel, et al., 2020):

> *“A Digital Twin is a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange.”*

This definition is also in line with literature. For example it aligns well with the characteristics Jones et al. (2020) or van der Valk et al. (2021) identified in their literature review and the aspect of a **virtual dynamic representation** is commonly accepted. However, there are also some differences. Regarding the physical system, some scholars, like Baltes and Freyth (2017), Boureanu (2017), or Tao, Sui, et al. (2019) focus their discussions on machines or, more broadly, on products. Others, including Kasote et al. (2017), Banerjee et al. (2017), or R. Stark et al. (2017) regard a company’s assets as the tangible counterpart, often termed the “real space”. Within this research, in alignment with e.g., J. Lee et al. (2017), Eigner (2021), Stjepandić et al. (2021a) or Vrana (2021), a broader perspective is adopted including entire systems including also their intangible entities such as services, or processes. The important part is that there is a real space, in which data is collected and a virtual space to process the data and to include functions that lead to actions in the real space.

Also, the aspect of **bidirectionality** is ambiguously used in literature. While some claim that bidirectional data exchange is the factor distinguishing DTs from other technologies (e.g. Grieves, 2023; M. Singh et al., 2021; Stjepandić et al., 2021a; Vogel-Heuser et al., 2023), M. Liu et al. (2021) found that more than half of 176 analyzed publications were refering to DTs but neglecting the bidirectional data exchange. These concepts where no automatic, respectively no bidirectional data exchange is implemented are called “Digital Model”, or “Digital Shadow” (Kritzinger et al., 2018) and will be outlined in section 2.1.3.3.

Lastly, the **lifecycle** characteristic differentiates the existing definitions of DTs and also implies a philosophical question – can a DT exist before the physical entity exists? According to the majority of literature analyzed by Jones et al. (2020) or M. Singh et al. (2021), it is essential, that the DT covers all lifecycle phases “from cradle to grave”, as it was suggested by Grieves and Vickers (2017). This implies that the DT can already exist during the design phase. Here, the physical product may not yet exist, however, there will always be a real space with which the DT can interact. This even applies for phases after physical disposal (Jones et al., 2020). According to Eigner (2021), a DT exists before physical existence of the product, but it is rather an instantiated simulation model. However, covering the entire lifecycle is a quite ambitious goal as a lifecycle can cover multiple years, often even decades. Thus, most publications focus on DT applications in very specific lifecycle phases, rather than the entire product's lifespan (Jones et al., 2020). To consider this, several subtypes of DTs can be found in literature that describe the states of DTs along the lifecycle (cf. section 2.1.3.3). In addition to a product's lifecycle, Schmitt and Copps (2023) also suggest DTs of enterprises and eco-systems as a further subset. These subtypes are introduced in the following section.

2.1.3.3 Related Terms and Concepts

Relation between Digital Twins, CPS, and IoT/IIoT

As described in section 2.1.1, DTs are closely related to other existing concepts. **CPS** share many common characteristics of DTs – a physical system, a virtual system and a bidirectional connection between these two worlds (Nardelli, 2022; Parnianifard et al., 2022; Tao, Qi, et al., 2019). But how do these terms differ? Looking at their origins, both paradigms emerged at the beginning of the 21st century. While CPS stem from industry 4.0 and are one of its core technologies (Wichmann et al., 2019), DTs are a further development of the PLM paradigm (Tao, Qi, et al., 2019). According to Tao, Qi, et al. (2019), mainly differ in the technologies being used, and the bidirectional cyber-physical mapping. CPS incorporate one-to-many correspondences. I.e., many physical assets are connected to one cyber system which analyses the data and triggers actions to the physical assets. A DT focuses on a one-to-one mapping, i.e., one virtual model per physical asset[7] (Tao, Qi, et al., 2019). Furthermore, the lifecycle aspect is a major difference (Tao, Qi, et al., 2019). CPS are predominantly used for operating systems. DTs on the other hand, as they stem from PLM aim at covering the entire lifecycle. Nevertheless, the majority of analyzed publications, do not separate CPS and DTs, but incorporate DTs within CPS (e.g. El Bazi et al., 2023; Josifovska et al., 2019; Lu et al., 2020; Schroeder et al., 2021; Uhlemann et al., 2017; Vogel-Heuser et al., 2023; Vrana, 2021). El Bazi et al. (2023) describe DTs as *„the seamless integration of data between the physical layer and the cyber layer of the cyber-physical system"*. For Uhlemann et al. (2017) and Xiong and Wang (2022), DTs are even a prerequisite for realizing CPS. According to them, each DT is a CPS and can be described as such. However, the beforementioned difference regarding the lifecycle and the one-to-one mapping is still used to differentiate the DT from other CPS.

Intersecting CPS and DTs is the internet of things, respectively the industrial internet of things (**IoT/IIoT**). As already described in section 2.1.1, IoT is the backbone of DTs and CPS. It is the necessary infrastructure that connects machines by 3C[8] technologies and thus offers the platform to collect the required real-time data from the use phase (Attaran & Celik, 2023; Fuller et al., 2020; Rathore et al., 2021; Sharma et al., 2022; Tao, Qi, et al., 2019; Xiong & Wang, 2022). However, as IoT only considers tangible systems, this only accounts for production and operation phases – DTs in the design phase are only rarely linked to IoT systems (Minerva et al., 2020).

---

[7] *This aligns with the concept of "DT instances", which is described in the next but one subsection.*

[8] *3C stands for computation, communication, and control (Y. Liu et al., 2017).*

Digital Model, Master, Shadow, and Thread

In addition to the ambiguity in the definitions of DTs, there are similar terms that are often used interchangeably. Some rather uncommon terms include “Product Avatar” (Barricelli et al., 2019), “Digital Blueprint” (Bajaj et al., 2016), “Digital Mirror Model” and “Digital Reflection” (Erikstad, 2017). These terms can be used synonymously, as they refer to the basic characteristics of a DT. However, the most prevalent terms used instead of DT are “Digital Thread”, “Digital Model” and “Device/Digital Shadow” (Alnowaiser & Ahmed, 2023; Riesener et al., 2019).

According to Eigner (2021), the **Digital Thread** in the context of Digital Modeling and the Digital Twin serves as a link that seamlessly connects all configured items present within the partial models specific to each phase of the product's lifecycle. It is the required connecting element, combining Digital Model, DT, and physical twin throughout the entire product lifecycle and thus is an inevitable element for developing the DT. For this objective, a Digital Thread integrates information from PLM, TDM, and authoring systems as well as additional product-relevant data sourced from various IT systems, including ERP, SCM, and CRM (Eigner, 2021). Consequently, the Digital Thread aims at shortening design durations and facilitating interdisciplinary data exchange to surmount organizational barriers (Siedlak et al., 2018). Therefore, these terms cannot be used synonymously – the Thread is a prerequisite of the DT and an integral part, not a distinct technology. However, in early phases of the product lifecycle, the DT often predominantly exists of a Thread, as no physical counterpart exists yet (Boschert & Rosen, 2016).

Another essential part of DTs are the **Digital Models** which are linked by the Digital Thread. According to Kritzinger et al. (2018), a Digital Model is *“[...] a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object”*. It includes models such as simulation models, mathematical models, geometrical models, physics-based models, data-driven models, system models, etc. (Kritzinger et al., 2018; Thelen et al., 2022; Wright & Davidson, 2020). According to Thelen et al. (2022) and Eigner (2021), a DT, is a Digital Model until, its physical twins exist, i.e. starting in the manufacturing phase (cf. Figure 2-3). Similarly, Stjepandić et al. (2021a) use the term **Digital Master** (cf. Figure 2-3) which is the combination of Digital Models within a Digital Thread. Thus, the master is the *“blueprint for all manufactured products”* and the starting point for a DT, before physical existence of the product. Looking at the definition of Kritzinger et al. (2018) as a digital model and its corresponding real world object are only connected manually, neglecting an important characteristic of DTs – bidirectional automated data exchange.

This characteristic is also neglected for **Digital Shadows**. According to Kritzinger et al. (2018) are Digital Models including an automated data exchange from the physical object to the digital object. These could be for example monitoring systems, that automatically depict the current state of a machine, or a product, but do not directly affect it – there is no automated data flow from the digital object to the physical (cf. Figure 2-2). Only the DT connects real space and virtual space in a bidirectional, automated way (Kritzinger et al., 2018). Therefore, although some are parts of another, all these terms have to be used distinctively and cannot be interchanged.

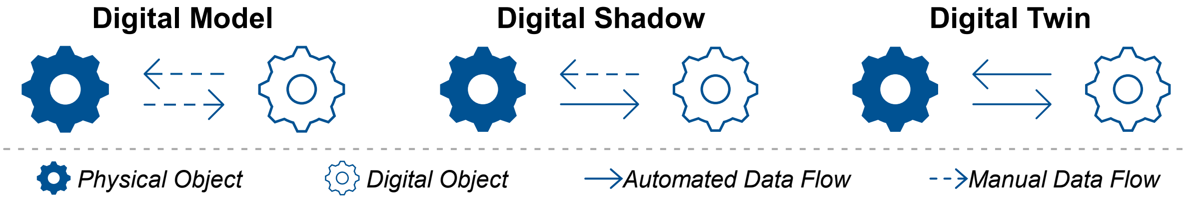


Figure 2-2: Distinction between Digital Model, Digital Shadow and Digital Twin, According to Kritzinger et al. (2018).

Digital Twin Subtypes along the Product Lifecycle

The characteristic of a DT to cover the entire lifecycle of its real-world counterpart is very hard to achieve. Therefore, it is important to develop DTs incrementally and iteratively (Schweigert-Recksiek et al., 2020). To consider these resulting partial DTs in the terminology, many different subtypes of DTs along the lifecycle were defined. Figure 2-3 depicts these subtypes in accordance with the product lifecycle based on Grieves (2005) and the DT lifecycle based on Adamenko et al. (2020b). After introducing the term DT, Grieves and Vickers (2017) defined the subtypes **DT Prototype**, **DT Instance**, **DT Aggregate**, and a **DT Environment**. The DT Prototype is the digital model, which is created in the phases, where no physical product yet exists. From this prototype, DT Instances can be defined for each manufactured product, interacting only with this one instance. Multiple DT instances can be combined in a DT Aggregate to allow for aggregated assessments and control of multiple products. All these concepts are managed within a DT Environment (Grieves & Vickers, 2017). Additionally, in industry, often a **DT Type** is defined (e.g. Grafe, 2023; Vrana, 2021). It is the final state of a DT prototype and therefore serves as a blueprint for all DT instances.

Trauer, Schweigert-Recksiek, Engel, et al. (2020) analyzed common DT use cases in their industrial study to define DT subtypes. Based on this analysis, the DT use cases could be clustered according to the lifecycle phase the DT solution is contributing to the most. These types are **Engineering Twins**, **Production Twins**, and **Operation Twins**[9]. This clustering is not comprehensive and there might be more subtypes, which also overarch the lifecycle phases (for example, **process** or **cost twins**), which is also claimed by Schmitt and Copps (2023). Stjepandić et al. (2021a) use the terms **Digital Master**, **Digital Manufacturing Twin**, and **DT Instance**, which is a combination of the previous two clusterings. Similarly Barricelli et al. (2019) substructure DTs in **Prototype DTs**, **Development DTs**, and **Product DTs.** In accordance with PLM, Eigner (2021) distinguishes the state of DTs according to the state of the product documentation – “as designed”, “as built/as delivered”, and “as maintained”. Similar to Grieves and Vickers (2017) he differentiates between the DT before physical existence of the product (digital model) and after production (DT core).

---

[9] *For example, an engineering twin can be used to automate simulation and design activities within product engineering, bridging different disciplines like engineering design, virtual and physical testing. A production twin could analyze and optimize the production process, improving the product’s quality or lowering manufacturing costs (e.g. Trauer, Pfingstl, et al., 2021). An operation twin focuses on the usage and service phase of a product and might be used for predictive maintenance activities.*

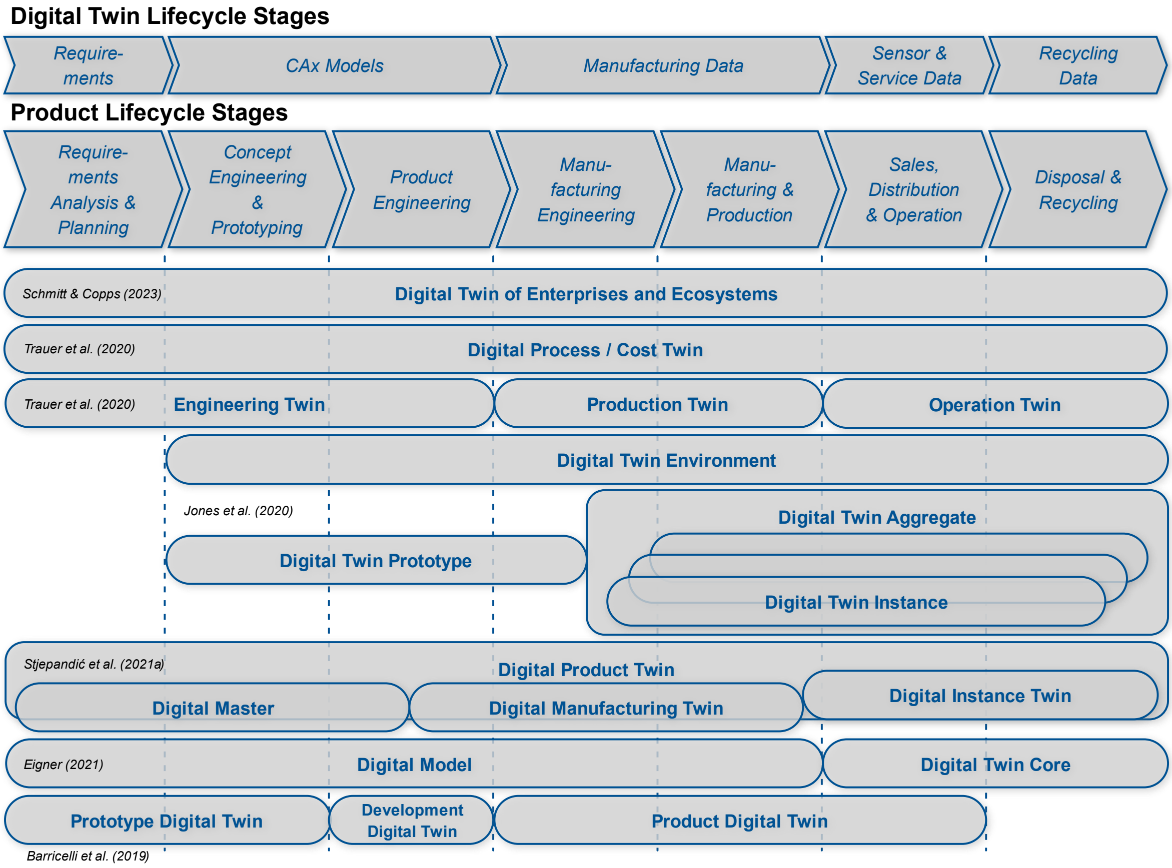


Figure 2-3: Subtypes of Digital Twins (based on Barricelli et al., 2019; Jones et al., 2020; Schmitt & Copps, 2023; Stjepandić et al., 2021a; Trauer, Schweigert-Recksiek, Engel, et al., 2020) Along the Product Lifecyle (based on Grieves, 2005) and the Digital Twin Lifecycle (based on Adamenko et al., 2020b).

2.1.3.4 Applications of Digital Twins

Similar to the number of definitions, the number of application areas for DTs is large too. Table A 1 gives an overview of the most common industrial application areas of DTs. Neither the areas, nor the list of publications is comprehensive, but shows how diversly DTs can be used. Within each of these categories uncountable use cases can be found (Attaran & Celik, 2023). The literature reviews of e.g. Lu et al. (2020), or Alnowaiser and Ahmed (2023) identified manufacturing and engineering-related areas as main application of DTs, which makes sense considering the origins of this concept. Within the engineering domain, specific use case along the entire product-lifecycle can be found – particularly in design, realization, and use phases (Jones et al., 2020). In an industrial case study Trauer, Schweigert-Recksiek, Engel, et al. (2020) identified typical, exemplary use cases for DTs along the lifecycle, which are depicted in Figure 2-4.

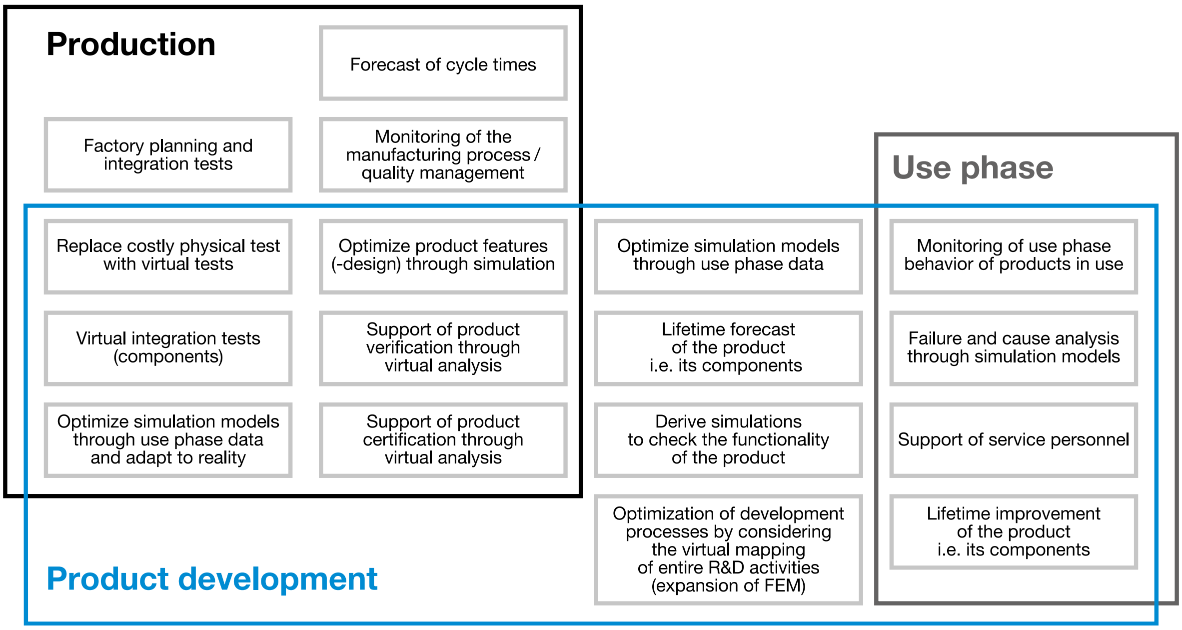


Figure 2-4: Collection of Use Cases for DTs (Trauer, Schweigert-Recksiek, Engel, et al., 2020).

2.1.3.5 Benefits of Digital Twins

DTs offer a wide range of benefits across various phases of the product lifecycle. Initially, their value was evident in the product's usage phase, where they provided insights into maintenance needs by analyzing the real-world condition of physical objects. Over time, this capability expanded to incorporate insights from product usage into earlier lifecycle phases to enhance product development (Negri et al., 2017). DTs have major importance for the provision of data-driven insights, as well as decisions and actions based on those insights (Raj & Surianarayanan, 2020). One significant advantage of DTs is their capacity to create virtual prototypes, reducing the need for physical prototypes (Sharma et al., 2022; M. Singh et al., 2021). Changes occurring in the physical object are mirrored in the digital model, providing valuable knowledge for informed decision-making throughout the entire product lifecycle (Dohrmann et al., 2022; West et al., 2021).

In general DTs offer many benefits, among others increased productivity, efficient resource utilization, improved energy efficiency, cost reduction across different lifecycle stages, innovation in product offerings, improved quality management, enhanced traceability, data-driven engineering and requirements, reduced risk, increased growth and competitive advantage, and adaptations of the organization's business model (D'Amico et al., 2023; El Bazi et al., 2023; Golovina et al., 2020; Raj & Surianarayanan, 2020; M. Singh et al., 2021; Stupar et al., 2023). The latter is one of the major benefits – several studies have emphasized the transformative potential of DTs in reshaping business models (El Bazi et al., 2023; Kumar et al., 2022; Schmitt & Copps, 2023; Stupar et al., 2023). For instance, Li et al. (2020) argue that DTs empower enterprises to evolve products into dynamic platforms. This enables continuous understanding of customer needs, timely and context-specific actions, superior product and service offerings, and disruptive enhancements in core processes and customer experiences.

Another important benefit of DTs is the opportunity to increase a product's or process' sustainability (Franciosi et al., 2022). On one hand, DTs can be used to enable companies in conducting sustainability assessments and policy evaluations (Edrisi & Azari, 2023). On the other hand, it can have a direct impact on increasing sustainability. For example Tzachor et al. (2022) investigated how DTs are contributing to the sustainable development goals (SDGs) of the United Nations (United Nations Development Program, 2023). According to this study, DTs contribute by: (1) enhancing effective allocation of resources, (2) safe innovation of environmentally friendly technologies, (3) promoting inclusive collaborations to support sustainable development, and (4) enabling monitoring and reporting of advancements in achieving the SDGs. Furthermore, there are several studies showcasing specific examples of DTs improving sustainability factors of the mirrored systems (e.g., section 4.3).

2.1.3.6 Challenges of Digital Twins

While there are many application areas and use cases being published by academia and the manifold benefits are often proclaimed, to date, only few implementations of DTs can be found in industry (Sharma et al., 2022; Trauer, Mutschler, et al., 2022). Consequently, there must be some barriers hindering companies in adopting this concept. Prior studies have already delved into various aspects of DTs, primarily focusing on their enabling technologies and associated challenges (Fuller et al., 2020). These technological advances, for example in physics-based and data-driven modeling, big data cybernetics, infrastructure development, and human-machine interfaces (Rasheed et al., 2020), address specific challenges often encountered in implementing DTs, such as security, privacy, data management, and data transfer issues (Fuller et al., 2020; Perno et al., 2021). Sharma et al. (2022) identified the management of vast volumes of data originating from IoT devices, and the complex bidirectional data exchange as the biggest challenge. Furthermore, the seamless integration of diverse software and simulation tools throughout the product lifecycle is challenging. Lastly, the authors underscored concerns related to cybersecurity, including issues of IoT security and the security of cross-industry partnerships (Sharma et al., 2022). Rasheed et al. (2020) mainly focus on modelling related issues regarding a real-time bidirectional connection, model evolution, safety and security, and usability of the DTs. These align with the data challenges identified by S. Singh et al. (2018) focusing on variety, mining, big data, and ownership of data. Additionally, they also focus on other challenges such as a lack of regulations and standards for DTs.

Technical challenges are also supported by many other publications (e.g. D'Amico et al., 2023; Kober et al., 2022; Saporiti et al., 2023; Stupar et al., 2023). However, DTs face not only technical challenges but also non-technical challenges. For instance, terminology ambiguity has been identified as a communication barrier (D'Amico et al., 2023; Stjepandić et al., 2021b). Neto et al. (2020) outlined issues related to process integration, resistance from personnel, competency gaps, unfavorable corporate cultures, and strategic challenges as challenges to DT implementation. S. Singh et al. (2018) identified cultural aspects and a lack of confidence and trust hindering information sharing for DTs. This is also confirmed by Saporiti et al. (2023), emphasizing organizational issues such as lack of necessary skills, unrealistic expectations, lack of trust, and missing value propositions.

According to D'Amico et al. (2023), the overall company's mindset and a lack of skill and understanding are strong inhibitors, hindering employees in adopting new approaches. Additionally, almost all identified sources emphasize cost and time required for the development of a DT as a major impediment (D'Amico et al., 2023; Kober et al., 2022; Möhring et al., 2022; Neto et al., 2020; Perno et al., 2021; Saporiti et al., 2023; S. Singh et al., 2018; Stjepandić et al., 2021b). Especially the management is often not aware of the benefits of DTs and it is difficult to assess the cost-effectiveness of a DT solution (Möhring et al., 2022). Further, several studies state, that developing a valid value proposition is a challenging task for companies (Kober et al., 2022; Perno et al., 2021; Saporiti et al., 2023). Like other disruptive technologies, DTs necessitate entirely new business models to fully harness their advantages (Benta et al., 2017; Li et al., 2020) as DTs fundamentally alter how products are delivered to customers and the payment methods involved (Aurich et al., 2019).

The most common challenges identified in literature are summarized in Figure 2-5. They serve as a starting point for an online survey conducted to identify the most crucial challenges in implementing DT from an industrial viewpoint (cf. Chapter 3).

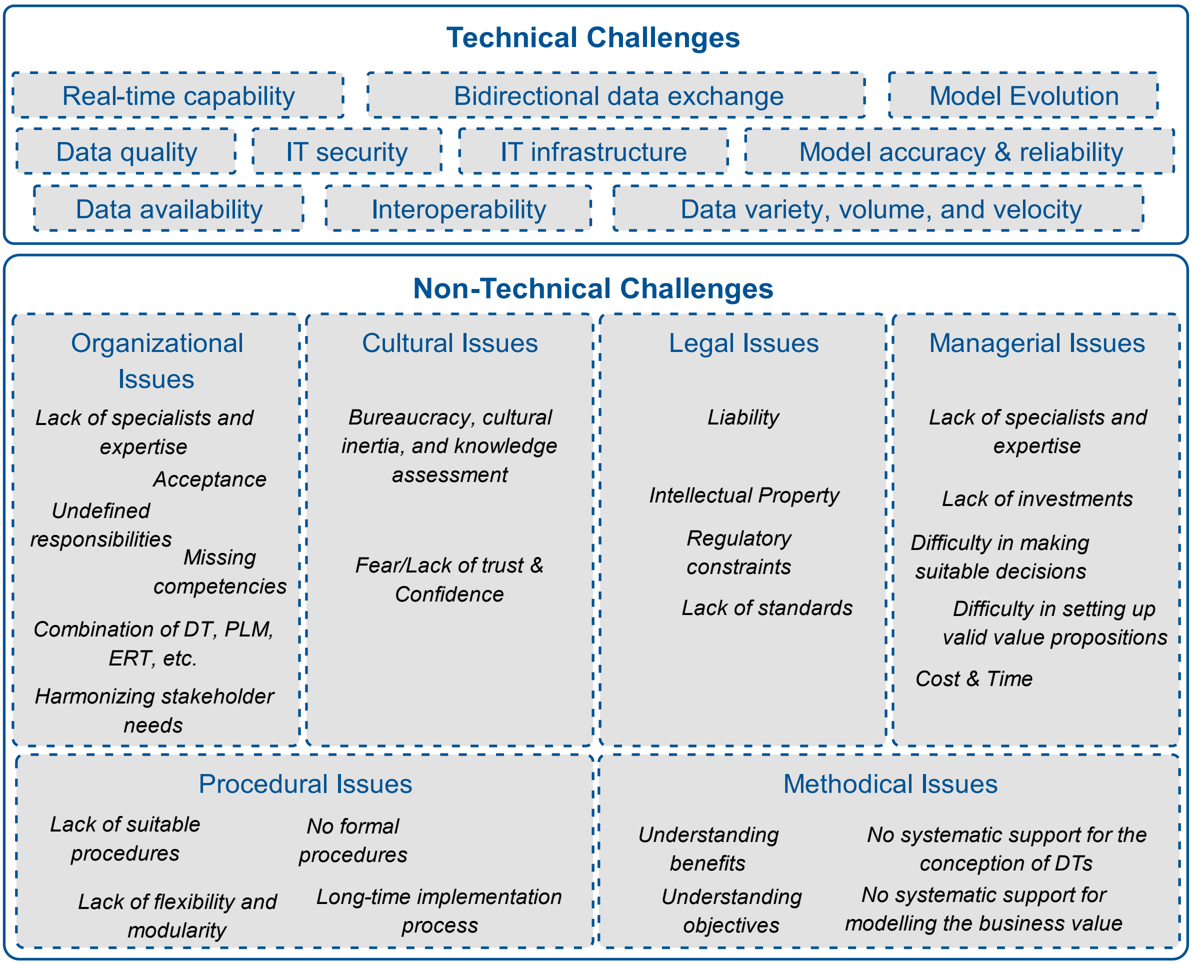


Figure 2-5: Common Challenges in Implementing Digital Twins Identified in Literature (based on D'Amico et al., 2023; Kober et al., 2022; Möhring et al., 2022; Neto et al., 2020; Perno et al., 2021; Rasheed et al., 2020; Saporiti et al., 2023; Sharma et al., 2022; S. Singh et al., 2018; Stupar et al., 2023).

2.2 Related Work

2.2.1 Systematic Support for the Development of CPS and IoT Systems

The complexity of product development processes can vary strongly. While simple development tasks can be executed individually, complex development processes require systematic approaches to handle their vast complexity. To structure these processes, they should be subdivided into distinct phases. To enhance execution, specific activities or work packages shell be defined for each phase, and these activities can be supported by methods and tools (Lindemann, 2009).

While there are numerous systematic approaches for physical product development processes available, this section focuses on basics and systematic support of the development of related concepts of DTs. For example in systems engineering, the problem solving cycle usually includes the phases, situation analysis, goal definition, target conception, and decision making (Haberfellner et al., 2019). These general phases were also observed by Gericke and Blessing (2012) – most process models in literature cover the stages analysis of task, conceptual design, embodiment design and detailed design. These general steps, namely goal definition, situation analysis, target conception, system selection and implementation, are included in the guideline VDI 2219 for the implementation of PDM and PLM systems (VDI Verein Deutscher Ingenieure e.V., 2016). This is particularly relevant as DTs originate from the field of PLM (cf. section 2.1.3.1).

V-Model for CPS

As outlined in 2.1.3.3, DTs are closely related to CPS. For the development and conception of CPS and mechatronic systems, the VDI Verein Deutscher Ingenieure e.V. (2021) released a standard based on the **V-model**[10]. This V-model is not a process model per se but rather a framework that outlines the interconnections between tasks, disciplines and stakeholders in mechatronic and cyber-physical system development. It provides a flexible structure that can be adapted to the uniqueness of each system. In addition to the V-model, the choice of the development approach, whether agile or traditional project management, should be tailored to each specific project. This results in a versatile development process logic for mechatronic and cyber-physical systems, varying depending on the application. The development of CPS in comparison to other systems differs regarding interdisciplinarity – the specific viewpoints, methods and knowledge have to be harmonized to ensure interdisciplinary cooperation (VDI Verein Deutscher Ingenieure e.V., 2021).

The V-model for CPS comprises three parallel strands (cf. Figure 2-6): one for system and subsystem modeling and analysis, one for core development tasks, and one for requirements

[10] *The "V" symbolizes breaking down the system into its components on the left side and gradually piecing these components and subsystems together into the complete system on the right side. Within this "V" shape, the characteristics and performance of the system being developed are consistently checked and confirmed (VDI Verein Deutscher Ingenieure e.V., 2021).*

engineering. It includes six checkpoints with control questions to support developers plan and execute their tasks systematically and keep track of the progress. However, these checkpoints do not align with project timeframes – users can freely integrate them in their project management or development procedure activities (VDI Verein Deutscher Ingenieure e.V., 2021).

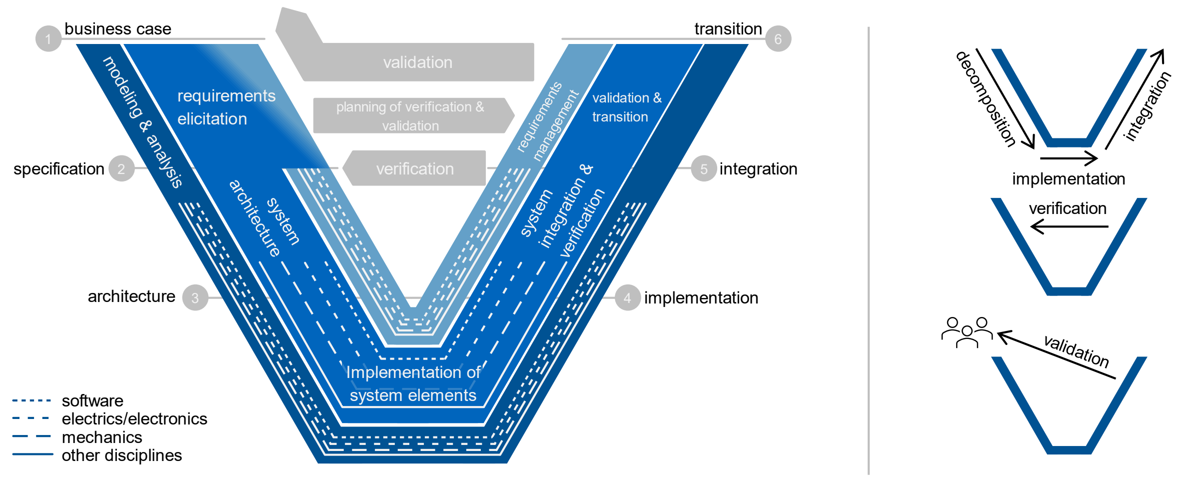


Figure 2-6: V-model for the Development of Cyber-Physical-Systems (based on Gräßler et al., 2021; VDI Verein Deutscher Ingenieure e.V., 2021) and the Core Idea of the V-Model (based on Gräßler, 2018).

Especially the business case driven development, the consideration of different disciplines and organizational aspects as well as the differentiation between internal and external customers are helpful. For each of the core tasks superficial descriptions are provided, suggesting some design methods to support execution of the task. Combined with the control questions, they offer a useful guideline for designers of CPS. However, they do not provide detailed support or a clear process on how to achieve the objectives which strongly reduces applicability and usability of the model.

IoT-Related Design Methodologies

Another related concept of DTs is IoT and its capabilities, e.g., for advanced data mining and integration of use phase data. As for DTs, many companies struggle extracting the value of this use phase data – especially due to difficulties in identifying suitable use cases and planning their implementation. Therefore, Wilberg (2020) developed a methodology for facilitating strategy development for connected products (cf. Figure 2-7). In contrast to the previously presented V-model, the methodology of Wilberg (2020) provides a clear and executable process model. Step 1 kicks off the development project for the **use phase data strategy** by assembling the project team and outlining the project's objectives. Step 2 initiates an internal analysis to assess the organization's digital readiness and as-is situation regarding available use phase data, the competitive landscape, and IT infrastructure. Simultaneously, an external analysis assesses the competitive context. Step 3 focuses on identifying potential application areas for use phase data and compiling a list of potential use cases. Step 4 delves deeper into these use cases by specifying their data requirements and consolidating them. Step 5 involves a detailed evaluation of the remaining use cases, followed by the selection of those that align with the overall use phase data strategy. Finally, Step 6 includes formulating the use phase data strategy and outlining an initial implementation plan (Wilberg, 2020).

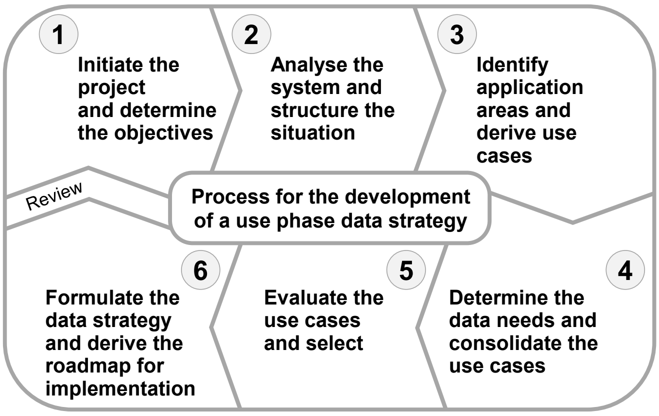


Figure 2-7: Process Model for the Development of a Use Phase Data Strategy (Wilberg, 2020).

A manual for the process model is available, providing detailed descriptions of each step to increase applicability of the process model. This includes specific task descriptions including recommendations, suggesting supporting methods and describing desired outcomes (Wilberg, 2020). For example, for the ideation of suitable use cases a use phase data use case catalogue was developed, which lays the foundation for the DT use case catalogue described in section 6.2.4.

Another methodology related to IoT is the Cross Industry Standard Process for Data Mining (**CRISP-DM**) (Wirth & Hipp, 2000). The methodology includes a process model with the general phases required for data mining, the phases' generic tasks, and their outputs. Furthermore, a user guide is provided including checklists, questionnaires, and other methods and tools supporting application of CRISP-DM (cf. Figure 2-8).

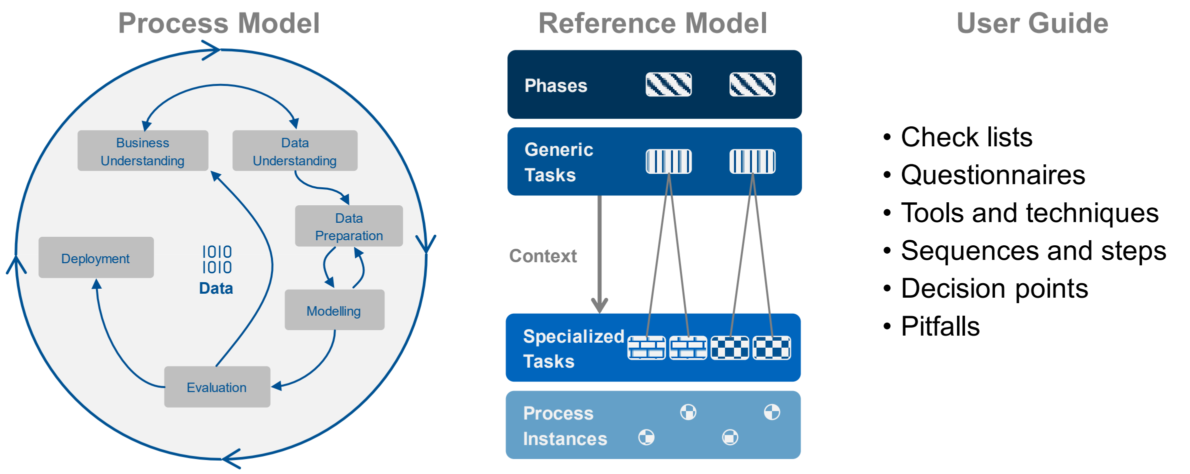


Figure 2-8: Phases of the CRISP-DM Process Model, Four Level Breakdown of the CRISP-DM Methodology, and User Guide (adapted from Wirth & Hipp, 2000).

As for the previously discussed methodology, CRISP-DM is an executable process, which is business case driven. Furthermore, as for all other analyzed methodologies, starting point for target concepts always is an detailed analysis of the as-is situation of the company, the process, and the environment. For all these approaches it is important to align business, organization, and the elements of digital enterprises – which is considered as the enterprise architecture. *"Planning, steering, and controlling of the Enterprise Architecture"* is considered as **Enterprise Architecture Management** (EAM) (Ziemann, 2022). Core paradigm of EAM is the business case driven design of digital ecosystems. Within EAM many frameworks and standards exist, describing different layers of enterprise architecture and how to handle them. One of the most prominent standard is TOGAF[11] (The Open Group, 2023), including processes, task descriptions, methods and tools on how to implement and conduct EAM.

2.2.2 Systematic Support for the Development of Digital Twins

Riedelsheimer et al. (2021) analyzed some of the most common design methodologies and recognized their insufficiency to properly support the development of DTs. As already mentioned, relatively few systematic approaches for the development of DTs exist. Especially, with regard to non-technical aspects. Table 2-1 provides an overview of the methodologies identified in a systematic literature review.

Clustering of the Identified Related Work

To cluster the identified approaches, categories and criteria were defined. Some merely focus on technical tools and platforms suitable to design a DT system (e.g. Adamenko et al., 2020a), which is marked by the category *"specific technologies"*. Furthermore, they can be categorized by the aspects they are considering and the challenges[12], they want to overcome – are they considering *technical aspects*, *non-technical aspects*, or both? Lastly, some papers suggest *architectures* for DT systems as part of their methodology (e.g. Erkoyuncu et al., 2020). In accordance with the research objective, in this review, methodologies that merely focus on technical aspects, or are only related to technologies were excluded. Only a few were listed as an example.

Assessment of the Suitability of the Identified Related Work

The identified related methodologies were subjectively evaluated regarding five criteria identified as crucial aspects to support engineers in developing DTs. The criteria were selected based on the experiences of the author of this thesis. (1) *Detailed descriptions* should be provided to enable also unexperienced users to apply the methodology. In general, the support should be applicable without further knowledge. To further improve usefulness especially for unexperienced users (2) *methods and tools* should be provided. Many activities necessary to the development of DTs are relatively complex and complicated and cannot be fulfilled

[11] The Open Group Architecture Framework

[12] For a brief overview of technical and non-technical challenges see section 2.1.3.6.

sufficiently without further support – therefore methods and tools are essential. (3) The methodologies should be *executable* meaning that a clear process with activities, tasks and outputs are suggested to guide the user. In addition, the approaches should provide a certain (4) *flexibility* in order to be applicable in different industries, for different DT types, or in different settings. Lastly, a key characteristic of DTs is its (5) *interdisciplinarity*, which should also be reflected in associated methodologies – Many different departments have to collaborate. Therefore, their discipline-specific viewpoints, procedures, terminologies etc. must be considered to enable cooperation.

Analysis of the Identified Related Work

Table 2-1: Overview of Related Systematic Supports for the Development of Digital Twins. Categorization and Rating of the Approaches Based on Subjective Evaluation.

Publications	Specific Technologies	Consideration of Technical aspects	Consideration of Non-Technical aspects	Architecture	Detailed Description	Methods and Tools provided	Executability	Flexibility	Interdisciplinarity
Adamenko et al. (2020a)	x				◑	◑	○	◔	○
Andrade et al. (2021)		x			◔	◔	◑	◑	○
Erkoyuncu et al. (2020)	x	x		x	◔	◔	◑	◑	◔
Eyre et al. (2020)			x		◔	○	◔	◔	◕
Follath et al. (2022)		x	x		◑	◔	◕	◑	◑
Göbel and Eickhoff (2020)		x	x		◔	◕	◑	◑	◕
Gogineni et al. (2023)		x	x		◔	○	◔	◔	◑
Göllner et al. (2022)		x	x		◔	◕	◑	◔	◑
Heindl and Stary (2022)		x	x		◕	◕	●	◑	◑
Human et al. (2023)		x	x	x	◑	◔	●	◔	◑
ISO International Organization for Standardization (2021)	x	x		x	◑	◔	○	◔	◑
Koch et al. (2022)		x	x		◔	◑	◑	◕	◕
Lünnemann et al. (2023)		x	x	x	◑	◕	◕	●	◕
Newrzella et al. (2022)		x	x		◑	◕	◕	●	●
Qamsane et al. (2021)		x	x		◕	◑	●	◑	◔
Riedelsheimer et al. (2021)		x	x		◑	◕	◑	◕	◕
Schroeder et al. (2021)	x	x		x	◑	◑	◔	◔	○
VanDerHorn and Mahadevan (2021)		x	x		◔	○	○	◑	◔

The analysis showed some commonalities and differences in the methodologies. For example, many approaches start with the identification of a user need or a business case, as it was also done in the methodologies identified in the previous section (e.g. Follath et al., 2022; Koch et al., 2022; Lünnemann et al., 2023; Newrzella et al., 2022; VanDerHorn & Mahadevan, 2021). The overview shows that there are several publications on methodologies considering also non-technical aspects other than the business aspects. For example, Lünnemann et al. (2023) considers the different viewpoints of the stakeholders in user stories and scenarios and thus enables a design of the organization. Also Göbel and Eickhoff (2020) included organizational aspects in their “Kaiserslautern Digital Twin Modelling Framework”.

Regarding provided methods and tools, the related work varies strongly. Riedelsheimer et al. (2021) included many different aspects in their “DT-V-model” – risk management, different design approaches, a DT readiness assessment, and others. Also Göbel and Eickhoff (2020) provide methods like customer journeys or business modelling canvases in their framework. The most specific methods are presented by Newrzella et al. (2022) suggesting a novel “Use Case Mode and Effects Analysis” and a “House-of-DT” to support the use case driven development of DTs.

Many methodologies are just theoretical frameworks and are not directly executable. Only Heindl and Stary (2022), Qamsane et al. (2021) and Human et al. (2023) provide clear and executable processes in their publications. Follath et al. (2022) presented an executable procedure based on the CRISP-DM approach. However, the task descriptions are too superficial to be directly applicable. Interdisciplinarity is considered by most publications, that also include non-technical aspects. However, they often are not specific about the different roles and stakeholders to be included and leave it to the user to decide on which disciplines would be required.

Interestingly, even though DTs are such a fast-growing research field, only a few standardized approaches can be found – neither methodology nor technology-wise. Only ISO 23247 (ISO International Organization for Standardization, 2021) provides superficial recommendations on how to design and implement a DT. They are not executable, do not provide methods and tools and also lack flexibility. Over the last three years, industry and governments have recognized the need for standardization in DT technology and methodology and founded the Digital Twin Consortium (Digital Twin Consortium, 2023) and the Industrial Digital Twin Association (Industrial Digital Twin Association e.V., 2023)[13].

[13] *The Digital Twin Consortium is rather active in the American area, while the Industrial Digital Twin Associating is stemming from European companies.*

2.3 Conclusions from the State of the Art

Basics

This Chapter outlined the related concepts of DTs, their origins, challenges, benefits, applications, and the basic terminology. The challenges lay the basis for a more comprehensive online survey on the challenges in implementing DTs (cf. Chapter 3). There is a gap in research – while non-technical challenges are claimed by many publications, only a few suggest solutions to them. The identified benefits inspire and enrich the value map and the business modelling approach (cf. sections 6.2.2 and 6.2.3). The applications are covered by the use case catalogue (cf. section 6.2.4). Section 2.1.3.3 gave an overview of the ambiguity in terminology and the resulting misconceptions. While there does not necessarily need to be a standardized definition for all aspects, the following terminology will be used:

- A **Digital Twin** is a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange.
- A **Digital Model** is a virtual representation of a real-world artifact, which is used to build DT Prototypes.
- DTs without a 1:1 connection to its real-world artifact is a **DT Prototype**.
- From the prototypes, **DT Types** can be derived which will be specified for each instance as a **DT Instance**[14].
- If required these DT instances can be accumulated in a **DT Aggregate** mirroring a whole system of DTs.
- DT solutions should be specified regarding the application scenario, therefore subtypes such as the engineering twin, production twin, operation twin, process twin, cost twin, etc. can be used.

Insights for the Development of DTs

The related work described in section 2.2 revealed some insights for the development of DTs:

1. Previous research has confirmed the need for **specified methodologies** for designing and implementing DTs (e.g. Riedelsheimer et al., 2021).
2. It is beneficial to choose a **business case or user need driven** approach.
3. Furthermore, the V-Model for CPS by VDI Verein Deutscher Ingenieure e.V. (2021) proposed consider **both internal and external customers** for DT solutions.
4. The suitability and usefulness of **checkpoint control questions** was confirmed e.g., by VDI Verein Deutscher Ingenieure e.V. (2021) and Eyre et al. (2020).
5. Another element that appears to be helpful in managing the procedures are **use cases**. For example Lünnemann et al. (2023) and Wilberg (2020) formulate use cases and user stories to build their strategies and to communicate the developed results.
6. Furthermore, **detailed manuals** to the methodologies, as provided by Wilberg (2020), are crucial to ensure applicability and usability of the developed support.

[14] *For example, a DT type might be created for a specific model of car. The instance refers to one unique car of these models of cars.*

Conclusions from Related Work

As described earlier, none of the methodologies listed in Table 2-1 fulfill the criteria set for this thesis. Especially in terms of detailed description, methodical support and executability, they do not seem to be suitable to offer sufficient support. These approaches do consider non-technical aspects, however they mostly focus on business aspects. Procedural, methodical, cultural, organizational, and managerial issues are neglected by most of the comparable approaches. Regarding the type and level of support, the most relatable work is the methodology for the development of a use phase data strategy by Wilberg (2020). However, content-wise it is not applicable to DTs – a use phase data strategy is companywide, not specified for one asset, and bidirectionality and lifecycle focus are not considered. These observations underscore the research gap this thesis is aiming to close by developing a systematic support including processes and methods to support the design and implementation of DTs with a special focus on non-technical issues.

3 Online Survey on Challenges in Developing Digital Twins

3.1 Study Design

Motivation and Goal of the Survey

As shown in Chapter 2, existing studies have focused on challenges around the implementation, literature reviews or the application of DTs in a university environment. Therefore, driven by the first research question[1], an online survey on the current status of DTs in industry as well as on challenges towards their implementation was conducted[2]. But it is not only about the challenges – there is still ambiguity in the terminology of DTs. Further, the characteristics of DT implementation projects in industry are mostly unknown. However, analyzing and understanding these aspects is crucial for developing targeted support for companies to overcome the challenges. Therefore, the research question presented in section 1.3 was subdivided into four specific questions driving this online survey (Trauer, Mutschler, et al., 2022):

> ***RQ1a:*** *"Is there still an ambiguity in the terminology of DTs?"*
>
> ***RQ1b:*** *"What are characteristics of DT projects in industry?"*
>
> ***RQ1c:*** *"What are the most crucial (categories of) challenges in implementing DTs?"*
>
> ***RQ1d:*** *"Are non-technical challenges more likely to cause problems, than technical challenges?"*
>
> *(adapted from Trauer, Mutschler, et al., 2022)*

Participants

Two channels were used to invite experts to participate in the survey – email and LinkedIn (https://www.linkedin.com/). The email-invitation was sent to 560 industry partners of the Laboratory for Product Development and Lightweight Design of the Technical University of Munich. Contacts on the list were not further filtered or preselected but the nature of the list ensured that they were all engineers in different positions in various companies in Europe operating nationally and internationally. This group is meaningful as they are all employed in engineering firms, which is a focal aspect of this thesis. Further, most of them have a background in product development and are actively working on product development activities, which increases the likelihood that DTs are of relevance to them. The final analysis of the

[1] *"What are the major impediments in implementing Digital Twins in engineering companies?" (cf. section 1.3).*

[2] *The survey was conducted in course of a semester thesis by Mutschler (2021). Parts of this survey were already published in Trauer, Mutschler, et al. (2022).*

survey results was conducted in the beginning of 2022. By January 31, 1031[3] people saw the post made on LinkedIn. In total 61 experts filled the questionnaire. Therefore, the response rate is approximately 5 % - 10 %.

As shown in Figure 3-1, most of the participants have an academic background in mechanical engineering. But also, other engineering disciplines as well as law, business, natural, and social sciences were part of the group. As described previously, the participants were inquired about their personal experiences with working on DTs. Out of the respondents, 29 confirmed having such experiences, while 32 reported otherwise. The majority of the participants possessed extensive professional experience of over 20 years. On average, they were 42 years old, with ages ranging from 22 to 64 years.

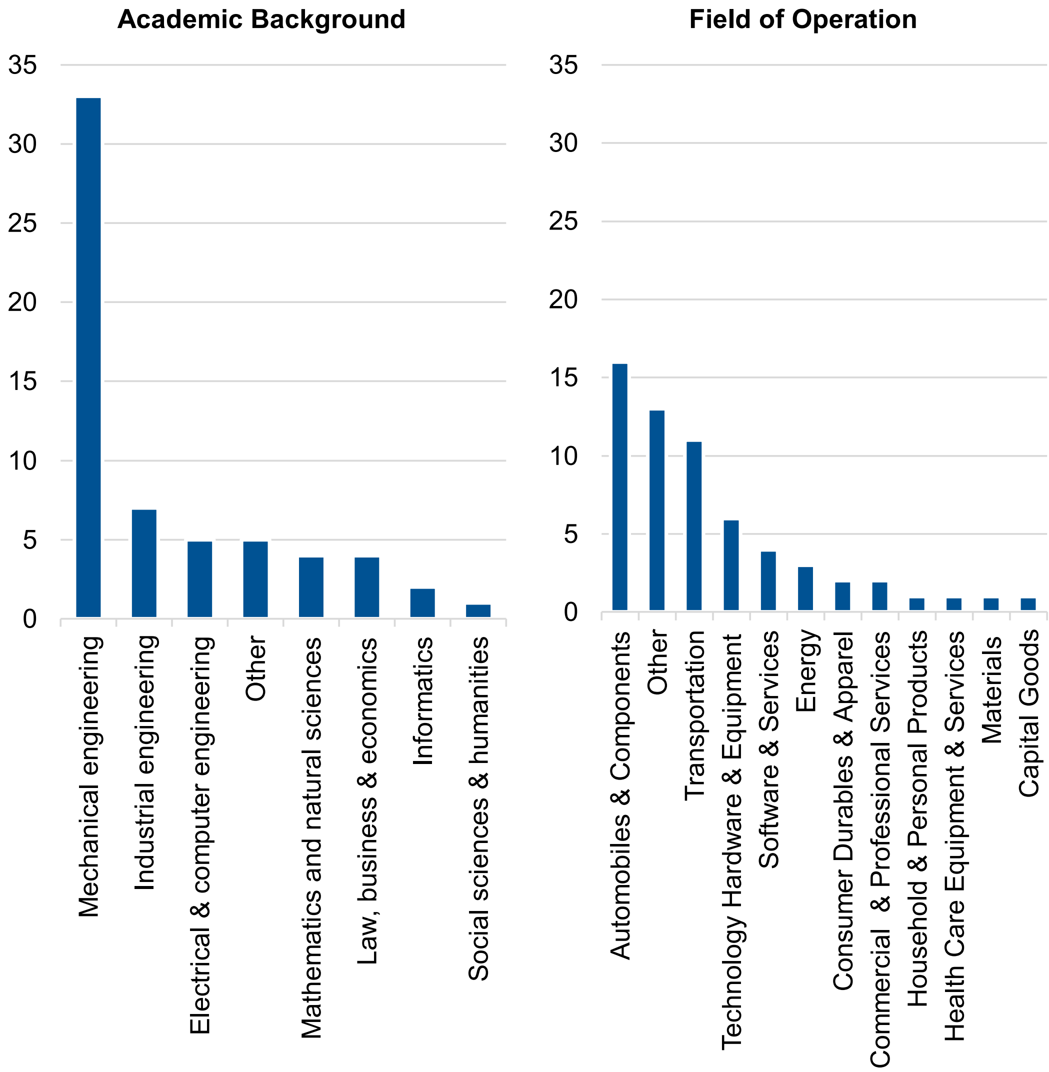


Figure 3-1: Academic Background of the Participants and Companies' Field of Operation (adapted from Trauer, Mutschler, et al., 2022).

[3] *According to the statistics provided by LinkedIn. It cannot made sure, whether these are unique views or not.*

Based on the Global Industry Classification Standard of MSCI Inc. (2021) a choice-list of different branches was presented to the participants in order to get an overview of the companies they are working for. As shown in Figure 3-1, the experts are employed in companies covering a broad field of operation. It is likely that more than two participants are working for the same company, however it cannot be assessed how many unique firms were represented. The included companies are rather large, employing more than 2000 people and operating internationally.

Basics of Surveying

This online survey includes several surveying techniques. Closed questions served either as filter questions, or to collect statistical data. Filter questions play a crucial role in guiding surveys (Schaeffer & Dykema, 2020). They are particularly useful when asking about past events or phenomena, as they ensure that respondents possess the necessary expertise on the specific topic (Schaeffer & Dykema, 2020).

For the statistical analysis[4], different types of closed questions were used. Choice-list questions presented the participants a list of options to choose from (Schaeffer & Dykema, 2020). Apart from these, questions to ask for an evaluation or judgement were used. For these type of questions, Likert-like scales were used. The Likert scale is a tool used to measure attitudes towards a specific issue. It usually consists of a series of statements related to the issue, and participants are asked to indicate their level of agreement with each statement on a five step scale from “strongly disagree” to “strongly agree” (Y. K. Singh, 2006).

Here, several variations from the classical Likert-scale are possible and useful. First, the number of response categories can be alternated. According to previous studies, a number between five to seven options is the optimal range in terms of reliability, validity and differentiability (Krosnick et al., 1996; Krosnick, 2017). Next, the labels of the response categories are relevant. There are two main options – labeling only the lowest and highest categories or labeling every category. Krosnick et al. (1996) recommend using verbal categories instead of numerical ones to avoid distortion of results. Menold et al. (2014) suggest labeling every verbal response category for clarity. However, Theil (2002) notes that the interpretation of quantification can vary between respondents, which is also supported by Schweigert-Recksiek et al. (2021). Therefore, to ensure uniform interpretation, this study labels only the lowest and highest categories verbally, with one exception. Lastly, the center of scale has an impact on the survey results. In bipolar scales[5], a middle category can indicate both, indifference (“neither nor”) or ambivalence (“yes and no”) (Schaeffer & Dykema, 2020). However, as shown by Wang and Krosnick (2020), omitting the middle option and thus forcing the participants to pick a side, does not improve the accuracy of responses. Following this study, within the present survey, middle categories were provided.

[4] *However, no systematic analysis methodology was applied. The analysis was predominantly focused on deriving some tendencies based on the distribution of responses, as shown in section 3.2*

[5] *..to which Likert-type scales belong.*

Structure of the Survey

The general structure of the online survey is shown in Figure 3-2[6]. The survey includes 36 questions. It was built and data was collected using “Microsoft Forms”. The survey was conducted in English.

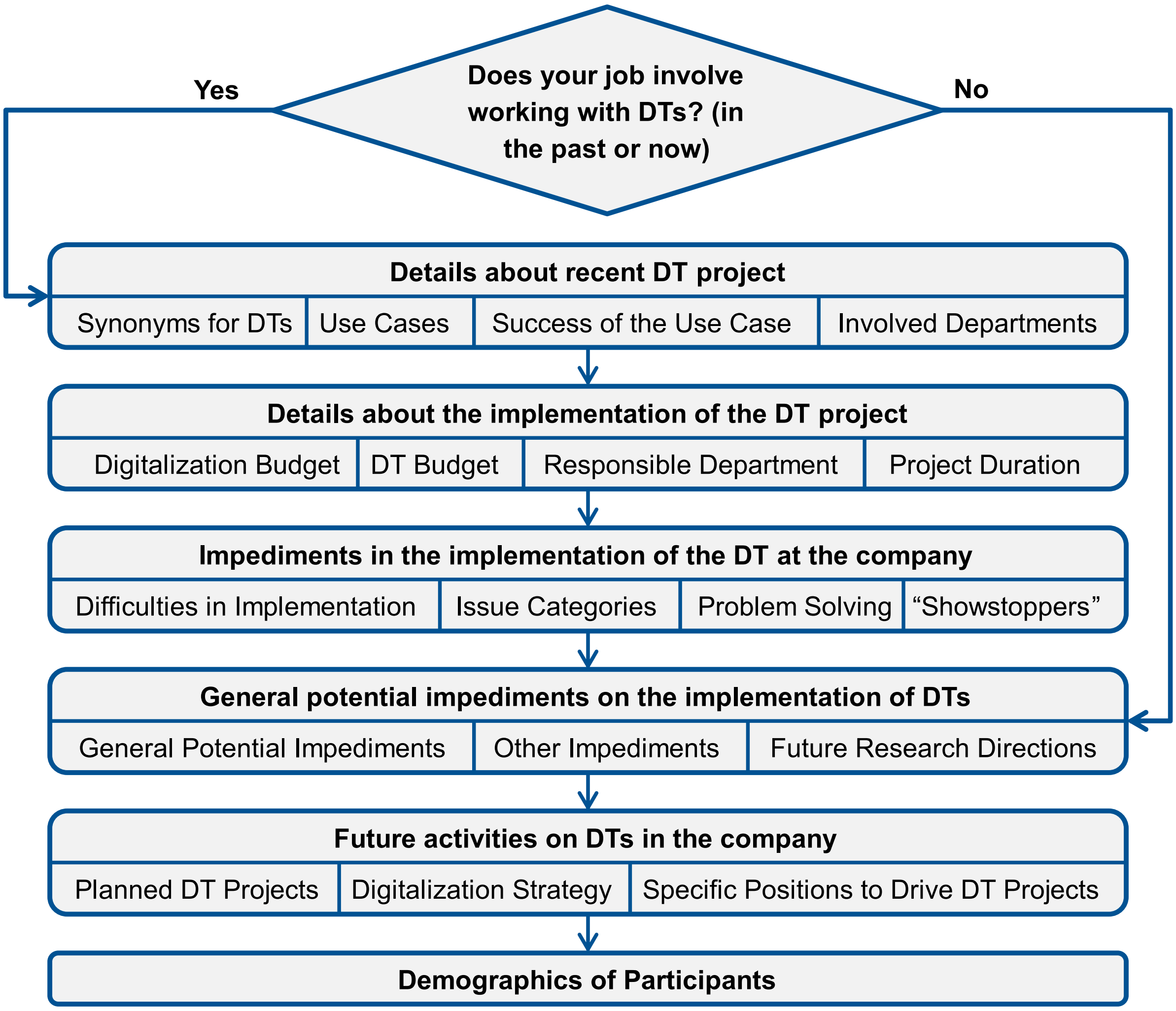


Figure 3-2: General Structure of the Survey (adapted from Trauer, Mutschler, et al., 2022).

The initial question of the survey – *“Does your job involve working with Digital Twins? (In the past or now)”* – asks for the participants’ personal experiences with DTs, allowing them to indicate their level of expertise. Participants who confirmed the first question were directed through the complete questionnaire (the experienced group). Conversely, participants who negated the question skipped the sections about characteristics of DT projects and were only asked about potential general challenges they might anticipate during a DT project. As they

[6] *The entire questionnaire can be found in the appendix A2.1.*

are all engineers working in companies working on DTs, they still should have appropriate expertise to answer these questions.

The experienced group was then asked for details on their most recent DT projects. In a multiple choice question, they were asked for the synonyms their companies are using instead of DT, as it is defined by Trauer, Schweigert-Recksiek, Engel, et al. (2020). In an open-ended question, they could describe their DT use case. The success of this use case was assessed in a unipolar closed question on a scale from zero to ten. In the following, in an interview style, details about the involved and responsible departments, the spent budget and the duration of the project were retrieved. These questions aimed specifically at answering RQs 1a and 1b. Lastly, they were asked to rate challenges in the implementation of their DT projects, regarding their criticality. This included filter questions on whether difficulties occurred at which department. Further, it was asked if and how these difficulties could be resolved and whether some of them caused a termination of the project ("showstoppers").

From there on, the two groups of participants joined together assessing the general potential of specific DT related challenges to cause problems. As the survey was meant to get a general insight into industrial practice, it was also investigated, on which DT related topics the companies are planning to work on in the future. Also, the research needs of the DT companies were collected. To end the survey, demographics of the participants were collected. This was posted at the end of the survey intentionally to not bore the respondents at the beginning of the questionnaire.

3.2 Results on the Challenges in Developing Digital Twins

Is there still an ambiguity in the terminology of DTs?

The first research goal of this survey was to understand the current level of ambiguity in the terminology of DTs. Throughout the literature review, the study distinguished synonyms from the definition of DTs used within this thesis (cf. section 2.1.3.2). Before starting the survey, the definition of Trauer, Schweigert-Recksiek, Engel, et al. (2020) was presented to the respondents[7]. Then, they were asked to select terms their company is using synonymously with the presented definition: *"Which of these synonyms are used in your company in the context of Digital Twins? (multiple selection possible)"*. The results are depicted in Figure 3-3. All 29 experts from the "experienced group" selected at least one of the options. Interestingly, more than half of the respondents indicated "Other" as their preference. The most frequently selected term was the "Digital Shadow".

[7] *The introduction to the survey as well as the questions can be found in the appendix A2.1.*

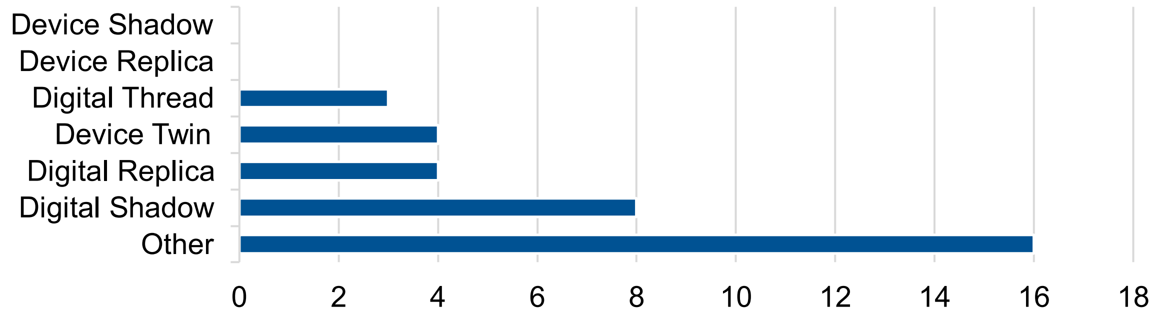


Figure 3-3: Terms Used Synonymously with "Digital Twin" (Adapted from Trauer, Mutschler, et al., 2022).

What are characteristics of DT projects in industry?

The survey included several questions to retrieve information on the DT projects of the participants in order to answer RQ1b. Initially, the participants were asked: *"Your job involves working with Digital Twins. Please describe the latest use case in a few sentences"*. Their responses revealed a wide range of contexts where DTs are applied including activities such as virtual testing through finite element modeling and thermal simulations, identifying and resolving bottlenecks in production planning, and managing operations and processes in transportation systems. Essentially, DTs have demonstrated their potential in various stages of the product lifecycle. In addition to product lifecycle management, one participant even utilizes DTs to automatically derive and validate business models for future products. Table 3-1 presents an excerpt of the responses. A detailed overview of the described use cases can be found in appendix A2.2.

Table 3-1: Excerpt of Use Cases, the Survey Participants are Working on. A detailed overview of the described use cases can be found in appendix A2.2.

Please describe the latest use case in a few sentences.
"We wanted to have a digital shadow of a production line, to ease tracking of bottlenecks in the production process."
"We wanted to create a digital twin of a part of the logistic."
"finite element calculation"
"Simulation and Modelling of processes"
"I'm working for the German railway (DB Netz) and I'm responsible for the System design of signal boxes. We are currently working on implementing digital twins of these systems for several purposes. We are still in a starting phase."
"1. Product Digital Twin - model of thermal system behavior and simulation in digital to avoid physical prototypes and tests. *2. Production Digital Twin - modelling and simulation of production processes for new factory. Here digital product data were used to model the objects of production processes"*

The success of these projects was assessed based on the question: *"How successful was that use case in your opinion?"*. The participants were able to select an option on a scale from 0 (not successful at all) to 10 (very successful). On average the use cases were rated with 6.55/10. The responses are depicted in Figure 3-4.

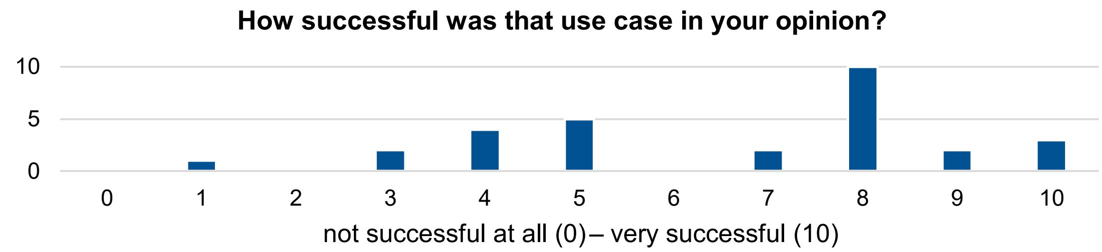


Figure 3-4: Success of the Collected Use Cases based on the Participants Own Opinion.

The temporal characteristics of the project were investigated using the following two questions: (1) *"How long did it take from planning to implementation?"* and (2) *"When did you or your company start planning the Digital Twin project?"*. The duration of these projects ranged from three months to five years, with an average duration of 25 months. Two companies initiated their projects as early as 2008 and 2012, whereas eleven out of the 22 industry partners embarked on their DT projects in 2019 or later.

Optionally, the participants were given the opportunity to provide information on the budgets allocated by their companies for digitalization projects in general and specifically for DT projects by answering the following open-ended questions: (1) "*What was the companies' budget for digitalization in general? (per year)"* and (2) *"What was the companies' budget for the latest Digital Twin project?"*. The results are illustrated in Figure 3-5. To account for the significant variations in budgets, the results are presented using a logarithmic scale. Additionally, four participants (#2, #4, #5, and #13) stated that their company had not defined a specific budget for DT projects. Respondents #16 - #19 were unaware of the details of their companies' digitalization budgets.

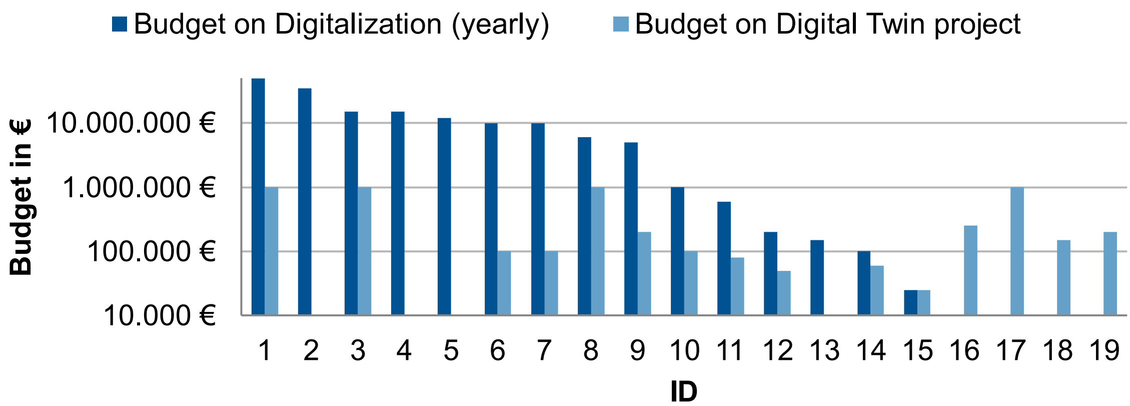


Figure 3-5: Budgets Companies Spent on Digitalization in General and on Digital Twin Projects Specifically (adapted from Trauer, Mutschler, et al., 2022).

To investigate the involved parties in the projects, a list of departments commonly found in industry was provided to the multiple-choice question: *"Which departments of your company were involved in the Digital Twin project? (multiple selection possible)"*. Additionally, the participants were able to add further departments. "Research and Development", "Production", and "Sales" were most frequently cited (cf. Figure 3-6).

Based on the open-ended question *"Which department was responsible for the implementation of the Digital Twin?"*, "Research and Development", "IT", and "Production" were identified to be most often responsible. Those three departments were also the departments that had the most problems during the projects, based on the open-ended question *"Which Department had the greatest difficulties with the implementation of the Digital Twin?"* (cf. Figure 3-6).

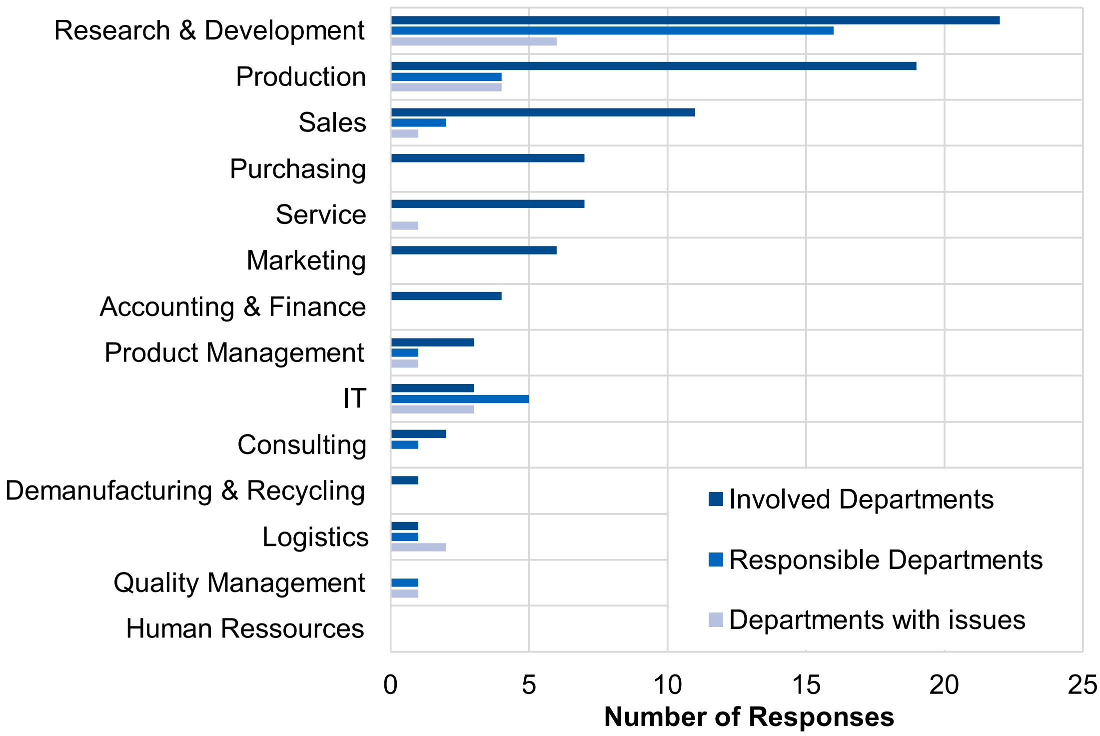


Figure 3-6: Overview of the Departments Involved, the Departments Responsible for Implementation, and the Departments that Have Had the Biggest Issues During the Project. Overview is Based on the 29 Digital Twin Projects of the Participants.

What are the most crucial (categories of) challenges in implementing DTs?

Two closed Likert-style questions were included to investigate the challenges in implementing DTs: (1) "*Please rate these categories according to their potential of causing difficulties in implementing Digital Twins."* and (2) *"Please rate the following aspects by their potential/likelihood to cause problems."*. First, the categories of the first question were briefly explained to the respondents (cf. appendix A2.1).

The findings are presented in Figure 3-7[8]. Technical issues are rated as most likely to cause difficulties. However, also softer factors play critical roles. At least half of the participants identified the first five categories as likely or very likely to cause problems in DT projects. Only cultural and legal issues were not considered as highly likely to cause problems.

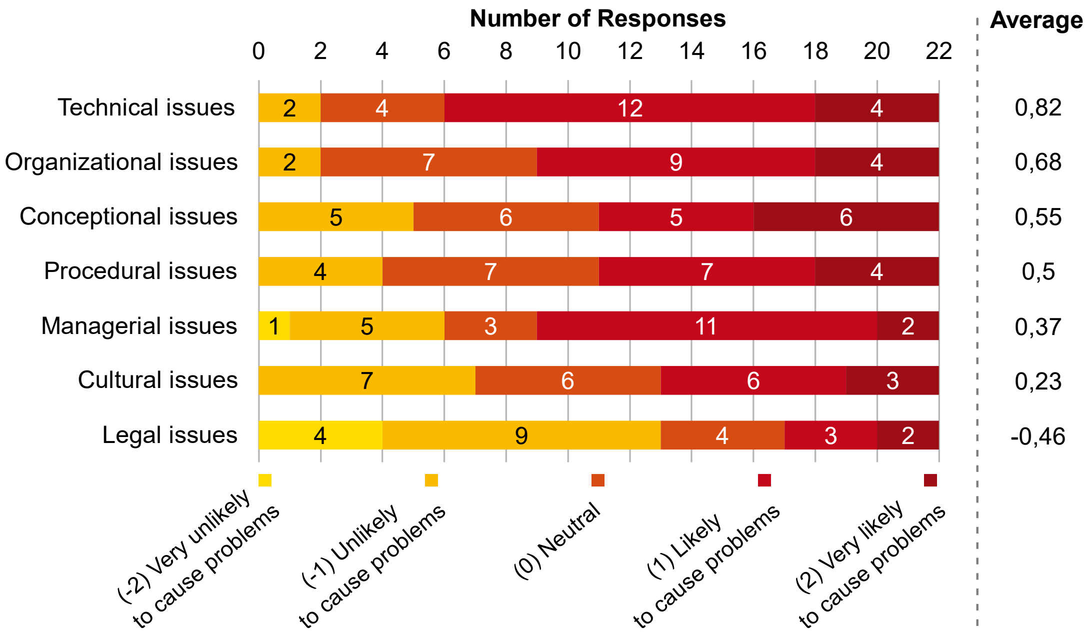


Figure 3-7: Rating of Categories of Issues According to their Likelihood to Cause Problems (adapted from Trauer, Mutschler, et al., 2022)[8] as well as the Average Rating on a Scale from -2 to 2.

Nevertheless, these categories are quite broad. To gain a more detailed understanding of these categories, specific challenges to DT implementation were presented to the participants in the second question. All 61 respondents were asked to answer this question, except for one who refused to do so. The top ten challenges are shown in Figure 3-8. The entire list of challenges can be found in the appendix A2.3. The specific aspects were predominantly deducted from literature. Four additional aspects were added based on own experiences, considering the potential influence of non-technical aspects on the success of DT projects. Thus, an equal number of technical and non-technical challenges were presented to the participants. Like Figure 3-7, these specific aspects were sorted based on their average likelihood to cause problems, as explained earlier.

[8] *The categories are arranged based on the average responses, which were calculated by translating the textual scale into a numerical scale ranging from one (indicating a low likelihood of causing problems) to five (indicating a high likelihood of causing problems). These numerical values were then multiplied by the percentage of respondents who selected each option. For clarity reasons in Figure 3-7 and Figure 3-8, each step was labeled, even though the participants only voted on endpoint labeled scales.*

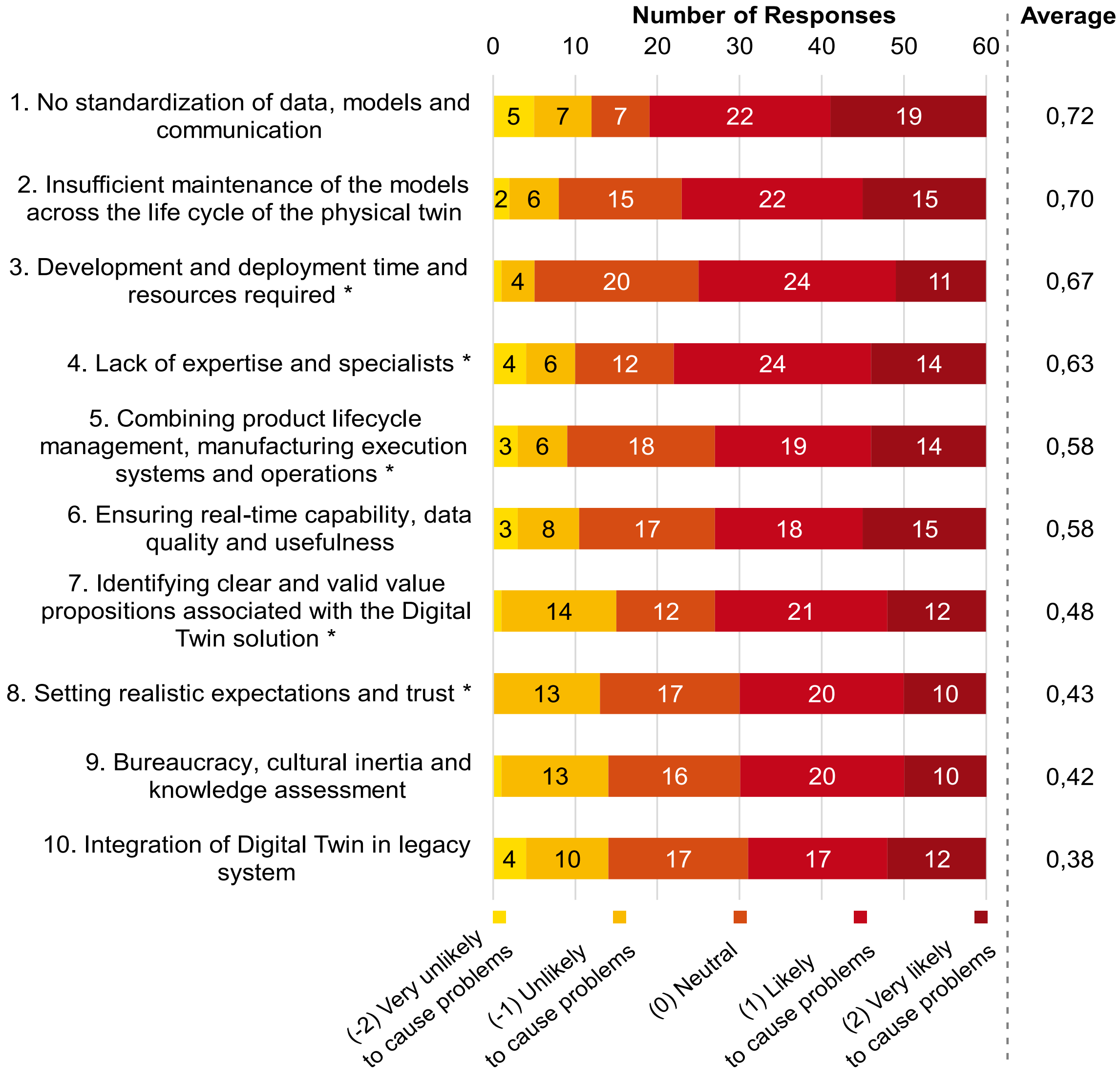


*Figure 3-8: Rating of the Ten Most Critical Specific Aspects According to their Average Likelihood to Cause Problems (on a Scale from -2 to 2). Nontechnical Aspects Are Marked with a * (adapted from Trauer, Mutschler, et al., 2022)*[8].

3.3 Discussion

Is there still an ambiguity in the terminology of DTs?

Based on the presented results, the subordinate research questions of RQ1 as described in section 3.1 can be answered. To answer RQ1a - *"Is there still an ambiguity in the terminology of DTs?"* – the survey presented the definition of a DT as it was published by Trauer, Schweigert-Recksiek, Engel, et al. (2020) and presented the participants a list of related terms, asking them which of them are used synonymously with DTs. All options of this multiple-choice question are not being used synonymously in literature. The question was optional, so the respondents did not have to choose an option. However, all of them selected at least one of the terms. Interestingly, more than half of the respondents indicated "Other" as their preference. Which indicates that they are using even other terms than the one provided. The survey was conducted in English, but many participants are German native speakers. Thus, misunderstandings cannot be avoided. Nevertheless, many companies seem to use terms synonymously with DTs, which are not synonyms. This indicates that there still is an ambiguity in terminology, and a discrepancy between academic and industrial understanding of the term. This is also supported by the collected use cases of the participants some of these use cases do also not comply with the three characteristics of a DT as described in section 2.1.3.2, but are nevertheless called a DT. It is valid to claim that a common definition is not necessary. However, this large divergence in terminology makes it difficult to communicate a specific DT solution and to assess its value objectively as this ambiguity might raise false expectations. Among the parties. Therefore, a shared and collaboratively developed understanding among all stakeholders is beneficial to DT projects.

> ***RQ1a –*** *Yes, the ambiguity in terminology related to DTs is still present. To avoid false expectations, it is beneficial to collaborate towards shared understanding of DTs among all stakeholders of a project.*

What are characteristics of DT projects in industry?

RQ1b – *"What are characteristics of DT projects in industry?"* aimed at deriving a better understanding of DT projects. The overarching goal was to deduct insights, which are needed to tailor the systematic support to the characteristics of DT projects. This survey focused aspects in terms of content, time, finances, and personnel and mapped them to the success of the projects as rated by the participants (cf. Figure 3-4).

Most of the participants started their DT projects in 2019 or later. In comparison to the substantial amount of research published on DTs between the first mention of DTs in 2002 (cf. section 2.1.3.1) and today, industry seems to lag behind by a few years, which is in line with literature (e.g. van der Valk et al., 2021). The duration of the projects did not correlate with the success indicated by the participants. However, as most of the projects are currently ongoing, the collected data cannot cover the final timespans of the projects.

In terms of budget, the budgets allocated for DT projects were considerably lower than the budgets allocated for general digitization initiatives. This could indicate that there is still some degree of skepticism among management regarding the concept of DTs. This would align with the challenge of assessing the value of implementing a DT, which is supported by most respondents (cf. Figure 3-8). However, one could also argue that the initial digitization budgets inevitably need to be higher, and that DT projects always will profit from higher digitization budgets.

Beneath the budget spent, the involvement of various departments is crucial for the success of DT projects. "Research and Development", "Production", and "Sales" Were most often involved in the captured projects (cf. Figure 3-6). This indicates that the use cases span various phases of the product lifecycle and offer potential benefits to these departments. It also aligns well with the lifecycle consideration of the subtypes "Engineering Twin", "Production Twin", and "Operation Twin" (cf. section 2.1.3.3).

Most often responsible are "Research and Development", "IT", and "Production" (cf. Figure 3-6). This aligns with the findings of the literature review, indicating that Research &

Development and Production hold significant responsibilities in DT projects. Remarkably, only three respondents mentioned “IT” as a contributing department and only five as the responsible department, despite its crucial role in DT development. Those three departments were also the departments that had the most problems during the projects, suggesting potential technical challenges in the twinning process or a lack of expertise and knowledge within the respective departments. All departments except “Human Resources” were mentioned, suggesting that depending on the project’s use case and design, involvement from various departments across the organization may be necessary, which underscores the interdisciplinary nature of DT projects. However, it is worth noting that 19 out of 29 respondents selected three or less departments involved in their DT projects. This suggests that full organizational engagement in DT projects is relatively uncommon. To investigate the effect of this observation, the involvement can be mapped with the success of the projects as indicated by the participants (cf. Figure 3-4). The ten projects with more than three involved departments were rated as more successful (on average 7.2/10) than the 19 projects with less departments involved (on average 6.2/10). Simply involving more departments does not necessarily lead to greater success in DT projects. Nevertheless, it indicates that DT projects are interdisciplinary and require many competencies to be successful.

> ***RQ1b –*** *DTs find applications across diverse domains. Most of these initiatives were started in 2019 or later, indicating the novelty of this concept in industry. Several companies seem to face challenges in implementing DTs, as indicated by an average success rating of 6.5 out of 10. Despite these difficulties, companies are investing considerable budgets in their DT projects, underscoring the industry’s strong demand for DTs. DT projects require interdisciplinary efforts.*

What are the most crucial (categories of) challenges in implementing DTs?

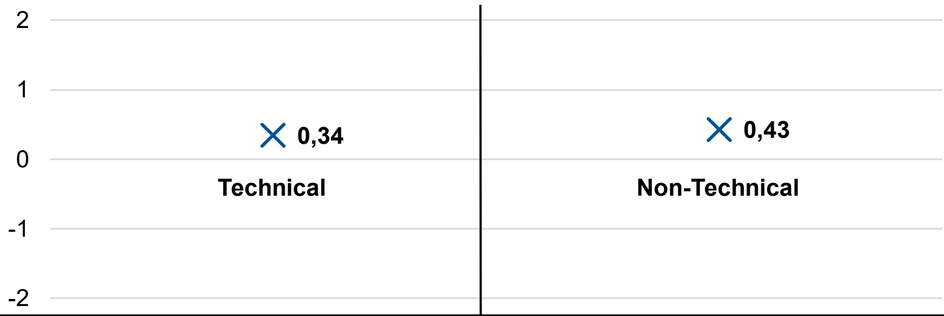
RQ1c – *“What are the most crucial (categories of) challenges in implementing DTs?”* – investigated the barriers companies are facing in DT projects. As described in the previous section the questionnaire investigated both broad categories of challenges, as well as very specific aspects of these categories. Figure 3-7 shows, that the participants selected “technical challenges” to be the most challenging category. However, also the other categories were considered to likely or very likely to cause problems. Only cultural and legal challenges were not confirmed by the survey. However, no lawyers were part of the participants. Therefore, this could be the case due to a coverage error (Dillman et al., 2014).

Consistent with the categories, the results in Figure 3-8 indicate that two technical issues are considered the most likely to cause problems during the implementation of DTs (* marks nontechnical challenges). However, they are closely followed by three non-technical issues, specifically the resources and competencies required for implementation, as well as the integration of product lifecycle management, manufacturing systems, and operations. In total, five non-technical challenges are among the nine most crucial aspects, rated as likely or very likely to cause problems by at least half of the participants.

> ***RQ1c –*** *The major categories of challenges in descending order are technical, organizational, conceptual, procedural, managerial, cultural, and legal issues. Only the last two do not seem to be very problematic. The specific challenges support the categories but emphasize the importance of non-technical issues. Further, they indicate needs for a systematic support.*

Are non-technical challenges more likely to cause problems than technical challenges?

This observation leads to RQ1d – *"Are non-technical challenges more likely to cause problems, than technical challenges?"*. To answer this question, the specific challenges presented to the participants were clustered by technical and non-technical aspects. An equal number of aspects of the two cluster were included in the multiple-choice list. Therefore, to assess criticality of the two clusters the average values of the respective aspects were summed up. The result is shown in Figure 3-9. The values indicate that based on this online survey, by now non-technical challenges are at least as problematic as technical issues. Here, the comparison of the two columns is more important than the value itself. 0,34 respectively 0,43 (On a scale from -2 (very unlikely to cause problems) – 2 (very likely to cause problems)). indicate that both categories are more or less equally considered to cause problems in DT projects.



1. No standardization of data, models and communication	3. Development and deployment time and resources required*
2. Insufficient maintenance of the models across the life cycle of the physical twin	4. Lack of expertise and specialists*
6. Ensuring real-time capability, data quality and usefulness	5. Combining product lifecycle management, manufacturing execution systems and operations*
10. Integration of Digital Twin in legacy system	7. Identifying clear and valid value propositions associated with the Digital Twin solution*
11. Security and privacy	8. Setting realistic expectations and trust*
13. Reliability and robustness	9. Bureaucracy, cultural inertia and knowledge assessment*
15. IT infrastructure	12. No systematic approach for identifying promising use cases*
17. Low latency communication, tracking and reporting	14. Difficulties in setting up a strategy for the implementation of Digital Twin use case*
18. Efficient storage, processing and analysis of large volumes of data	16. Lack of suitable procedures for an efficient implementation*

Figure 3-9: Comparison of Technical and Nontechnical Aspects with Respect to their Likelihood to Cause Problems in the Implementation of DTs. The Numbering Represents the Ranking of the Aspects as Shown in Figure A 1. (Adapted from Trauer, Mutschler, et al., 2022).

> ***RQ1d** – By now, non-technical challenges are at least as problematic as technical issues emphasizing the need for systematic support considering also non -technical challenges.*

Discussion of the Online Survey

Naturally, this survey has its limitations. First, the number of participants was relatively small. Further, the participants were not specifically selected, as the survey was advertised on LinkedIn. It is uncertain whether the participants constitute a relevant and meaningful group of experts. Therefore, a coverage error could be present, meaning that not all relevant stakeholders of DT projects are included. An indicator for this error could be the rating of legal issues in Figure 3-7 – Legal aspects were rated as rather unlikely to cause problems. However, no lawyers participated in the survey. Given the specialized nature of DTs, only individuals working in this field were able to provide meaningful responses to the survey questions. To mitigate this limitation, preselecting the invitees or conducting interview studies could have been beneficial.

The response rate to the survey was only 5% - 10%. However, such low response rates are not unusual for online surveys and do not necessarily imply an error or bias in the results (Dillman et al., 2014). Based on the distribution of participants, it can be argued that the sample covers diverse fields of industry, companies, and academic backgrounds, which supports representativeness of the group of participants.

Another limitation lays in the survey structure. The survey predominantly consisted of closed questions, potentially limiting the participants' ability to provide detailed insights in the open-ended questions. Especially for the specific impediments only a choice-list was given, but there may be additional factors that were not included. Nonetheless, this was the right approach, as thus, not too much effort was required from the participants, which would increase the nonresponse error (Dillman et al., 2014). In summary, while acknowledging the limitations, this study offers valuable insights into the challenges and barriers of implementing DTs.

Most findings presented in the previous section align with literature. For instance, the ambiguity in the definition and understanding of DTs is described by e.g. Jones et al. (2020), Trauer, Schweigert-Recksiek, Engel, et al. (2020), or Vogel-Heuser et al. (2023). The challenges were mostly derived from literature. For example, Fuller et al. (2020) and Pires et al. (2019) identified a lack of trust and unrealistic expectations as major challenges. However, there is a discrepancy between the significance of these technical aspects as rated in this survey compared to the existing literature. While literature primarily focused on technical aspects, the survey revealed that non-technical challenges are slightly more important. Additionally, two recent expert studies also confirmed the overall outcome of this survey (D'Amico et al., 2023; Saporiti et al., 2023).

These findings underscore the importance of a support for companies, which also addresses non-technical challenges such as identifying clear and valid value propositions (cf. Figure 3-9). Based on the specific challenge in Figure 3-8, the need for concrete solution elements can be derived (cf. Chapter 5). The results on the characteristics of DT projects offer insights to ensure applicability of the methods. For example, based on Figure 3-6 it can be derived, which departments need to be addressed in the development of DTs. Further, it emphasizes the importance of interdisciplinary teams.

4 Empirical Studies on the Conception and Implementation of Digital Twins

4.1 Overview of the Conducted Empirical Studies

This Chapter presents the empirical studies, which were conducted in the course of this thesis. The studies are mainly part of the DSI of this thesis but deliver first insights for the PS. Figure 4-1 shows an overview of the conducted empirical studies and the solution elements of the PS they are contributing to. Goal of the studies is to provide insights to RQ2 – *"How to support DT-responsibles in the conception and implementation of Digital Twins more efficiently with a higher usefulness?"* (cf. section 1.3). To understand the needs for such a support, case studies were selected that cover DT subtypes along the product lifecycle – i.e., an Engineering, a Production, and a Operation Twin use case (cf. section 2.1.3.3). The first case study on Engineering Twins for climate solutions (cf. section 4.2) as well as the second case study on Production Twins for aluminum extrusion processes (cf. section 4.3) are industrial case studies. The characteristics of support for the development of Operation Twins were investigated in an academic case study on a model bottle filling line. Here, the project team consisted of interdisciplinary master's students. Each case study was guided by an own DRM and included elements of participatory research (Cornwall & Jewkes, 1995). The participatory elements referred to researchers actively participating in the case studies and the case study partners influencing the evolution of the projects. Further, as creating trust in DTs seems to be challenging (cf. Figure 3-8), an interview study was conducted to investigate how to overcome this challenge (cf. section 4.5). The projects were guided by the author of this thesis in collaboration with other researchers, whereas each one had their own focus. The specific case study designs are described in detail in the respective section.

Empirical Studies	6.2.1 Procedure Model	6.2.2 Business Modelling Approach	6.2.4 Use Case Catalogue	6.2.5 Use Case Template	6.2.6 Trust Framework
Section 4.2 – Engineering Twin*	X		X	X	
Section 4.3 – Production Twin*	X			X	
Section 4.4 – Operation Twin**	X	X	X	X	
Section 4.5 – Trust in Digital Twins***					X

**industrial case study   **academic case study   ***interview study*

Figure 4-1: Overview of the Conducted Empirical Studies, which are Described in the Following Subchapters.

4.2 Engineering Twins for Climate Solutions

4.2.1 Case-Study Design

Case Study Partner

This case study was conducted from 2018 to 2020 in cooperation with a company developing climate solutions[9]. The company is an internationally active, family-owned, German company in the field of heating technology. With over 10,000 employees, the enterprise develops and produces heating and cooling technology products for residential and commercial applications. Over recent years, the company has been undergoing a significant transformation driven by the capabilities of digitalization and new market demands. They are facing challenges such as evolving customer needs, data collection and utilization, and shortened innovation cycles. Moreover, the introduction of digital technologies in general is a challenging and exhaustive task for the company.

Motivation and Goal of the Case Study

As part of this transformation, a case study was initiated to explore the conception and initial implementation of a DT in engineering. In this context, the business aims to leverage the potential of digitalization while addressing the complexities of the changing environment. Derived by the second research question of this thesis (cf. section 1.3), this case study was guided by the question *"How to support DT-responsibles in the conception and implementation of Engineering Twins"*. Based on an initial literature review as well as the experience of the industrial participants, the need for a common understanding and definition of a DT emerged. Further, a methodical and replicable procedure for the conception and implementation of a DT is needed. For replicability, a model is needed to guide this procedure. To support the applicability of the procedure model, recommendations, tools, and templates needed to be defined, and examples will be shown. The focus of this work was on technical product development as a part of engineering design – i.e., an Engineering Twin[10].

Case Study Methodology

This case study was guided by a DRM with several iterations. The RC was based on an extensive literature review on the concept of the DTs, including its potential applications and existing challenges[11]. As there was no existing process model available for the integration of a DT in product development, a systematic analysis of general implementation processes was carried out as DSI. Based on this analysis in the PS, an initial process model was developed

---

[9] Section 4.2 is based on the student theses of Stöhr (2018), Mahlau (2018), and Saygin (2019). The theses were supervised and actively guided by the author of this thesis. Parts of this study were already published in Schweigert-Recksiek et al. (2020), Trauer, Schweigert-Recksiek, Engel, et al. (2020), and Schweigert-Recksiek et al. (2022).

[10] The developed definition of a DT in general as well as of the Engineering Twin was presented section 2.1.3.2.

[11] The results of this literature review are part of section 2.1.3.

based on literature. This model as well as the definition were then iteratively further developed as part of the case study. This PS was guided by 14 regular workshops and expert interviews. The workshops were moderated by the researchers and identified stakeholders of the company participated. The academic team consisted of the author of this thesis and one more researcher, who focused on supporting the collaboration between engineering and simulation departments (Schweigert-Recksiek & Lindemann, 2020). The stakeholders of the company included the core team consisting of the Head of Processes, Methods, and Tools and the Head of Function Development. Additionally, up to four System Engineer Function Development experts partly participated in the workshops. Drawing insights from these observations, the literature-based process model was further refined and evaluated as a practice-oriented framework for conceptualizing and implementing a DT in product development. In the end, an interview-based initial evaluation was conducted in a DSII. Consequently, this case study followed a type 5 DRM with iterations in between. An overview of the case study is presented in Figure 4-2.

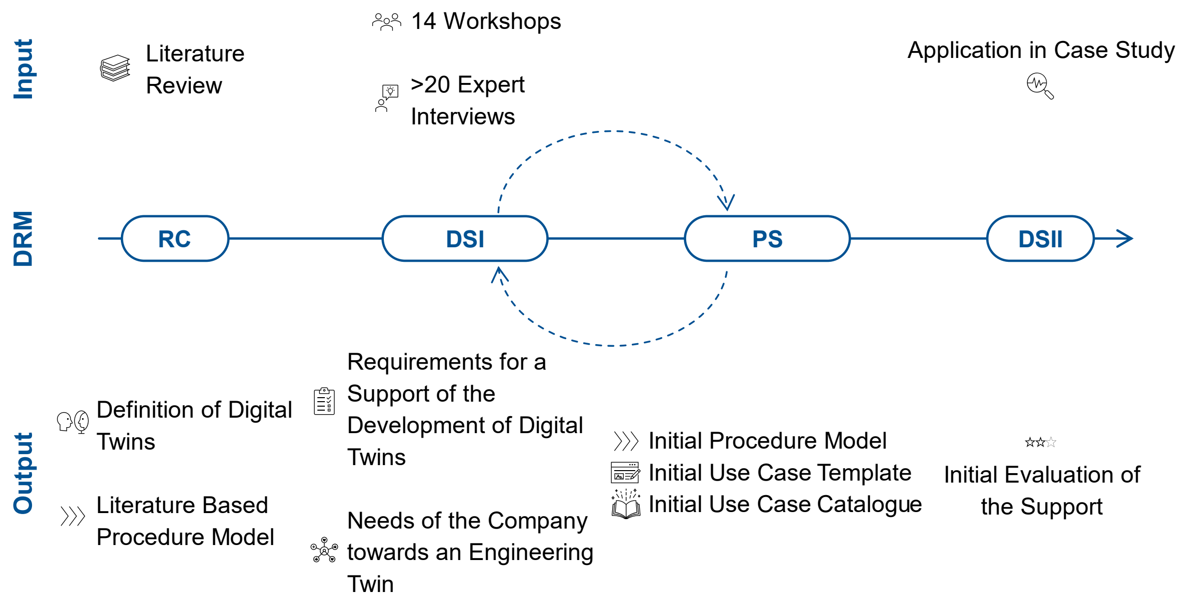


Figure 4-2: Overview of the Design Research Methodology Applied in the Case Study on Engineering Twins.

4.2.2 Results

The Procedure Model and Use Case Template

Based on the state of the art of procedure models for the implementation of methods and tools (cf. section 2.2), existing models were analyzed for commonality to identify the most common steps. Further, theoretical requirements for a procedure model for the development of DTs were derived (cf. Table 4-1). Based on these requirements a first literature-based model was developed.

Table 4-1: Theoretical Requirements on a Procedure Model for the Conception and Implementation of a Digital Twin Derived in a Case Study on Engineering Twins for Climate solutions.

ID	Theoretical Requirements	Derived from
R1	Targeted focus on specific problems: specifics of the conception and implementation of a Digital Twin.	*Ponn (2007); Lindemann (2009); Trauer, Mutschler, et al. (2022)*
R2	Logical, structured sequence of steps.	*T. Fischer et al. (1998)*
R3	Explicitly extend the process model to include methods and tools - Provide sufficient support for the conception and implementation of a Digital Twin.	*T. Fischer et al. (1998)*
R4	Template of the procedure model - situational, need-based, user-oriented provision of methodological knowledge.	*Braun (2005); Ponn (2007); Vajna and Burchardt (2014)*
R5	Granularity/logic of the procedure model - balance between applicability and generality without being arbitrary.	*Ponn (2007); Lindemann (2009)*

The initial model was applied at the industry partner and discussed with the participating stakeholders. Based on these expert interviews further empirical requirements were derived and iteratively incorporated in the procedure model as shown in Table 4-2.

Table 4-2: Empirical Requirements on a Procedure Model for the Conception and Implementation of a Digital Twin Derived in a Case Study on Engineering Twins for Climate solutions.

ID	Empirical Requirements	Derived from
R6	Identify and develop relevant digital twin use cases for the company - Structure format and content of use cases.	*Case Study; Wilberg, Fahrmeier, et al. (2018)*
R7	Type of procedure model - iteration in the necessary steps.	*Case Study; Lindemann (2009)*
R8	Provide information about the input and output (input and output information) of the method (user-friendly).	*Case Study*
R9	Adaptability - Modular - Scalable - Transferability - Possibility to extend and update the procedure model.	*Stetter et al. (2009); Graupner (2010)*
R10	Early analysis of the "feasibility" of the Digital Twin target concept and the (later) identified requirements.	*Case Study*

ID	Empirical Requirements	Derived from
R11	Development of target concept and processes of a Digital Twin to close the gap between current situation and target state.	*Case Study; Wilberg, Fahrmeier, et al. (2018)*
R12	Provide information about the necessary input and output of the activities and method (user-friendly).	*Case Study*
R13	Identify & unlock added value of a Digital Twin for internal and/or external stakeholders under the company's framework conditions.	*Case Study; Trauer, Mutschler, et al. (2022); Trauer et al. (2023)*
R14	Designed for technical product development.	*Case Study; Wilberg, Fahrmeier, et al. (2018)*
R15	Cover the essential sub-processes within the introduction process of a Digital Twin; from target definition to implementation.	*Case Study*

Subsequently, both the literature- and case-study-based requirements were incorporated in the procedure model depicted in Figure 4-3.

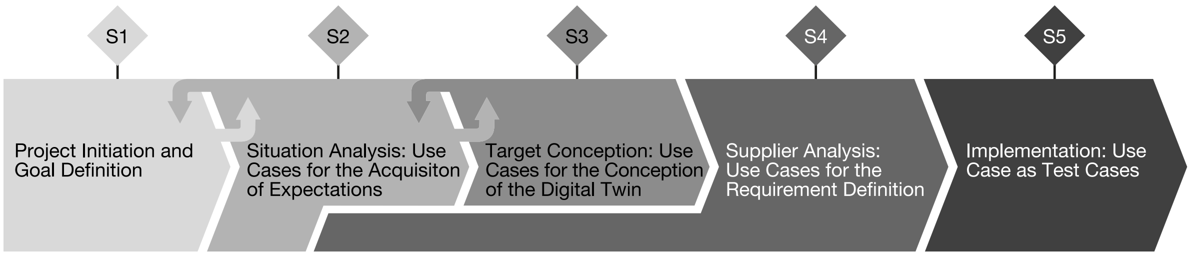


Figure 4-3: Procedure Model for the Conception and Implementation of a Digital Twin in Industry as Applied in a Case Study on Climate solutions (Schweigert-Recksiek et al., 2020).

Following the initiation of the project and goal definition (**step 1**), the focal point shifts to the use cases, which play an important role in all project activities (cf. Figure 4-3). Initially, they serve as a means to gather the expectations of internal stakeholders. Subsequently, they drive the conception of the DT during the **third step**. The resulting target concept from this step then serves as a basis for deriving requirements in the **fourth step**, which involves the analysis of potential vendors. These requirements are further refined into test cases that are instrumental in the implementation phase (**step 5**) to validate the use cases.

While the overall sequence of the procedure model follows a linear progression from steps one to five, there are iterations between steps one and two, as well as steps two and three. These iterations are crucial as they allow for the comprehensive development of the use cases in steps two and three, leading to a well-defined objective and deeper insights into the current scenario. The case study highlights the benefits of initiating the supplier analysis (step four in Figure 4-3) at an earlier stage. Conducting an initial assessment of various potential vendors during step two can offer valuable insights into the potential scope of a DT. Additionally, considering the specific form of implementation requirements based on the chosen vendor can minimize rework, particularly when the elaboration of use cases gains momentum in steps two and three. To improve applicability of this procedure model, one-pagers were developed containing inputs/outputs, specific activities as well as supporting methods and tools for each step (cf. appendix A3.1).

Furthermore, to support the application of the procedure model, a DT use case template was developed. It especially supports a consistent and comparable documentation of DT use cases (cf. Figure 4-4), which is one of the major challenges in the development of DTs (cf. Figure 3-8). The template with its six tabs follows the structure of the procedure model and thus serves also as a practical guide for the DT core team. Moreover, it can be used as a decision-making basis for management and as a general form of communicating and presenting the developed use cases.

It captures the most important data of a project: The goal, involved stakeholders, affected products, components and functions, the models and data needed and the requirements on the DT in form of user stories (cf. Figure 4-4). Further, the most important results of step 2 and 3 of the procedure model are captured – the as-is processes and data structure as well as the corresponding target states. A completed use case template for one use case can be found in appendix A3.2.

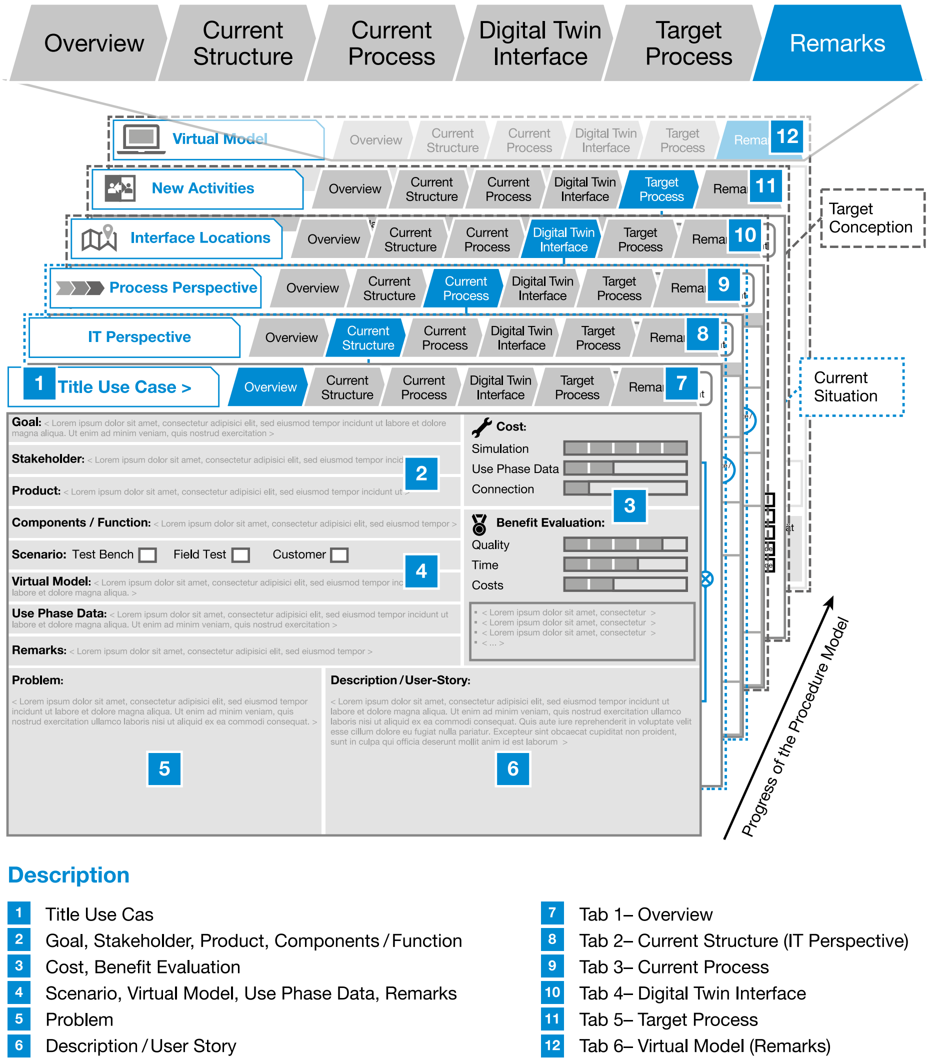


Figure 4-4: Digital Twin Use Case Template as Applied in the Case Study (Schweigert-Recksiek et al., 2020).

Application of the Procedure Model and the Use Case Template

At the beginning of the project, as part of the *project initiation and goal definition*, a common understanding of the DT had to be built. Therefore, a definition of a DT was elaborated together with the industry partners (cf. section 2.1.3.2). Further, the project team was assembled and structured. It was decided to assemble a core team, consisting of simulation, data-analytics, and IT-experts, to encompass all necessary competencies. In addition, using stakeholder analysis and mapping (Murray-Webster & Simon, 2006; Reed et al., 2009), a user group was identified and engaged. This group included potential profiteers as well as users of the digital twin. Furthermore, responsible stakeholders for implementation were identified. Thus, use case descriptions determine not only the profiteers and users, but also implementation team with its necessary expertise. In addition, the implementation team is supported by the implementation partner selected later (step 4), who primarily implements the IT infrastructure. This partner is assigned to the support team, works on networking the tools and system landscape, and becomes a "member" of the implementation team as required. Based on a “modified 9-

field method" (Ehrlenspiel & Meerkamm, 2017), the projects vision was derived.

Proceeding from this vision, rough use cases were collected. First, problems related to the current product development process and simulation process as well as expectations on the DT were gathered through expert interviews. Then, use cases for a DT that might contribute to solving these problems were identified. This process was supported by creativity methods such as brainstorming (Furnham, 2000) or the use phase data use case catalogue by Wilberg, Lau, et al. (2018). A total of 15 relevant use cases were derived. These use cases were assigned to four main clusters based on the engineering domain of the stakeholder group. Furthermore, seven sub-clusters were identified that exhibited similar or strong similarities in content[12]. The clusters as well as the selected use cases are shown in Table 4-3.

Next, the added value of each use case was assessed, applying a benefit-effort analysis (Lindemann, 2009). A special focus was put on the required use phase data, as this aspect was identified as the major complexity driver in the company. In the data path of the customer installation (customer scenario), there is only limited availability of usage data. In addition, there are other limiting factors, such as the restricted data quality and the lack of information regarding the usage context of the installations. For the considered use cases, the IoT data at the case study partner, which were used for customer apps and service applications, would not be sufficient for the DT use cases. For example, applications such as lifetime predictions are not possible due to the low number of data points. Therefore, use cases requiring customer data were ranked lower and saved for later project iterations. One use case was chosen from each sub-cluster to obtain different perspectives on the digital twin concept (cf. Table 4-3). Use case G1 was excluded due to its high evaluation effort and the customer scenario. Out of the six use cases, only E1 *"fault analysis of customer installation"* relies on usage data from the customer installation. Nevertheless, it was included as an "exception" use case to uncover the prerequisites that need to be established to implement a use case in an operation twin scenario during the later phase of implementation. In addition, it should reveal the differences in requirements between the internal data in the test bench or field trial scenarios and the external customer installations.

[12] *For clarity, the 15 use cases were numbered using letters and numbers. The letter represents the sub-cluster and the number is a unique identifier.*

Table 4-3: Overview of Clusters, Sub-Clusters and Use Cases of this Case Study. Selected Use Cases are Marked as Bold.

Cluster Stakeholder Group	**Sub-Cluster Use Case**	**Use Case**
AB – R&D mechanical design	A – Dimensioning of hydraulic components	**A1 Dimensioning of flat-sealing water fittings (test bench data)**
		A2 Dimensioning of flat-sealing water fittings (use phase data)
		A3 Dimensioning of flat-sealing water fittings (different component)
	B – Dimensioning of plastic components	**B1 Dimensioning of the connector from boiler to heat cell (test bench data)**
		B2 Dimensioning of the connector from boiler to heat cell (use phase data)
		B3 Dimensioning of the composite housing of the pump
CD – R&D function development	C – Parameterization of simulation models	**C1 Parameterization of the simulation model of the hot water tank**
		C2 Parameterization of the simulation model of the heat cell
	D – Error detection	D1 *redacted for confidentiality reasons*
		D2 Development of a simulation model for end-of-life prediction (plate heat exchanger)
EF – R&D final product design	E – Error analysis of customer installation	**E1 Error analysis of insufficient hot water treatment**
		E2 Error analysis insufficient flow rate
	F – Assurance of safety-relevant components	**F1 Assurance of the safety-relevant functions (safety chains)**
		F2 *excluded for confidentiality reasons*
G – R&D heat cell	G – Error analysis control unit	G1 Error analysis of the control unit of the boiler

With the value assessment at hand, the use cases were aggregated in a roadmap applying a *"shell model"* (cf. Figure 4-5). This model consists of multiple levels where use cases can be implemented. The first shell includes use cases that do not fully meet the definition of a DT, as for example, not all lifecycle phases are included. Moving outwards through the shells, the complexity increases, incorporating data from different phases of the product's life cycle and enhancing the virtual model. In the conducted case study, the initial use cases focused on data from the test bench. However, in the coming years, it was planned to expand the DT system by incorporating additional use cases. This gradual expansion will allow the company to leverage data from production, use, maintenance, and recycling phases, enabling a more comprehensive representation and interaction between the DT and the physical product.

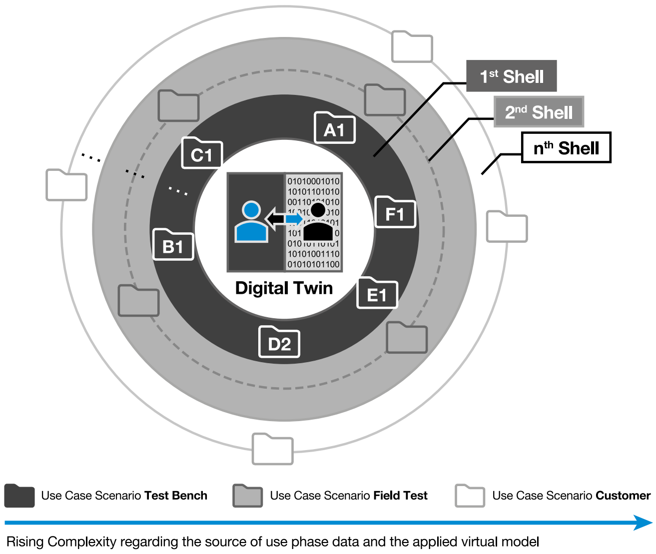


Figure 4-5: Shell Model for the Conception and Implementation of Digital Twins (Trauer, Schweigert-Recksiek, Engel, et al., 2020).

Starting at the innermost shell, the "as-is" processes of the use cases were analyzed and documented in the use case template (cf. Figure 4-4)[13]. This step involved continuous documenting and reflecting on existing processes, resulting in an overview of the company's readiness for a DT and a more refined description of the target state based on step one. Further, for each use case a Business Process Modelling Notation (BPMN 2.0) based process model was developed to document the current processes (ISO International Organization for Standardization, 2013). These models were enriched by swim lanes to show the relationship between activities and stakeholders (based on Holt et al., 2012). An example is shown in A3.2.

Step three "target concept" is the main step in the procedure model. Here, in cooperation with the core team, the target concept of the DT solution for the selected use cases was developed. The required inputs for this step were a clear understanding of the current situation, a well-defined, detailed understanding of the DT concept, availability of stakeholders and resources, and particularly the collection of use cases. The definition of the target processes and organizations was based on the recorded as-is processes and organizations in the situational analysis, as well as the recorded current structure with its IT systems and tools. The development of the target process occurred in two steps. Using the current process as a basis, the interface of the DT within the sequence of activities was initially identified. The overarching question to guide this activity is *"Where does the digital twin integrate into the activities for biggest impact?"*. The affected activities were identified in collaboration with experts during individual expert interviews. Subsequently, they were marked in the as-is process. The preparation for target process development, in the form of identifying the DT interface, concluded

[13] The filled use case template for the use case A1 can be found in appendix A3.2. The other use cases cannot be shown due to confidentiality reasons.

when all affected activities had been marked. The second step included the actual development of the target process. Based on the identified activities that would change with a DT, each activity was adjusted guided by the question: *"How will the activities change with the digital twin?"*. As for the current processes, the target processes were modeled in a BPMN2.0 process model. The resulting target process of use case A1 is shown in appendix A3.2. The other use cases cannot be shown due to confidentiality reasons.

Step four of the procedure model – the supplier analysis – aims to select a suitable implementation partner and prepare the implementation of the DT. This activity can take various forms, depending on the company's specific circumstances. While some companies may already have a fixed vendor providing the necessary PLM tools, others may actively have to scout for new suppliers to ensure a sufficient IT infrastructure for implementing a DT[14]. For this purpose, possible providers should first be acquired and compared in a detailed market analysis. After a cost-benefit analysis, a suitable partner can finally be selected. As a potential implementation partner should understand all company-specific circumstances, constraints, and needs, it is beneficial to start this process in parallel to step two and three of the procedure model (cf. Figure 4-3).

Most important for the preparation of implementation is to derive the specific requirements for the DT solution from the developed target process. First, the requirements format should be aligned with the implementation partner. I.e., the requirements hierarchy should be clearly defined and a "transfer key" to derive requirements from use cases should be elaborated. For the former activity, epics[15] were formulated based on the described goal and the problem definition of the use cases, which were assigned to an identified use case cluster (cf. Figure 4-6).

In the focal case study, the epics were developed according to the three identified clusters (cf. Table 4-3, first column). The epics were formulated using the basic structure of user stories: "As a ‹role›, I want ‹goal›, so that ‹benefit›" (Lucassen et al., 2016). The user stories from the individual use cases of the cluster under consideration are combined and subordinated to the epic (cf. Figure 4-6). Tasks are then derived from the subordinate user stories, particularly using information from the current structure, documented previously. The current structure represents the IT-ecosystem of the use case and thus is an essential input for the implementation partner.

[14] *At the case study partner, no implementation partner has yet been selected.*

[15] *An epic in agile project management is considered as a "large" user story, summarizing several user stories. (Dimitrijević et al., 2015)*

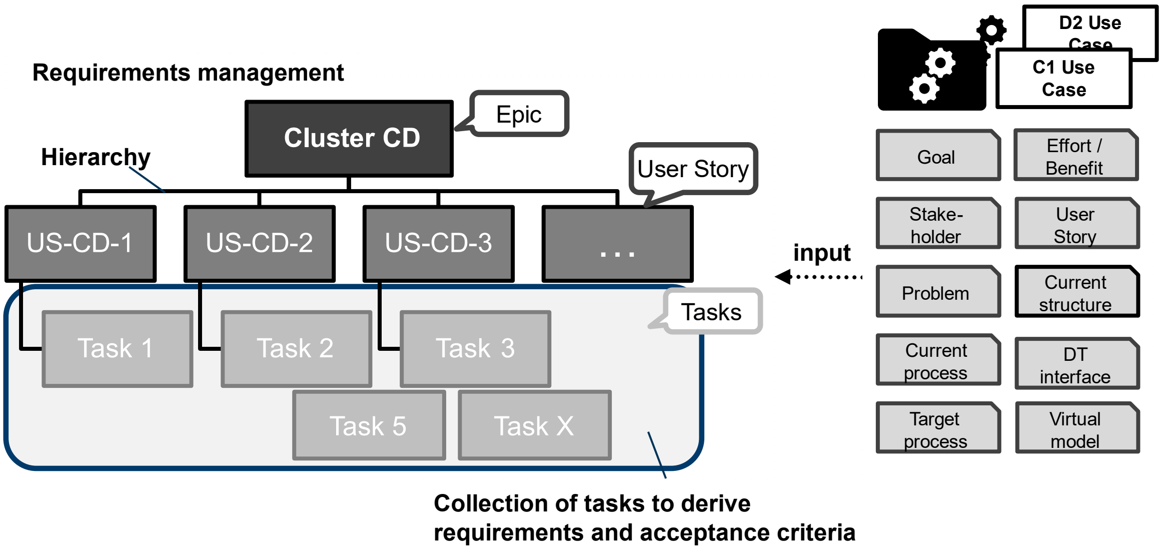


Figure 4-6: Hierarchy of Epics, User Stories, and Tasks.

Finally, the requirements are derived from the tasks. To do so, a "transfer key" was selected. In the course of this case study, the requirement template of Pohl and Rupp (2021) was applied (cf. Figure 4-7). Again, due to confidentiality reasons, the requirement specification of this project cannot be presented.

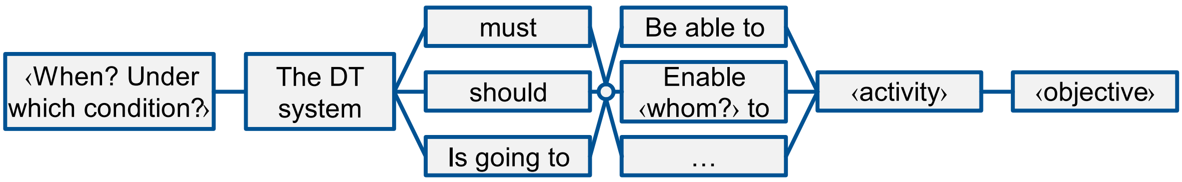


Figure 4-7: Requirements Template based on Pohl and Rupp (2021).

The last step of the procedure model is the implementation. With the use cases as acceptance criteria and the test cases, the implementation roadmap is successively implemented. The changes in the company are communicated, current processes and organizations are adapted, and the piloted DT is used for the first time. In the process, the achievement of objectives should be monitored. Continuous lessons learned build up an understanding of the next steps and, under certain circumstances, supplement the target concept. As in the previous step, step five heavily depends on the context of the company and the chosen vendor. To minimize the risk of failure and maintain the confidence of internal stakeholders, the shell model suggests starting with a "simple" use case that might not have even relied on data from the use phase but could have been developed using internal data from test environments. In addition, risk management methods, like the user story risk map of Trauer, Schweigert-Recksiek, Gövert, et al. (2020). Within this case study, this last step was not applied, as the negotiations between the company and the implementation partner exceeded the project frame.

4.2.3 Discussion

As described in section 4.2.1, the developed support for this case study was initially evaluated, focusing on applicability and usability of the procedure model and methods. Workshops involving one or two experts were conducted for this purpose. Six experts were involved: Head of Processes, Methods, and Tools; Head of Function Development; and four System Engineers. They were selected based on their comprehensive understanding of the current processes or their specific knowledge of the use cases. Following a presentation summarizing the accomplishments of the case study and providing a detailed explanation of the procedure model, the participants were individually asked to complete a questionnaire[16], which is composed of five parts, A to E[17]. The main part is structured in three categories: Assessment of the procedure model in a theoretical context *(B.I)* and in a practical application *(B.II),* assessment of applied methods and achieved results *(C.I),* and overall assessment of the developed support *(D).* The questions in the main part B to D consist of closed questions using six-stepped Likert-scales ranging from "strongly disagree" to "strongly agree" (cf. section 3.1). The even number of response options leads to clear tendencies, as no neutral middle category is offered – consequently, the participants had to decide whether they agree with a statement or not. The survey was conducted in German, as all participants are German native speaker. The results are depicted in Figure 4-8[16].

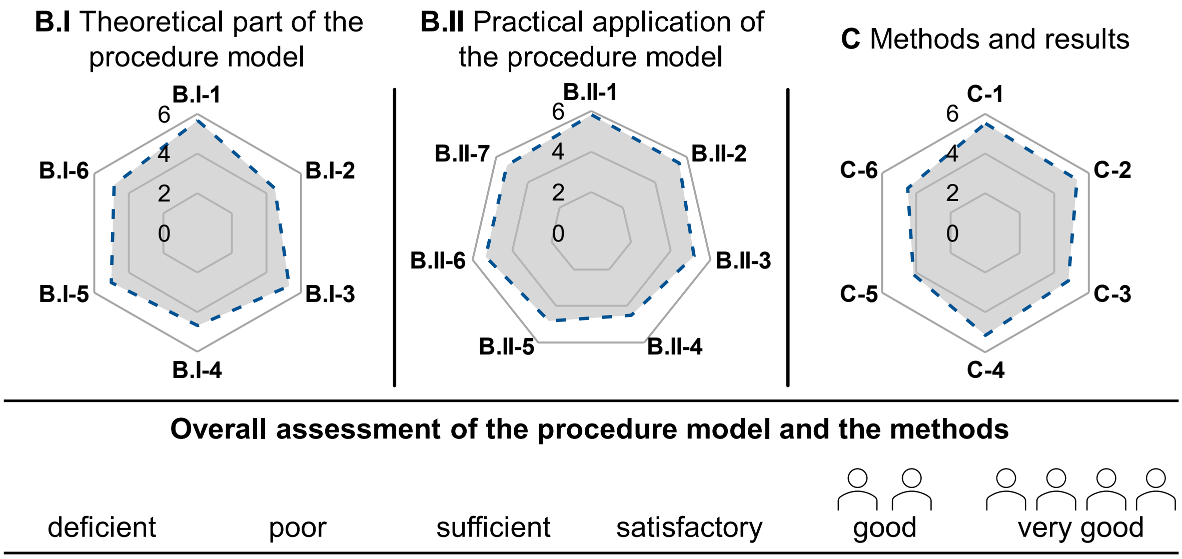


Figure 4-8: Initial Evaluation of the Procedure Model and the Applied Methods Within this Case Study (based on Schweigert-Recksiek et al., 2020).

[16] *The questionnaire as well as a detailed overview of the evaluation results are presented in appendix A3.3.*

[17] *Part A includes two open questions on the opportunities and challenges of DTs to make it easier for the experts to start the evaluation. The fifth part E was excluded within this thesis as it was used to collect data on barriers in the collaboration of design and simulation departments. This part is not related to the developed procedure model or the applied methods. The results were published by Schweigert-Recksiek (2022).*

B.I Theoretical Part of the Procedure Model

Based on the statement *"A structured approach to the conception and introduction of a digital twin is necessary"*, The need for a structured approach to designing and implementing a DT *(B.I-1)* is confirmed by all experts, with a rating of 5.67 out of 6.0.

Likewise, the inclusion of necessary steps in the procedure model *(B.I-2 – "The process model contains the necessary or essential steps, from initiation & target definition to implementation")* is positively acknowledged by all experts except one, indicating "Strongly disagree". According to this expert, the implementation step lacks sufficient "depth" and noted the need to further differentiate the implementation step or, if necessary, to expand it based on a real application. However, no further, concrete suggestions were given.

The implementation step is also addressed in the item regarding the completeness and usefulness of the methods and activities *(B.I-4 – "The steps contain the necessary methods and activities to adequately support the conception and introduction of a Digital Twin")*. Although this aspect received overall positive ratings, two out of the six experts noted that complete approval would require at least one complete run-through of the model since the last implementation step was not executed due to time constraints in the current study.

However, regarding the logical sequence of steps in the procedure model *(B.I-3 – "The sequence of steps in the process model makes sense")*, there is consensus, and no further comments were provided during the interview.

Regarding the statement *"It makes sense to carry out provider analysis activities such as feasibility studies as early as the situation analysis and target concept phases in order to ensure the "feasibility" of the requirements identified later" (B.I-5)*, all but one expert, "agreed" or "strongly agreed"[18]. According to the dissenting expert, it would be sufficient to start the vendor analysis in step three – target conception.

All experts agreed with the statement *"The format and content of the use cases are sufficiently structured" (B.I-6)*. According to the participants, the number of the use cases rather than the level of detail is a crucial success factor for a DT concept. They suggest deriving a larger number of use cases to enhance the differentiation of the concept. Nonetheless, the content and format of the use case template was described as "very clear".

B.II Practical Application of the Procedure Model

Regarding the applicability of the procedure model in practice, first, the shell model was assessed. All experts agreed that it is appropriate to define or restrict the scope of a DT using strategies such as the shell model *(B.II-1 – "The limitation of the application area was useful for the implementation process - Engineering Twin, shell model, fine/coarse/fine")*. Four out of six experts strongly agreed on this approach – the experts considered the targeted selection of use cases in conjunction with the shell model strategy to be highly useful as otherwise ongoing change processes might put the project at risk.

[18] *As shown in Figure 4-3 in section 4.2.2.*

Further, they equally recognized the importance of identifying the use cases for deriving specific requirements on the DT *(B.II-2 – "The formulation of use cases for the digital twin is a helpful approach for deriving requirements")* and for the implementation of the DT itself *(B.II-3 – "The identified use cases are useful for the implementation of a digital twin concept")*. In addition, they support the selection of the use cases based on the benefit-effort ratio. However, half of the experts were skeptical as to whether the assessment comprehensively evaluates the added value of the use cases. Therefore, a systematic approach to business modeling of DT use cases would be useful (cf. section 6.2.2).

The experts positively assessed the statement *"The selected use cases have a sufficient and sensible cost-benefit ratio" (B.II-4)*. However, half of the surveyed experts expressed reservations about how this assessment would hold up after the final implementation. Three experts pointed out that the hypothesis can only be confirmed or disproved once the implementation of the use cases is completed.

Regarding feasibility, all experts, except one, agreed that *"The implementation of the selected use cases is considered realistic" (B.II-5).* The outlying expert highlights that, in his opinion, technical issues are not the main challenge in implementing the use cases or the DT concept. Instead, he believes that the main hurdle lies in effectively utilizing the necessary resources, such as employees, for the successful introduction of the DT in the company. Further, he emphasizes that collaboration between different departments is ultimately the key success factor in this context.

Lastly, both the useability of the approach for identifying the interfaces of the use cases *(B.II-6 – "The consolidation and identification of interfaces of the use cases supports the design of a digital twin")* as well as the procedure model itself was confirmed by the participants *(B.II-7 – "The process model enables a structured approach to the introduction of a Digital Twin")*.

C Methods and Results

Part C evaluated the applicability and usability of the applied methods and the achieved results. The current situation *(step 2)* was confirmed to be helpful both to uncover breaks between tools, data sources, and activities *(C-1 – "The structural modeling of the actual structure/IT view (use case tab 2) is helpful to uncover breaks between tools, data sources and activities")*, and to systematically derive the target process *(C-2 – "The representation of the CURRENT process and the Digital Twin interface (Use Case tabs 3 & 4) helps to derive the TARGET process and the associated change in process steps through the Digital Twin in a structured manner")*.

Apart from one expert, the presentation of the identified use cases, which illustrate the specific characteristics of the DT, is seen as helpful for understanding *(C-3 – "The modeled TARGET process (Use Case tab 5) makes the change in process steps through the Digital Twin transparent")* and deriving requirements *(C-4 – "The entire presentation form of the use case with ACTUAL structure, ACTUAL process, digital twin interface and TARGET structure as well as virtual model (use case tabs 2 to 6) is helpful for deriving requirements for the digital twin concept")*. This expert tends to agree with the statement, arguing that other departments should also be involved in defining the requirements.

In addition, the elaboration of the specific aspects, especially in the activities of clustering and elaboration of interfaces, is seen as useful *(C.5 – "The identified use cases illustrate the specific characteristics of the digital twin")*.

Lastly, four of the six experts agree with the statement *"The description of the virtual model of a digital twin (use case tab 6) clarifies/concretizes the abstract image/understanding of the digital twin concept" (C.6)*. Two experts, on the other hand, complained about too much effort in documenting the content. One expert mentioned that it depends very much on the individual's capacity for abstraction. In this context, he thinks that employees who work with many virtual models or simulations do not require such extensive documentation. Nevertheless, the expert understands the need to make the concept of the DT clear to all participants in the project by describing the virtual models.

Finally, the overall procedure and methods in general were assessed as "very good" by four of six participants *(D –" Please give an overall rating")*. The insights of this case study were summarized in Chapter 5.

4.3 Production Twin for Aluminum Extrusion Processes

4.3.1 Case-Study Design

Case Study Partner

The case study was conducted from 2020 to 2021 in collaboration with an internationally renowned European company specialized in aluminum production[19] (Trauer, Pfingstl, et al., 2021). The company has grown into an innovative group of companies with over 1500 employees and an expected turnover of more than EUR 500 million in 2021. The company's operations primarily revolve around three key technology areas: casting, extrusion, and processing. The presented DT module was implemented specifically within the extrusion sector, which focuses on manufacturing customized aluminum profiles tailored for the transportation, manufacturing, and construction sectors with an estimated annual capacity of 100,000 tons.

Motivation and Goal of the Case Study

Over the last years, the company had been gathering extensive data from their extrusion plants, encompassing parameters such as ram pressure, extrusion speed, container temperature, billet temperature, and various others. Nevertheless, at the beginning of the case study, process enhancements were primarily reliant on retrospective analyses that were manually derived and lacked precision. Active and predictive approaches were yet to be implemented to drive improvements in the production process. Therefore, based on the results presented in section 4.2 and anomaly detection methods, a DT system should be developed to improve the

[19] *Section 4.3 is based on the student thesis of Finsterer (2021). The theses were supervised and actively guided by the author of this thesis. Parts of this study were already published by Trauer, Pfingstl, et al. (2021).*

current production process. On a theoretical level, the focus of this work was on adapting the existing methodology, to an application of a Production Twin and therefore addresses the question *"How to support DT-responsibles in the conception and implementation of Production Twins"*.

Case Study Methodology

Due to time constrictions, only one use case was developed. This project was guided by a DRM type 5. In a literature-based RC the state of the art of aluminum extrusion processes, anomaly detection methods, and applications was examined. In several workshops with industry experts of the company, a goal and a vision for the project were developed and required know-how on the process was gathered as part of a comprehensive DS-I. Based on these findings, it was decided to choose Gaussian processes for the anomaly detection. For the conception of the DT, the procedure model and use case template presented in section 4.2, were adapted according to the needs of production processes. Thus, the comprehensive PS, was twofold – developing the anomaly detection algorithm and further developing the methodology for the conception and implementation of DTs in a production context[20]. To conclude the project, the results were initially evaluated in a DS-II.

4.3.2 Results

Aluminum Bar Extrusion Process

In the context of this case study, direct bar extrusion is employed, which is one of the most common manufacturing processes for extruded aluminum products (Saha, 2000). Figure 4-9 illustrates the process of direct bar extrusion. According to Tekkaya and Chatti (2019) in this method, a ram (6) exerts pressure on a heated aluminum billet (3) with temperatures ranging from 350 to 500 °C. Together with a dummy block (4), the billet is pushed against a die (2), resulting in the formation of an extruded profile (1) from the material. To withstand radial forces, the billet, ram, and dummy block are enclosed within a container (5). On the left of Figure 4-9, a typical force-displacement curve of a direct bar extrusion is shown. As mentioned in Saha (2000) and Tekkaya and Chatti (2019) the extrusion process can be divided into three phases. Firstly, the billet is introduced and compressed against the die until the maximum force is achieved. Secondly, as the billet is pushed through the die, the pressure decreases, and the extrusion enters a "steady state" phase. Lastly, after reaching the minimum pressure, the ram force rapidly increases again as the excess material is compressed. Typically, the process is halted at this stage, and the remaining material is discarded and recycled. It should be noted that this standard curve may vary depending on factors such as container and die temperatures, material type, and extrusion temperature, speed, and ratio (Tekkaya & Chatti, 2019). Using these data for the control and management of the production process can significantly improve quality and efficiency, which is a major competitive advantage.

---

[20] *The focus of the present thesis will be on the methodology-related findings. More on the Gaussian process applied for anomaly detection, can be found in Trauer, Pfingstl, et al. (2021), and Pfingstl (2023).*

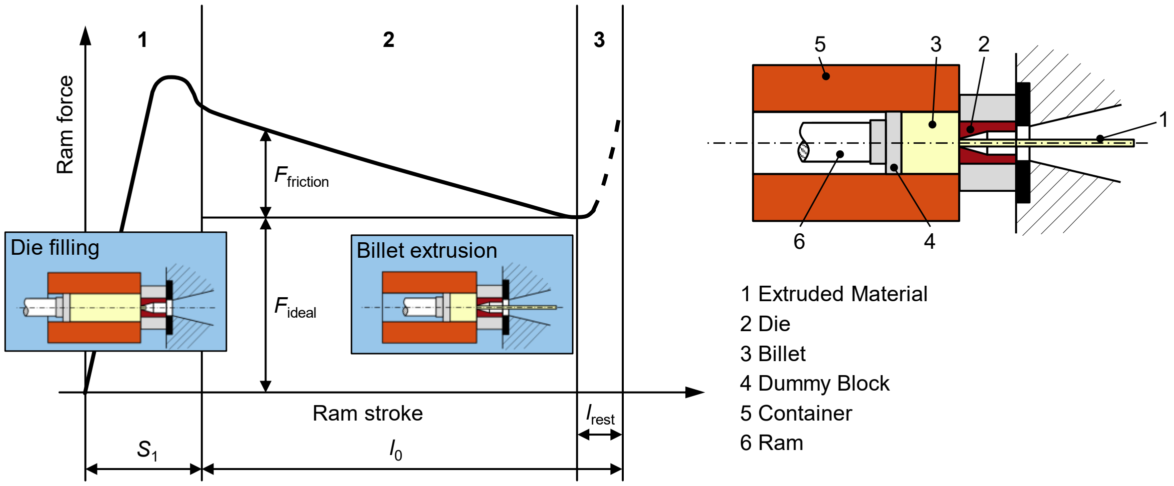


Figure 4-9: Force–Displacement Curve (Left) in Direct Bar Extrusion Processes (Right) (adapted from Tekkaya & Chatti, 2019).

Conception of a Digital Twin and Further Development of the Methodology

As already mentioned, this case study was guided by the procedure model for the conception and implementation of DTs, supported by the DT use case template (cf. Figure 4-10)[21]. At the beginning of the project, in several workshops a goal was developed with relevant stakeholders based on the company's initial situation (cf. section 4.3.1): *"The data already recorded during extrusion are to be used efficiently and reliably for quality assurance of the aluminum profiles. In the process, anomalies in the extrusion pressure curve are to be detected and suitable measures derived from them."* (Trauer, Pfingstl, et al., 2021). To accomplish this objective, again user stories were formulated to express the needs and requirements of the case study partner (cf. Figure 4-10). The partner's objective was to generate an ideal pressure curve that could be utilized to assess the material quality of a produced profile quantitatively and qualitatively. Based on this assessment, an immediate response mechanism to address anomalies should be implemented. Thereby production quality and performance can be enhanced, and the press can be protected from severe damage. Similar to the case study on climate solutions, the effort required for this use case was evaluated qualitatively using the simulation, use phase data, and network dimensions based on stakeholders' estimates. The value of the use case was assessed in the same way through three factors: quality, time, and cost.

As in the previous study, in step 2 of the procedure model, the as-is situation was analyzed. Here, the current data structure was modelled to identify gaps in the data landscape and to get an overview of all available sources and tools (cf. Figure A 13). In addition, the as-is processes were modeled using the previously presented BPMN 2.0 notation (cf. Figure A 14). Ensuring comprehensive coverage of the entire production process, rather than solely focusing on the specific step where errors may occur (particularly in pressing), is crucial for two reasons.

[21] *The detailed tabs of the use case template can be found in appendix A4.*

Firstly, taking actions beyond the process steps is often necessary to achieve significant process improvement. Secondly, analyzing all steps allows for the examination of subsequent process changes and the quantitative evaluation of the solution's effectiveness. However, in contrast to the Engineering Twin, it was not sufficient to identify just the DT interfaces. As the production process actually includes physical machines and the spatial layout of the production process as well as the layout of the production line are interfering, it was necessary to add the *"Process Environment"* tab to the use case template (cf. Figure 4-10 and Figure A 15).

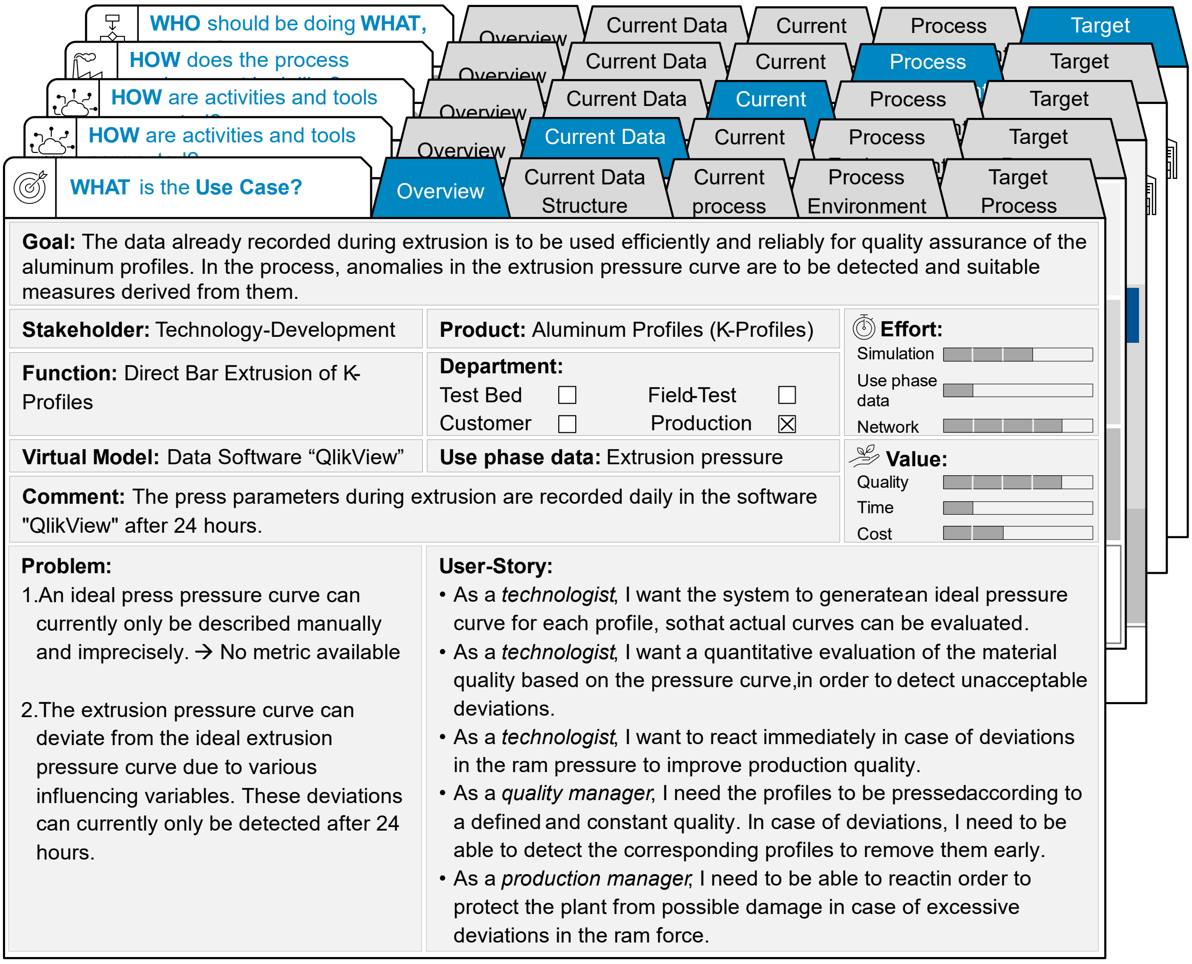


Figure 4-10: Filled Use Case Template Applied in the Case Study (based on Trauer, Pfingstl, et al., 2021).

The same applies for step three of the procedure model – the target process. In addition to the data structure and the current process (activities) that might need to be adapted, the whole production line might have to be adjusted. For example, according to the use case shown in Figure 4-10, the case study partner aims to remove the defective items from the production process based on the analyses of the anomaly detection. One feasible solution to do so is to mark the faulty profile for exclusion after the sawing process to subsequently separate it from the proper products and recycle it for billet casting. To mark the defective product, a needle roll can be employed, which will be activated, when an anomaly is detected (cf. Figure A 15). The proposed concept was developed, trained, and tested using historical data. Additionally, an interface was implemented to receive near real-time data. With this prototype of the DT, a technology readiness level 6 (TRL6)[22] was achieved. After the project, the company continued working on the implementation of the DT.

The case study on Engineering Twins showed the importance of proving the added value of the developed solution. Therefore, an initial success evaluation (Blessing & Chakrabarti, 2009) was conducted to partially assess the effect of the DT use case regarding the three categories: cost reduction, reduction of energy consumption, and overall production quality improvement. The first factor was calculated based on machine hour rate and personnel expenses, resulting in an estimated min. cost reduction 80,560.48 EUR/a. The other two benefits, should have been analyzed applying the Overall Equipment Efficiency (OEE; R. Singh et al., 2013). However, due to insufficient data, these results still need to be verified. Based on the reduced resources calculated for the cost savings, it can be implied that early removal of faulty parts will result in energy savings. Furthermore, the overall production quality will be enhanced by reducing the number of defective products reaching the customer.

4.3.3 Discussion

The case study partner confirmed the usefulness and applicability of both the procedure model and the use case template. The use case template has proven valuable in assisting engineers in transforming vague ideas into well-defined target processes with compelling value propositions. In line with the previously described studies of Neto et al. (2020) and Trauer, Mutschler, et al. (2022), it was essential to have a clear implementation pathway and standardized processes. The structured format of the template proved to be a key advantage, ensuring that crucial aspects are addressed when conceptualizing and implementing a DT use case. In accordance with the case study on Engineering Twins, it is emphasized that starting from the current process rather than from scratch is advantageous. Although the procedure model and use case template developed for Engineering Twins was applicable in general, the case study revealed that certain aspects have to be adapted. This implies that there might be more necessary deviations for other types of DTs such us Operation, Process, Sustainability or Cost Twins.

[22] *A TRL6 is reached, when a "subsystem model or prototype in a relevant environment" is implemented. (Mankins, 2009)*

4.4 Operation Twin for a Digital Twin Demonstrator in Academia

4.4.1 Case-Study Design

Motivation and Goal of the Academic Case Study

Both the literature review (cf. section 2.1.3) as well as the online survey (cf. section 3.2) have confirmed the ambiguity in the definition and understanding of DTs. Therefore, goal of this academic case study[23] was to develop a DT demonstrator. This demonstrator should serve as a showcase of a production line, which is simple enough to be easily understood, but complex enough to demonstrate the benefits of DTs. In addition, the manageable academic context offers a good environment to further develop the previous methodologies developed in the industrial setting. For example, due to the restricted projects' time and budget, it was not yet possible to consider the operation phases for the implementation of a DT. Thus this case study is guided by the question *"How to support DT-responsibles in the conception and implementation of Operation Twins"*. Further, business modelling activities were not yet considered, as previous industrial case studies were more focused on the technical aspects of the DT use cases rather than the economic. Consequently, this academic case study also served to develop a DT Business Modelling Approach (DTBMA).

Case Study Methodology

This academic case study followed a type 3 DRM of Blessing and Chakrabarti (2009). For the procedure model for the conception and implementation of DTs, first the previous versions (as presented in sections 4.2 and 4.3) were analyzed in a DS-I while applying them to the academic case study at hand. The identified weaknesses were documented, potential solutions were identified using literature review. These changes were implemented in a PS. The adapted approach was again applied to the case study. For the DTBMA, literature was reviewed to identify common elements in business models suitable for assessing the value of a DT (RC and DS-I). The current section rather focuses on the case study itself, rather than the developed methodologies. They are presented in detail in Chapter 6.

4.4.2 Results

Case Study Demonstrator

As a demonstrator, the EduKit PA Advanced with the IoT kit extension from the company ADIRO Automatisierungstechnik GmbH was used. Originally, it is intended for didactic purposes in the field of process and control engineering (ADIRO Automatisierungstechnik GmbH, 2023a, 2023b). The demonstrator has two tanks, one above the other, which are

[23] *Section 4.4 is based on the student theses of D. Fischer (2022), Matondang (2021), and Mac (2022). The theses were supervised and actively guided by the author of this thesis. Parts of the case study, i.e. the business modelling approach were already published in Trauer et al. (2023).*

connected via a piping system. The centrifugal pump in the lower section transports the liquid from the lower to the upper tank and can be controlled electronically. The piping system contains both analogous and digital sensors for measuring flow rate and pressure downstream of the pump. The upper tank has an ultra-sonic sensor for a continuous measurement of level and capacitive sensors in the upper and lower sections of the tank for discrete measurements. Manually adjustable valves in the upper and right pipes of the system are used to control the flow. By using valves 1 and 7 (cf. Figure 4-11) the filling mode can be adjusted – either the upper tank is filled from above, or from below, allowing for less turbulent flow. The liquid can be poured from the upper into the lower tank with a manually adjustable valve or an electronically controllable solenoid valve. All sensor data and control voltages are collected via cable connections to a common interface (EasyPort) and made available via a USB connection. Figure 4-11 shows the real demonstrator on the left and a schematic representation of the components on the right using a P&ID modelling notation, which will be described in the following.

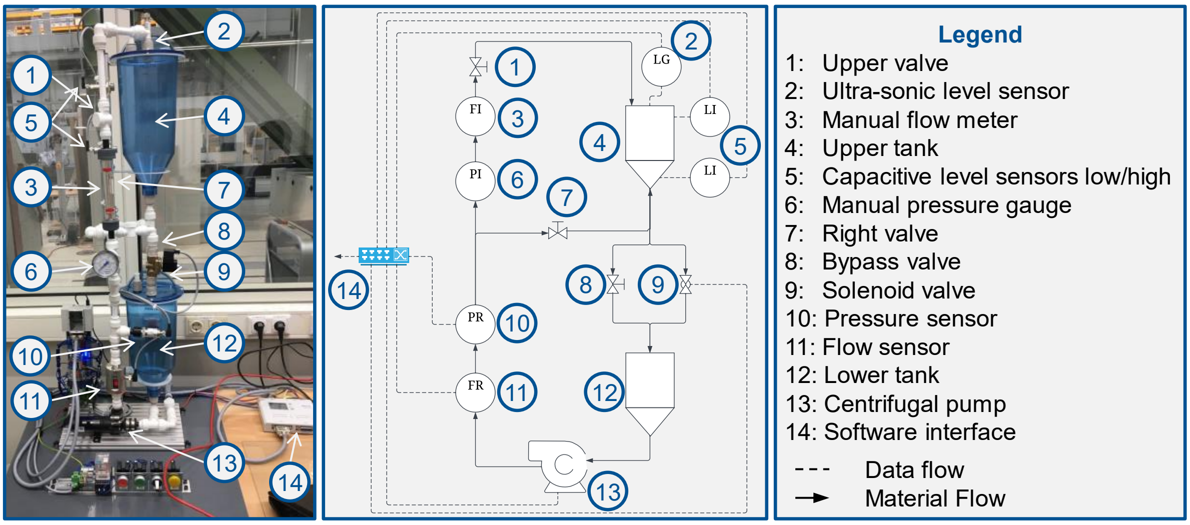


Figure 4-11: Overview of the EduKit PA Advanced with IoT kit extension by ADIRO Automatisierungstechnik GmbH (2023a).

Case Study Scenario

The original demonstrator already offered an IoT use case within the context of a bottle filling plant. In this scenario, a customer can place an order to a producer, who then uses the demonstrator to produce the requested fictional beverages. This can be simulated by draining defined amounts of water from the upper tank to the lower tank through a solenoid valve. The upper tank represents the manufacturer's inventory. If a certain fill level is exceeded, new liquid needs to be requested and delivered from the supplier (lower tank). This is simulated by pumping liquid from the lower tank to the upper tank. To develop a DT case study scenario a problem statement was identified, and key details were gathered through a literature review. The scenario was developed based on the recommendations of Wellner and Pierce-Friedman (2019). Based on the findings, the case study scenario was initially set up and adjusted throughout the case study incorporating additional information. The scenario revolves around a fictional German medium-sized company in the brewing industry called "Zwillings-Bräu GmbH". The company brews and fills beverages for private and commercial customers using its in-house bottle filling plant, which is partially represented by the demonstrator. The company's focus is on digital transformation, which is why the use of a DT is being discussed. The DT is intended to focus on the maintenance of the plant and, among others, address the following challenges – (1) repairs can be costly when dealing with clogged pipes or improperly adjusted valves, as adjacent components such as pumps continue running and might be affected. (2) Components occasionally fail before their specified lifespan or are replaced based on the repair schedule despite being in good condition. The scenario further provides information on the company's business aspects and introduces personas as representations of different groups of stakeholders with their desires, problems, and interests. The personas included in the scenario are plant operator, plant developer, service personnel, and manager[24].

Further Development of the Procedure Model

Based on the analysis of the methodology applied in the case studies on climate solutions and aluminum extrusion processes (cf. sections 4.2 and 4.3), a the existing approach was developed and detailed further. The procedure model is still structured in the basic five steps. However, the presentation has been changed to emphasize the development of the DT in use cases. After an initial phase in which, among other things, the overarching DT strategy is defined, the model splits into several threads. This illustrates that after the first step, the other four steps are to be carried out individually for each use case. Of course, this does not have to be done in parallel, but can also be done sequentially, depending on the situation. In addition, synchronization steps were introduced to harmonize the development of several use cases and to exploit synergy effects. Since other activities than the selection of a provider are also necessary in step, this step has been renamed "Preparation for implementation". In order to increase the applicability of the procedure model, the existing one-pagers were significantly detailed and expanded to include additional methods. The further developed procedure model is depicted in Figure 4-12[25].

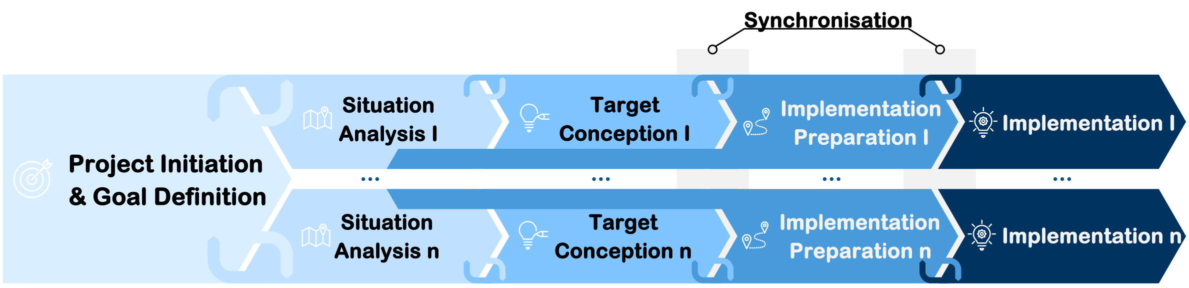


Figure 4-12: Further Developed Procedure Model as Applied in the Academic Case Study[25].

[24] *The entire case study scenario is presented in appendix A9.1.*

[25] *The final procedure model is presented in detail in section 6.2.1.*

Development of a Digital Twin for the Demonstrator

With the case study scenario, most activities of step one of the procedure model were already done. Therefore, the project started with the collection of use cases. Based on the analyzed literature on the application of DTs in the process industry and the use case catalog of Wilberg, Lau, et al. (2018)[26] promising use cases were identified and briefly described by the project team, consisting of an engineer, a business responsible, a software developer, and a team lead (cf. appendix A5.1). Profitability was determined by conducting an initial assessment of each use case's benefit and the effort required for implementation. Here, the project team individually rated the benefit and effort of each use case qualitatively on a scale from one to five. The individual ratings were then averaged, and the results were discussed (cf. appendix A5.2).

Next, the use cases were categorized based on four predefined categories: benefiting stakeholders, life cycle area, benefit dimension, and input data. The assignment of the categories was documented using a Domain-Mapping-Matrix (DMM) (Danilovic & Browning, 2007). Since the implementation of a single use case was not the focus, but rather the interaction among use cases in a DT strategy, the interconnections of the use cases were also examined. A Design Structure Matrix (DSM) (Steward, 1981) of the use cases was calculated through matrix multiplication according to Lindemann et al. (2008) using the previously mentioned DMM. Manual clustering was performed to identify use case clusters. The result is shown in appendix A5.2. *Cluster 1* is focused on improving product quality as well as engineering aspects. *Cluster 2* consists of use cases regarding production and operation of the plant while *Cluster 3* emerged around use cases focusing on procurement and order processing activities. As the estimated benefit/effort ratio of the use cases of Cluster 2 is relatively high, it was selected to be most promising to start with. Therefore, the value of the DT can be shown early in the process.

Next, the use cases within the selected cluster were prioritized for implementation using the pairwise comparison (Lindemann, 2009) considering both technical and economic aspects. The highest-rated use case, *"Preventive Operations"*, was selected for implementation. The overview of the selected use case is shown in Figure 4-13, forming the basis for all further results of the study. For this use case the current situation was described.

As described in section 2.1.3, this use case can be seen as an instance of an operation twin. Here, the same use case template as in the case study on aluminum extrusion processes was applied (cf. section 4.3.2). As for production twins, it is essential to also consider the environment of the DT context in addition to the mere processes. As suggested by Azangoo et al. (2022), in the process industry, P&ID modelling notation (ISO International Organization for Standardization, 2005) can be used to document the environment of the DT use case[27]. The "as is"-process was modelled using BPMN 2.0 as described in sections 4.2 and 4.3. The data structure was defined by summarizing the hardware setup of the demonstrator as a complete

[26] *The use case catalogue will be described in detail in section 6.2.4.*

[27] *The entire filled template for the use case "preventive operation" can be found in appendix A5.4.*

system. The software components were examined in terms of their functions and the artifacts (data) generated.

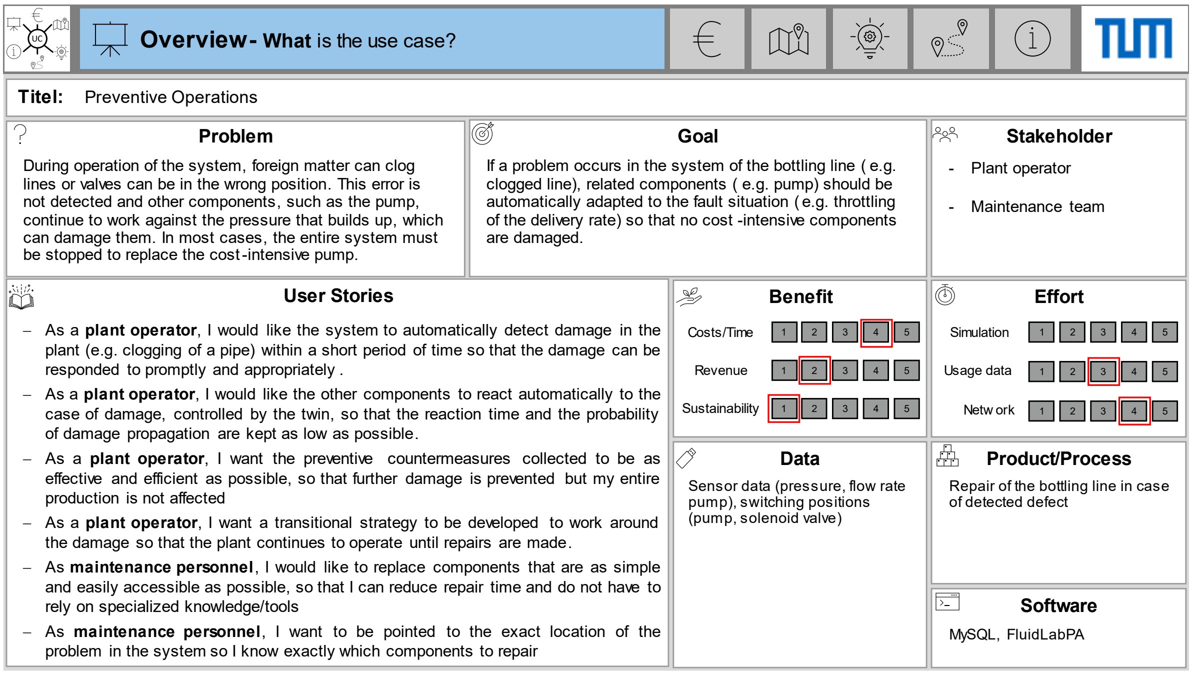


Figure 4-13: Overview of the Selected Use Case "Predictive Maintenance".

Based on the analysis of those three perspectives on the current demonstrator, missing interfaces and artifacts were identified, and the target process was deducted. This target process aims at lowering the workload of the plant operator. If a pipe gets clogged – which can be simulated by slightly closing one of the manual valves – the DT is supposed to prevent all components in the system from further damage, while maintaining normal operation as long as possible until the defect has been removed. To do so when a faulty pressure or flow is detected in the system, first measures to bypass the defect are explored. Thus, if using the other filling mode normalizes the process parameters, the DT detects a damage in the former filling mode, contacts all required stakeholders to fix the defect, and maintains the systems operation using the alternative filling mode. If switching mode does not result in normal process parameters, the power of the pump is reduced so that it will not be damaged, but the plant does not fully stop. To be suitable for this and other DT use cases, the demonstrator had to be slightly reconfigured. All operations need to be digitally controllable. Therefore, to be able to automatically switch filling mode, a 3-way solenoid ball valve was implemented in the system. To simulate clogged pipes, in each part of the system a manual valve was implemented. Further, to allow consideration of energy consumption a DC-Wattmeter was added to the system (ADIRO Automatisierungstechnik GmbH, 2023c). The redesigned demonstrator is described in section 7.1.2.

In step 4 *"implementation preparation"* a specification of the DT system was derived based on the VDI/VDE standard 3694 (VDI Verein Deutscher Ingenieure e.V., 2014). The specification document includes the objective of the use case, general information, the current and target situation, requirements, the required organization, test-cases, and acceptance criteria. As for the case study on climate solutions (cf. section 4.2), a requirements template was applied. However, it was extended by a systematic approach, guiding the deduction of requirements and acceptance criteria from user stories. Further, the format of user stories, requirements, and acceptance criteria was defined (cf. appendix A5.4). For example, for the user story *"As a plant operator I want a notification about malfunctions in real-time, so that the defect can be solved timely"*, one could deduct the requirement *"When a malfunction happens, the DT system must send a notification to the plant operator to ensure a timely repair"*. The acceptance criterion might then be *"Reduction of maintenance time by 10 %"*.

This concept of preventive operations was not finally implemented within the project at hand due to time constraints. However, it was implemented during a subsequent practical course[28]. In addition, a DT business modelling approach (DTBMA) was developed and applied (cf. section 6.2.2). For this use case, the focus was on internal customers, which means that the DT does not directly generate revenue. Instead, it aims for cost savings and sustainability improvement. By minimizing downtimes, production volume can be increased, resulting in higher revenue. Even in a conservative scenario, it is estimated that the DT will have recovered its initial investment within 4 years of project initiation. The canvas that captures the entire model can be found in Figure 4-14.

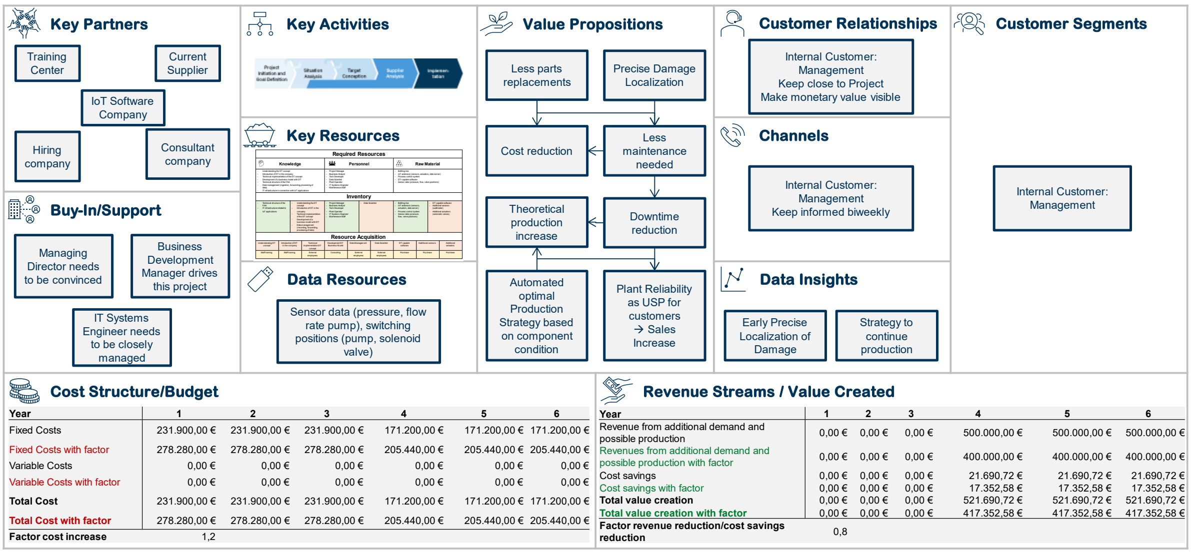


Figure 4-14: Business Model regarding "Preventive Operations" (Adapted from Trauer et al., 2023).

[28] *More details on the technical implementation as well as the practical course can be found in chapter 7.*

4.4.3 Discussion

To evaluate the findings of this academic case study, two DT experts of a German IT consultancy were interviewed. Overall, the usefulness of the methodology was rated as good to very good, with potential improvements regarding traceability and complexity of the steps and activities. However, the clear and comprehensible presentation of the entire process was still confirmed. The structured activity flow within the individual steps was positively received. As in previous case studies, it was acknowledged that all essential steps for the conception and implementation of a DT were included. The seamless flow between the individual steps and the top-down approach in the one-pagers made a significant contribution. However, after completing the first step, the absence of a strategy roadmap, which includes the planning of individual use case implementations was recognized. The templates were perceived as helpful although the diversity of documentation formats could be enhanced according to the experts.

In addition, it was confirmed that the methodology could effectively be applied to industrial use cases. In particular, the one-pagers with its described goals, activities, and methods/tools, contributes to the applicability of the methodology. However, the requirement documents received only a moderate rating from the experts due to their limited flexibility in adapting to changes. During development, the focus of the DT can often change, requiring an agile approach to requirements elicitation. The constant modification of requirements in the specification document would lead to significant effort, which diminishes usefulness as with many other approaches for requirements management. Overall, the evaluation results indicate good applicability, usefulness, and usability of the procedure model with its activities, methods, and tools.

Also, the DTBMA was perceived as very positive[29]. The overall structure of the DTBMA was affirmed to be comprehensible and logical, same as the subordinate steps, activities, and methods. Similar to the procedure model, the industrial applicability of the DTBMA was confirmed by all experts. Further, according to the experts, the DT use case was significantly improved by using the DTBMA. Also, the supporting methods and tools were considered to be comprehensive and helpful. However, one expert noted the need for a method supporting the ideation of value propositions. In addition, the interplay of the procedure model and the DTBMA were positively highlighted by the experts, especially in the process of identifying and prioritizing use cases and building the DT strategy.

Overall, the biggest limitation of this case study is that it was only applied to a single academic use case. Therefore, transferability of the results to industry, or to branches other than process industry cannot be ensured. Although described as comprehensive approaches, the complexity of both the procedure model and DTBMA can be perceived as overwhelming. Most likely in the current form, it would not be efficient for simple standalone use cases due to its complexity. Another minor limitation is that the use case could not completely be implemented. However, all essential steps of both the procedure model and DTBMA could be applied, and the DT use case was finally realized in a subsequent practical student course (cf. section 7.1).

---

[29] *A description and discussion of the developed DTBMA can be found in section 6.2.2 and chapter 7.*

4.5 Trust in Digital Twins

4.5.1 Interview Study Design

Motivation and Goal of the Interview Study

As already described in sections 1.1 and 2.1.3, in future, marketplaces and ecosystems of DTs will emerge, where diverse stakeholders can create, modify, acquire, and exchange information about DTs, fostering collaboration and feedback (Rosen et al., 2019). The interdisciplinary nature of DTs is inherent to their purpose of covering the entire lifecycle, requiring collaborative efforts from multiple parties to fully unleash their potential (Stjepandić et al., 2021b). There are initial technical formats and interfaces for exchanging DTs or simulation models. However, in the industrial environment, the adoption of these technologies is limited to cases where partners have a long-standing relationship or where the use of DTs does not pose critical implications for development processes or runtime environments (Rasheed et al., 2020; Thielsch et al., 2018). This is also supported by the results of the online survey (cf. section 3.2), identifying *“setting realistic expectations and trust”* as one of the top ten challenges in implementing DTs (cf. Figure 3-8). Several participants of the survey emphasized this challenge, stating e.g. that *“Companies are afraid to upload and share data because they fear loss of know how to their competitors”*. Therefore, the goal of this interview study[30] was to develop a *“Digital Twin Trust Framework”*. Similar to how individuals or companies decide whom to trust when making a purchase, this framework should define the scope of “Trusted Digital Twins”, providing guidelines and criteria for building trust, ensuring reliable and trustworthy DTs. Consequently, this interview study shell provide an answer to the question *“How to support companies in creating trust in their DT solutions?”*.

Methodology

To achieve this project goal, a methodology, consisting of three elements was set up – a literature review, a market analysis, and an interview study. Overall, the project followed a DRM type 5 project (Blessing & Chakrabarti, 2009). In the review-based RC, literature on the importance of trust in DT and digitalization projects was reviewed. The current situation was derived in the comprehensive DS-I. Here, first an understanding of trust was developed based on literature[31]. Using the market analysis as well as insights from the interview study, common measures to create trust were identified and combined with requirements on the trust framework, which were formulated by the interviewed DT experts. The framework itself was developed in the comprehensive PS, combining all previous elements. Lastly, the framework was initially evaluated in a one hour workshop with 12 DT experts of the industrial project partner.

---

[30] *Parts of this study were already published by Trauer, Schweigert-Recksiek, et al. (2022).*

[31] *The literature review was guided by a literature research strategy, which can be found in appendix A6.1.*

The conducted semi-structured interviews lasted approximately one hour. The interviews were guided by an interview guideline consisting of eleven open-ended questions (cf. appendix A6.2). As all participants were German native speakers, the questions were presented in German to ensure effective communication. The interview questions covered topics such as stakeholders, user stories, and solution elements. The results of the interview study are presented in appendix A6.3.

Participants

This project was conducted together with Siemens Digital Industries AG, an internationally operating large-scale technology company focused on industry, infrastructure, transport, and healthcare. With this diverse portfolio, the company operates as a developer, a vendor, and user of DTs. Consequently, building trust in their DT solutions is inevitable for their success. Initially, a list of 41 potential industrial experts in the field of DTs, digitalization, and trust was compiled for the interview study. From this list, 17 experts were identified as most relevant and invited to participate. Eventually, 10 individuals from various industries and companies confirmed their participation in the study. These interviewees possess extensive knowledge in the development and use of DTs (cf. Figure 4-15).

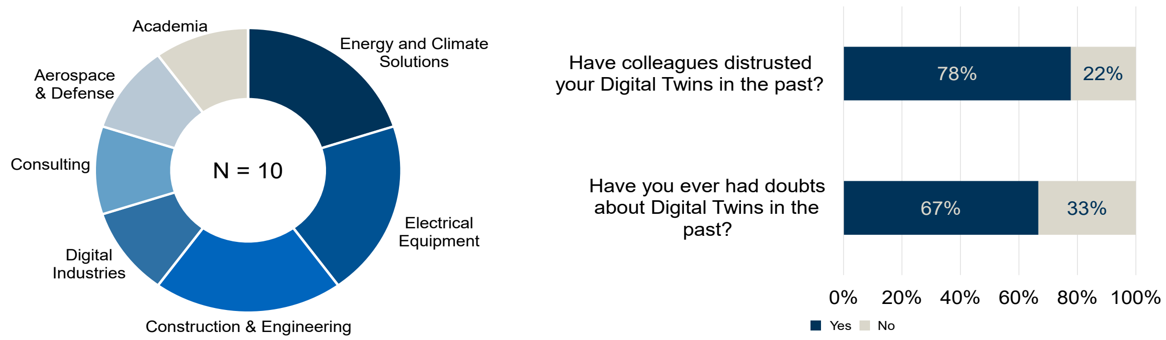


Figure 4-15: Background of Interview Partners (Trauer, Schweigert-Recksiek, et al., 2022).

4.5.2 Results

Based on the literature review, an understanding of "trust" was built. Within this study, the definition of Mayer et al. (1995) on organizational trust was chosen to be most suitable:

> *"[Trust is] the willingness of a party to be vulnerable to the actions of another party based on the expectation that the other will perform a particular action important to the trustor, irrespective of the ability to monitor or control that other party."*

Same as other definitions (e.g. J. D. Lee & See, 2004), this definition highlights the willingness to accept vulnerability in interactions with others. According to Hoff and Bashir (2014), there are three fundamental components common to most trust definitions: the trustor (the party giving trust), the trustee (the stakeholder accepting trust), and something at stake. Consequently, it is important to identify the parties interacting in DT projects.

Trust is particularly crucial in complex and uncertain situations, which are increasingly prevalent due to digitalization and automation (German & Rhodes, 2018; J. D. Lee & See, 2004; L. Liu & Loper, 2018). Developing trust enables individuals to navigate and adapt to the challenges posed by complexity and uncertainty, thereby facilitating the adoption of technologies like DTs (German & Rhodes, 2018; J. D. Lee & See, 2004). Thus, in addition to the interacting parties, the situations in which these parties collaborate must also be identified.

Regarding the elements that might help to increase trust, Ba and Pavlou (2002) identified three primary sources of trust: familiarity, calculativeness, and values. Familiarity arises from repeated interactions with a trustee and can contribute to trust or mistrust. Calculativeness involves assessing the costs and benefits associated with trusting a party, often supported by strong liability agreements. Values play a role in trust by instilling confidence in the trustworthiness and goodwill of a party, often supported by institutional structures such as standards and norms. However, it is important to establish an appropriate level of trust. As J. D. Lee and See (2004) point out, insufficient trust can result in underutilization of a system, while "overtrust" can lead to misuse. Hence, the trust measures must be selected with respect to the current situation.

Based on the findings from the literature review, there are three important aspects a DT Trust Framework has to cover – (1) stakeholders of the DTs, (2) user stories describing situations in which these stakeholders interact with each other, and (3) solution elements with concrete measures to develop trust. The overall framework is shown in Figure 4-16.

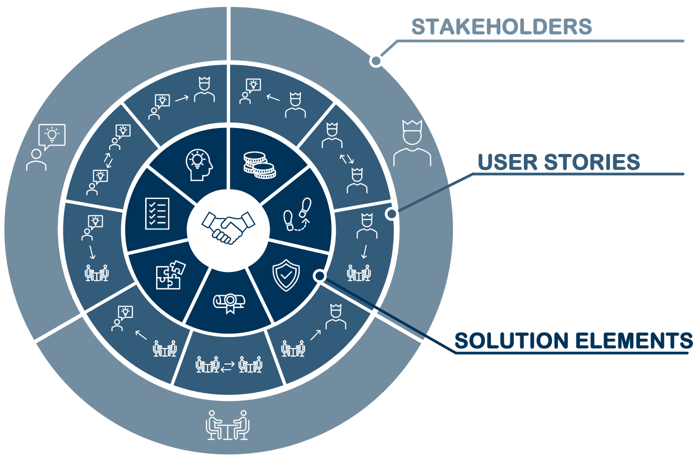


Figure 4-16: Overview and Landing Page of the Digital Twin Trust Framework (adapted from Trauer, Schweigert-Recksiek, et al., 2022). The entire framework will be described in detail in section 6.2.6.

In the conducted interview studies[32], these elements of the DT Trust Framework were elaborated. Three basic stakeholders of DT projects were named by the interview partners – (1) the supplier of the DT, (2) the user of the DT, and (3) partners of the user. These stakeholders can

[32] *All contributing quotes of the interview partners are listed in appendix A6.3.*

also be found in literature (e.g. Saari et al., 2023). As these stakeholders need to collaborate and trust is crucial in all possible combinations, nine user stories were organized to reflect this collaborative nature. For the seven solution elements and the concrete measures, the findings of the market analysis and the insights from the interview study were combined. The market analysis covered the following software vendors and digital marketplaces: Apple Appstore (www.apple.com/de/app-store/), Google Playstore (www.play.google.com/), Microsoft Store (www.microsoft.com/en-gb/store/apps), Steam (www.store.steampowered.com), Amazon Marketplace (www.sell.amazon.de/), and simercator (www.simercator.com/). Interestingly, the interviewed industry experts, as well as the case study partner and literature (e.g. Schwarzburg et al., 2024) stated, that trust in the interacting party is more important than trust in the technical solution. Therefore, the solution elements predominantly focus on social aspects rather than technical aspects. The developed solution elements assigned to their origin, are listed in Table 4-4. In addition to these seven solution elements, concrete measures were derived supporting the implementation of these elements, improving applicability and usefulness of the DT Trust Framework.

Table 4-4: Solution Elements of the Digital Twin Trust Framework. The Marks Show the Origin of the Solution Element.

	Apple Appstore	Google Playstore	Microsoft Store	Steam	Amazon Marketplace	simercator	Interview Study
Explain your twin properly!							X
Create a common (economic) incentive	X	X		X	X	X	X
Make one step at a time!							X
Protect the IP & ensure safety!	X	X	X	X	X	X	X
Prove your quality!	X	X			X		X
Ensure a uniform environment!	X	X	X			X	X
Document thoroughly!	X	X	X	X	X		X

In general, all elements can be applied to all user stories. However, for the sake of enhancing the usability of the framework, only the three most relevant solution elements are linked to the user stories.

4.5.3 Discussion

Concluding the research project, the DT Trust Framework was presented in an online workshop to twelve DT experts of the case study partner with significant experience, who were not part of the interview study. They were asked to provide anonymous feedback on the strengths and weaknesses of the Trust Framework, as well as to rate its applicability and usefulness on a scale from zero to ten. The participants identified several strengths of the framework, including its comprehensive overview, the consideration of diverse and interconnected facets, and its ability to provide clear starting points while allowing for customization. However, some attendees perceived the generic nature of the DT Trust Framework as a weakness, as it does not offer a ready-to-use solution for building trust in the company at hand. However, this was done on purpose to not be too company-specific. Moreover, the framework is not limited regarding the use case of the DT and can be applied for Engineering Twins as well as Production or Operation Twins. Further, the absence of quantitative metrics to assess trust levels was criticized. Here, in a subsequent project the research of Schwarzburg et al. (2024) tried to derive the essential aspects relevant to measuring confidence and trust in modelling and simulation. Lastly, the lack of a real-world implementation of the framework and the limited number of interview participants restricts the generalizability of results. Therefore, final validation of the Trust Framework is still pending. On average, the Trust Framework was rated with a usefulness and applicability of 5.8/10 (cf. Figure 4-17). The spread of the votes is quite large. The participant who rated the framework the worst, expressed general doubts in DTs and did not refer to the trust framework itself. The next three who rated applicability low (3/10) emphasized the lack of quantitative metrics as a weakness reducing applicability.

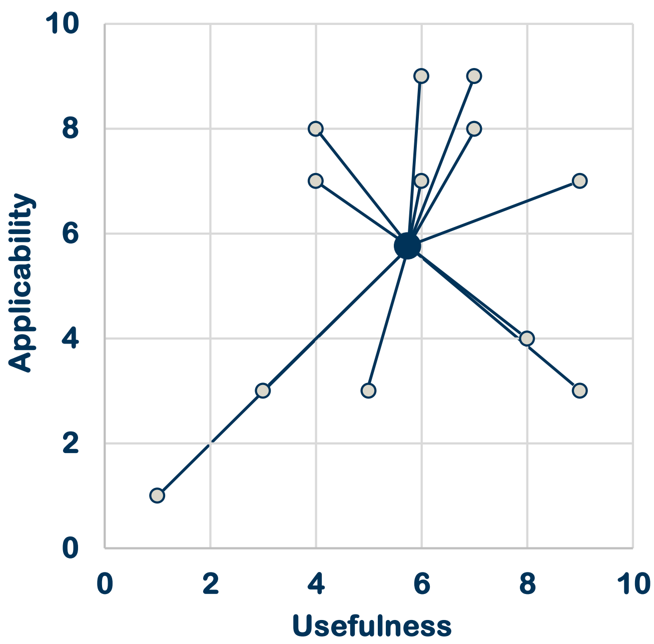


Figure 4-17: Initial evaluation of usefulness and applicability of the digital twin trust framework. (Trauer, Schweigert-Recksiek, et al., 2022).

5 Conclusions for Designing a Systematic Support for the Development of Digital Twins

In the Chapters 2 and 3, the barriers towards DT implementation were investigated based on literature and empirical findings. Further, the characteristics and needs of DT projects were identified based on case studies. This Chapter aims at drawing conclusions from these insights and deriving specific needs and requirements towards a systematic design support.

In the survey described in Chapter 3, the most important specific issues in the conception and implementation of DTs were identified and prioritized (cf. Figure A 1). As identified in the research gap, most existing approaches focus on technical issues (cf. section 2.3), but the survey showed that non-technical challenges are at least as hindering. Therefore, the focus here is on the latter. Based on these findings some needs for solution elements can be derived. Highest ranked non-technical challenge is *"Development and deployment time and resources required"*. According to Graner (2013), the duration of engineering projects can significantly be reduced by the use of methods. The efficiency and effectiveness of product development is depending on well-defined and implemented procedures and processes (Binz et al., 2011). This also became apparent in the previously described case studies. Therefore, a **procedure model** for the conception and implementation of DTs is an important solution element. This would help not only regarding development time, but also to set up a strategy for the implementation of DTs and to increase the general efficiency of the implementation[33]. Here it is important that the procedure model is flexible enough to be applicable for all different types of DT use cases. This flexibility must also be given by the suggested methods and tools.

Another challenge that has been rated among the top ten most critical challenges by the survey participants, is the task of *"identifying clear and valid value propositions associated to the DT"* (cf. Figure A 1). This is also in line with the case study findings – e.g., the participants of the case study on climate solutions claimed, that it is crucial to showcase the value of the DT early in the process and make the concept tangible, in order to not lose support of the relevant stakeholders – which is crucial for the success of an engineering project (Graner, 2013). As literature showed, modelling the business value of a DT is a difficult task (cf. section 2.1.3). Therefore, a **DT business modelling approach** shell support solving this problem – a first application of this approach has been presented in the academic case study in section 4.4. Based on the DT project characteristics identified in the online survey, and the insights from the other case study, the need for the consideration of different customer relationships in the business modelling approach is crucial to its success.

Within the academic case study, it could be observed that especially the step of deriving value propositions is challenging. Therefore, a **DT value map** would be beneficial to accompany the DT business modelling approach[34]. This element should help in identifying the value

[33] Referring to challenge 14 and 16 in the survey results shown in Figure A 1. The procedure model is described in section 6.2.1.

[34] The DT Business Modelling Approach is described in section 6.2.2 and the value map in section 6.2.3.

propositions, a DT use case can offer, to translate DT-specific benefits into business goals, or to identify promising use-cases starting from desired benefits. Especially the identification of promising use cases is important for the formulation of a DT strategy. The previous case studies showed that it is beneficial to identify as many use cases as possible in the beginning, to prioritize them and to initially pick a “low-hanging fruit” to prove the value of the DT in a lighthouse project. A solution element addressing this challenge is the **use case catalogue** based on Wilberg, Lau, et al. (2018) (cf. section 6.2.4).

A further identified challenge within the online survey (cf. Chapter 3), is the *“integration of the DT in the legacy system”*. Consequently, it is important to first be aware of the “as-is situation” of the project’s environment, which is also considered in the procedure model (step 2). Among others, the **DT use case template** is a solution element that shall support the integration. This was also acknowledged by two of the industry participants of the case study on engineering twins (cf. section 4.2). According to them, the template helped them to quickly immerse themselves in the DT project. This indicates, that it is even helpful for setting the right expectations (challenge 8 in Figure A 1), for guiding knowledge assessment (challenge 9 in Figure A 1), as well as for supporting unexperienced developers (challenge 4 in Figure A 1). Derived from the case studies in on the different DT types, it is required that the use case template considers the different required forms for engineering, production, or operation twins.

Connected to the challenge of setting realistic expectations in the DT solution is missing trust. This challenge has been addressed in section 4.5. Combining best-practices from industry and academia, the **DT Trust Framework** is one solution approach to cope with the lack of trust[35]. Another identified challenge is “security and privacy”, which is considered in the trust framework, although on a more social, than technical level – which seems to be useful, based on the results of Schwarzburg et al. (2024), suggesting that trust in the modeler is more important than trust in the models. Nevertheless, these technical aspects do matter, and there are several projects in academia and industry e.g., trying to set up secure interfaces for data exchange.

To assess the quality and trustworthiness of a DT one has to have certain knowledge. However, as DTs are still a relatively new topic in industry, and the ambiguity in definitions and concepts is large, there is a *“lack of expertise and specialists”* (challenge 4 in Figure A 1). This implies several calls for action. First, it is a requirement to the systematic solution approach – all methods, tools, approaches, handbooks, etc. must be usable with basic engineering knowledge. Second, the engineers working on DTs should be trained. In an attempt to do so, a **teaching concept** has been developed for a practical student course, which is described in section 7.1.

The connection between challenges and proposed solution elements is shown in appendix A7.

[35] *The Digital Twin Trust Framework is presented in section 6.2.6.*

6 The Digital Twin Toolbox for Implementation and Design

6.1 Overview of the Approach

This Chapter summarizes the developed systematic support for the conception and implementation of DTs. Combining the required solution elements described in Chapter 5, a toolbox is formed – the ***D**igital **T**win **T**oolbox for **I**mplementation and **D**esign (DITTID)*. As no approach, method, or tool will be equally applicable to different situations and descriptions are often ambiguous, it is important to be very specific about terminology of these elements (Gericke et al., 2022). According to Blessing and Chakrabarti (2009) all the tools and resources aimed at assisting designers in their work can be described as "design support". Within this thesis the definitions of Gericke et al. (2017) are used (cf. Table A 10). In addition to the definitions of the core vocabulary, the suggested elements of a method based on Gericke et al. (2022) are used to describe DITTID and its elements clearly.

DITTID – The Digital Twin Toolbox for Implementation and Design

Figure 6-1 shows an overview of DITTID[1]. Core of the toolbox is the **Digital Twin Procedure Model** (cf. section 6.2.1). It is accompanied by supporting design methods, which are connected to the procedure model in different steps. In general, each of these methods can be applied standalone, but their maximum value can only be reached if applied together. The upper three methods are connected to each step of the procedure model. The **Digital Twin Business Modelling Approach** (cf. section 6.2.2) draws information of the entire procedure and delivers inputs, such as the prioritization of use cases at the end of step 1. It is accompanied by the **Digital Twin Value Map** (cf. section 6.2.3), which can be used to formulate meaningful value propositions as an input for the business modelling approach. But it can also be used to identify suitable use cases or to validate the DT solution from an economic perspective. Therefore, the Value Map also aligns well with the **Digital Twin Use Case Catalogue** (cf. section 6.2.4) that offers an analogy and ideation method to identify suitable use cases. At the end in step 5, the developed use cases can be entered into the catalogue again for further DT projects. The **Digital Twin Use Case Template** (cf. section 6.2.5) supports each step of the procedure model by offering a standardized documentation format for the use cases to be developed. Lastly, the **Digital Twin Trust Framework** (cf. section 6.2.6) supports DT developers in building trust in their offered DT solutions and between all involved partners. It draws information from the situation analysis as a starting point and delivers important input for the implementation preparation. The implementation itself is supported by detailed implementation roadmaps, with checkpoints responsibilities, and defined test cases. In the upcoming sections, each part of DITTID will be described in detail.

[1] *DITTID is published online: https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/*

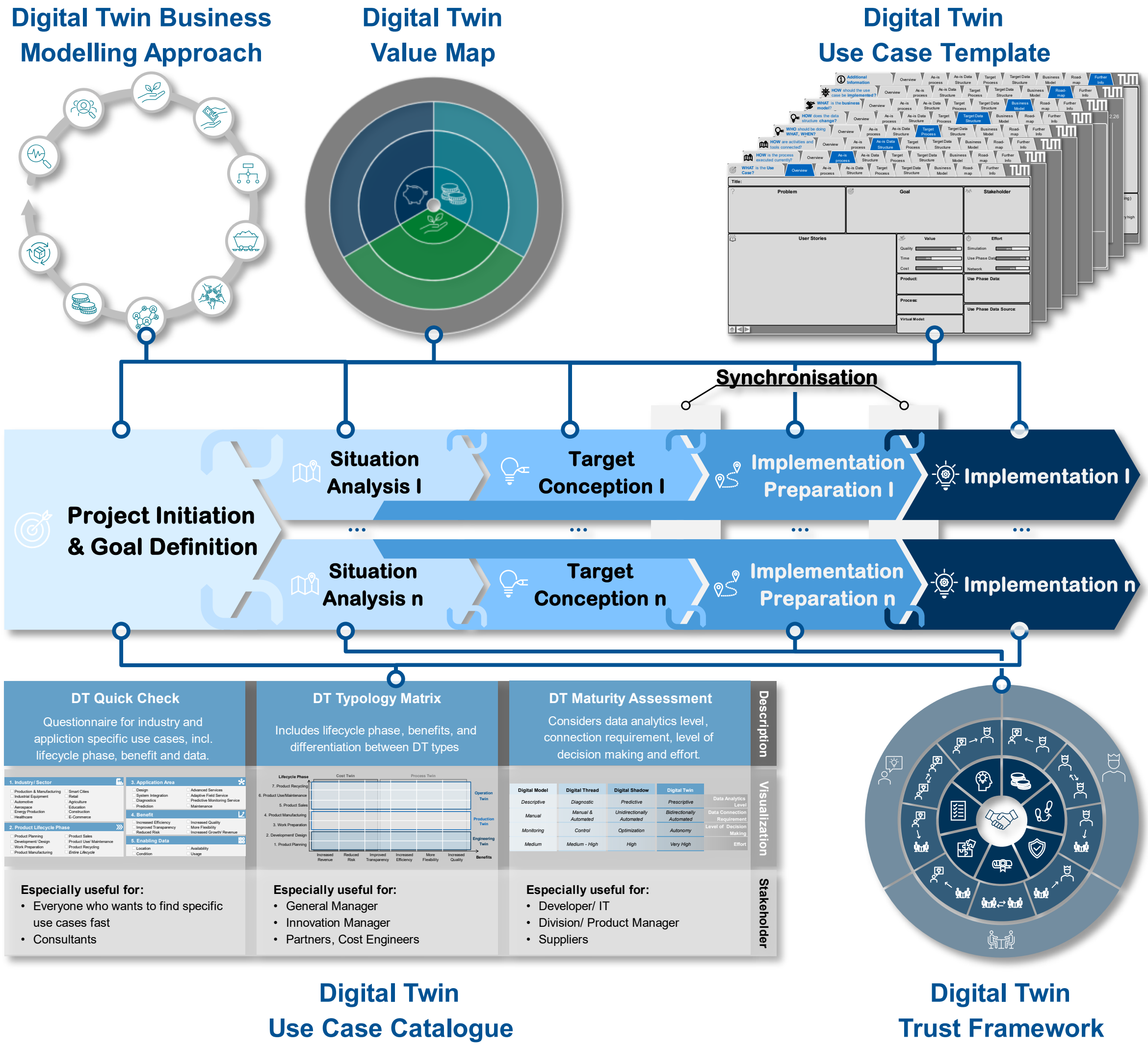


Figure 6-1: Overview of the Digital Twin Toolbox for Implementation and Design (DITTID).

The *purpose* of DITTID is to support the DT team of a company to efficiently develop economically and technologically successful DTs. The developed toolbox has only been applied to engineering case studies. Therefore, claims about the *scope* in which DITTID will be applicable can only be made about engineering, and even has to be narrowed down to the branches and sizes of the company. However, on a theoretical level all methods were designed to be as generically applicable whilst not becoming arbitrary. Within the case studies, the methods were developed and applied for engineering, production and operation twins to cover the most significant phases of the product's lifecycle. Consequently, the coverage within the scope includes these three lifecycle phases. In applying the systematic approach, it is expected to achieve the following *benefits*:

- reduction of development times,
- more holistic assessment of the value of the developed solution,
- improved business cases,
- improved trustworthiness of the developed solution, and
- better compatibility with legacy systems.

DITTID is designed to be applicable by people with general engineering background. Specific knowledge is not required, although for the creation of the DT various disciplines must be involved.

6.2 Modules of the Approach

6.2.1 The Procedure Model

Overview and Intended Use of the Procedure Model[2]

The core element of DITTID is the Digital Twin Procedure Model. Purpose of the DT procedure model is to guide a DT team from the first vague idea of a DT over the development of different use cases towards the implementation of the final DT system. It includes specific activities as well as helpful methods and tools. It provides a systematic and methodical approach to structuring the complexity of the conception and implementation of DTs. It aims to make the process efficient, goal-oriented, and manageable, with appropriate risk management activities to avoid failure of the project. As for DITTID, the scope of the procedure model in general includes all types of DTs – however, claims can only be made about the applications described in Chapter 4. Within the scope, the model covers all phases of the DT project from project initiation to implementation of the DT system. However, the use phase of the DT is not covered. Main benefit of the procedure model is reducing development effort and improving quality of the solution. It also promotes high comprehensibility, structured identification of use cases, communication within the project, and integration of new technologies. The model itself consists of five basic steps, from project initiation to implementation of the DT (cf. Figure 6-2).

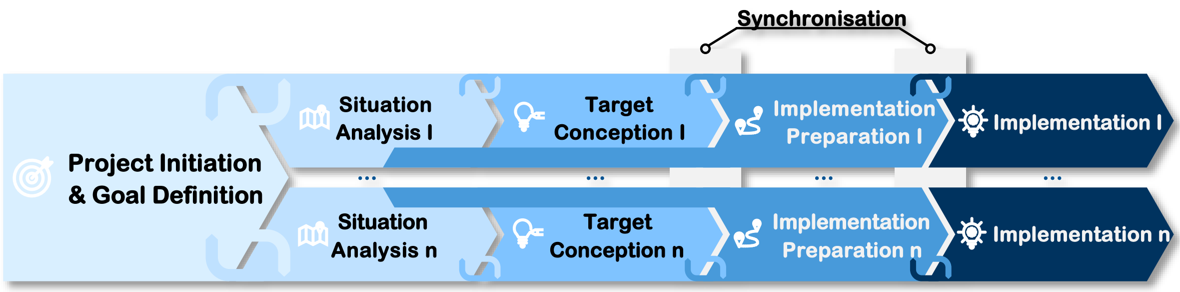


Figure 6-2: Overview of the Digital Twin Procedure Model. The Two Streams Exemplify the Development of Different Use Cases.

[2] *Section 6.2.1 is based on the student thesis of D. Fischer (2022) which was supervised and actively guided by the author of this thesis.*

The procedure model has been developed in a case study on engineering twins (cf. section 4.2) and has been further refined in three more case studies (cf. sections 4.3 - 4.4). Part of that further development was the adoption of the procedure model to different types of DT use cases and an increase in the level of detail of the descriptions, methods and tools of the procedure model. As already described in section 4.2, the implementation of the use cases is to be designed flexibly coherent with the shell model (cf. Figure 4-5), in order to facilitate the introduction of the DT. Thus, compared to the initial version presented in section 4.2 there is no longer one large thread of development; instead, there are several parallel developments. To illustrate this, two exemplary development threads are shown in the procedure model (cf. Figure 6-2). These stand for any selected use cases and can be executed both sequentially or in parallel. The modular implementation in individual use cases makes it possible to perform an early analysis of the added value of the DT in the company. Furthermore, subsequent use case implementations can be adapted based on the findings from initial implementations which reduces development complexity (Lindemann, 2009).

However, this division into separate development threads requires thorough coordination. Therefore, in order to be able to use synergies between the use cases, synchronization points were introduced. The first one takes place after the target conception since the knowledge of similarities and differences between the target concept and the "as-is" situation facilitates the preparation of implementation. The second synchronization step is located after the preparation of implementation and deals with the coordination of implementation tasks. To ensure the flexibility of the procedure model, iterations between the steps are included (the small arrows in Figure 6-2). In each step some basic information is already gathered for the subsequent step and if changes become apparent, the DT team can iterate. For example, while modelling the as-is process of a use case, further problems are identified leading to additional user needs, which must be considered in the goal definition.

This upper level of the model is quite generic and vague. To make it applicable, detailed descriptions of the processes required for each step are documented. Figure 6-3 exemplarily depicts the one-pager for step 1 – "Project Initiation & Goal Definition". Based on the findings from literature and the empirical studies, a clear process that a DT team can follow is beneficial to reduce development times and to ensure nothing important will be missed. Therefore, these one-pagers include the required inputs *(2)*, the necessary activities *(3)*, the desired outputs (4), and the competencies (5) required to fulfill this process step. Inspired by the V-Model for CPS (VDI Verein Deutscher Ingenieure e.V., 2021), a checklist *(6)* is provided to track progress. For each activity, it is shown which methods or tools *(3b)* can be used to support execution of this task (e.g., *"PM-M1.1 Expert Interview"*). Further, the icons above the activities indicate which competencies are required and responsible for executing this task *(3a)*. In addition, the procedure model is closely linked with the DTBMA (cf. section 6.2.2). Outputs of the DTBMA are taken as inputs for some activities and vice versa. Some activities are to be conducted together with DTBMA *(3c)*, for example *"PM-A1.3 Create a pre-selection of vague use cases"*. All one-pagers of the process steps can be found in appendix A8.1.

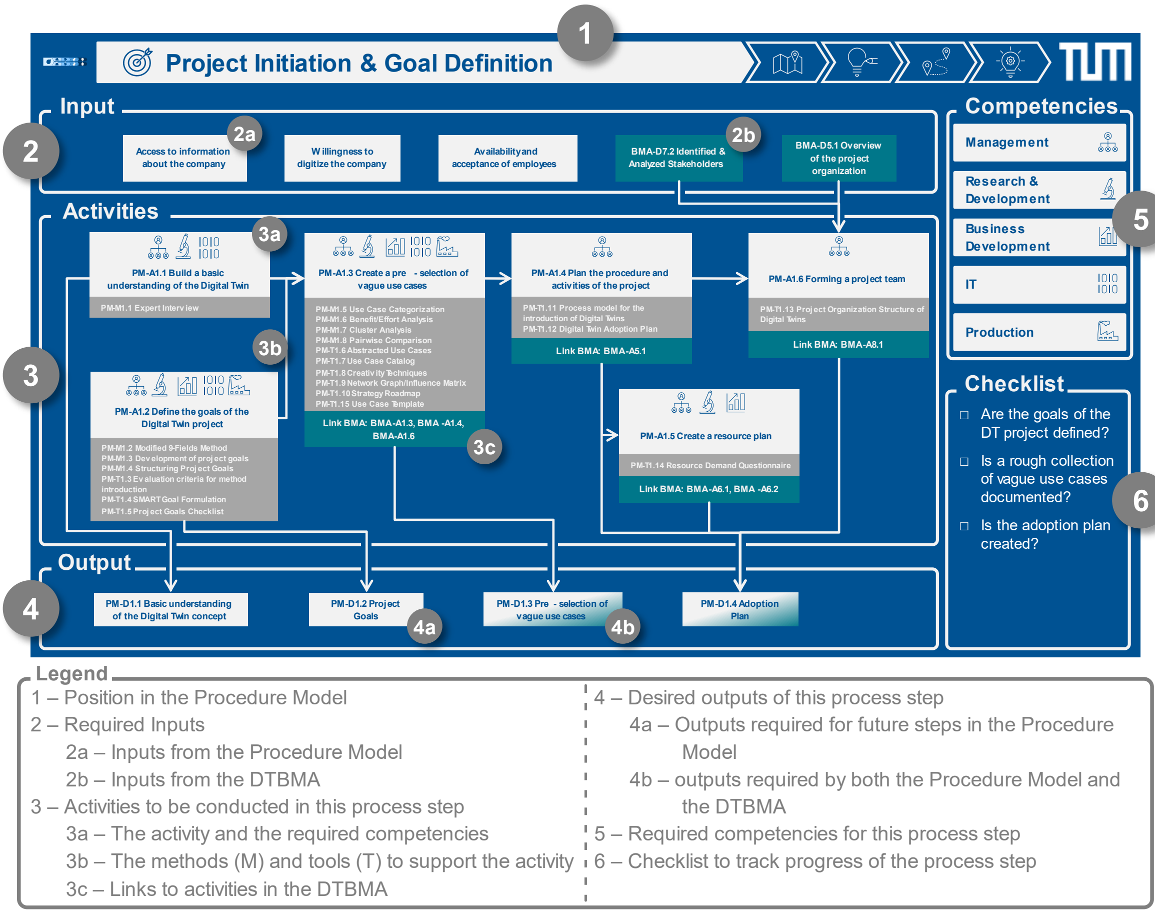


Figure 6-3: Overview of the One-Pagers for Each Step Shown Exemplarily for Step 1 – Project Initiation & Goal Definition.

Similar to the one-pagers for the process steps, each activity, method & tool, and deliverable is described in detail (cf. Figure 6-4)[3]. Each of them includes a unique index *(1a, 2a, 3a)* and a title *(1b, 2b, 3b)* to unambiguously identify them. Additionally, the overall position within the procedure model is indicated *(1e, 2d, 3e)*. Furthermore, it is indicated to which element the activity, method & tool, or deliverable is needed for *(1d, 2c, 3d)*. For activities and deliverables, a prioritization is given *(1c, 3c)*. Based on the categories "nice to have", "should have", and "must have" the user can decide on whether achieving this element is essential for the overall project or not. This is intended to improve flexibility and usability of the approach. For activities and methods, detailed descriptions on how to execute the element are given *(1f, 2e)*. The methods & tools are linked to the activities *(1g)* and if possible, references, links, and template are provided for each method & tool *(2g, 2h)*. For the deliverables, goals to be reached are provided and – as for the steps – checklists to check for fulfilment of the output. In the following, the steps of the procedure model are described in detail.

---

[3] *The entire procedure model with all one-pagers is published online: https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/*

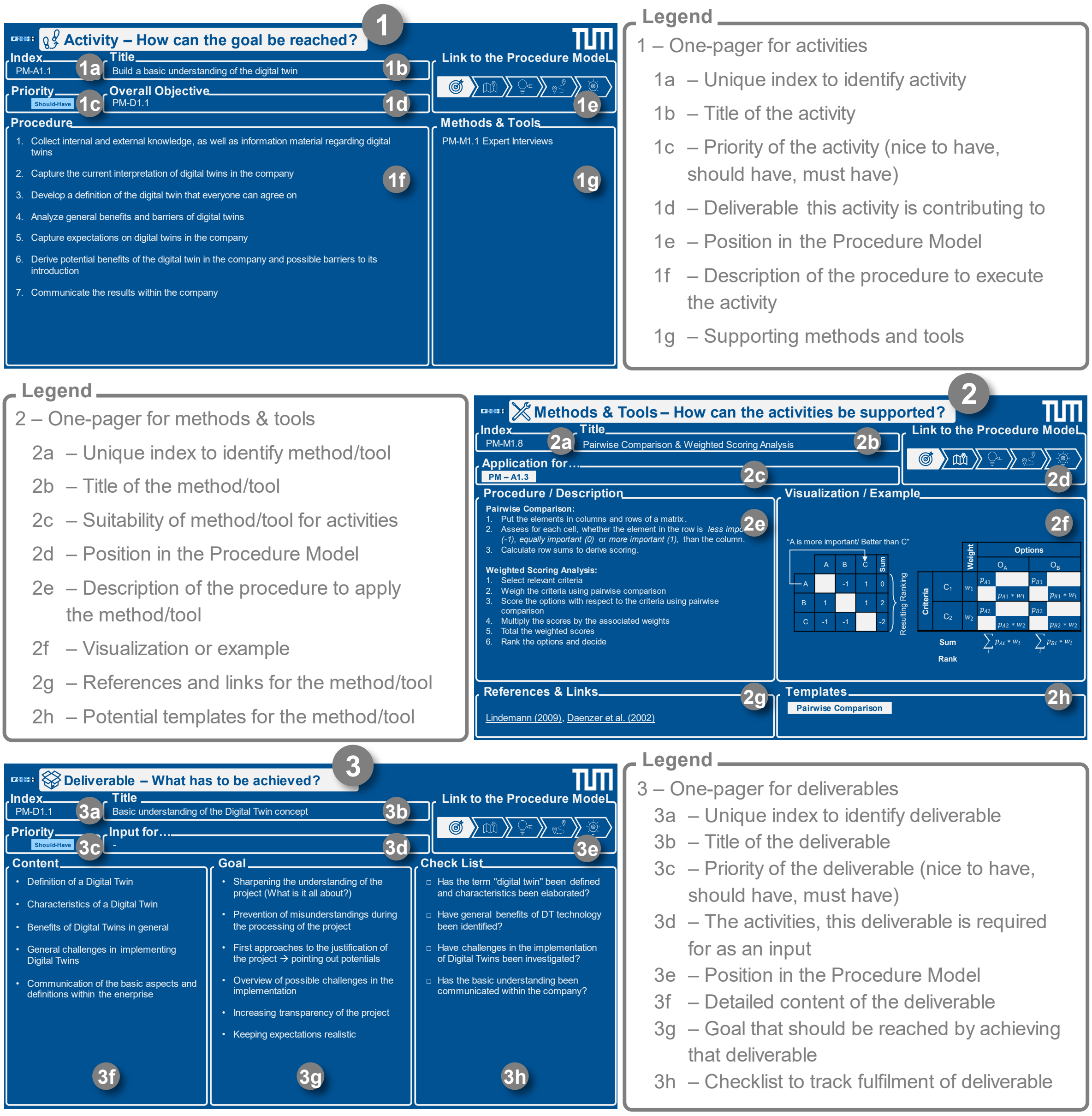


Figure 6-4: Overview of the One-Pagers for Activities (Top), Methods 6 Tools (Middle), and Deliverables (Bottom). Exemplarily Shown for Elements of Step 1 – Project Initiation & Goal Definition.

Step 1 – Project Initiation and Goal Definition

Step 1 “Project initiation and goal definition” supports the introduction and implementation of the DT through a clear project definition based on the questions: What needs to be done, how, and with what resources. Initiating a DT project requires certain prerequisites from the organization of the company – a willingness for digitization, availability of resources, and general openness to new concepts. Additionally, access to relevant information and organizational knowledge is essential. Information about relevant stakeholders and project organization should be incorporated as well (cf. Figure A 30).

To start, a shared fundamental understanding of the DT is established. Due to varying definitions and divergent perceptions of and expectations from DTs within the company, a unified understanding is necessary to prevent false expectations. Furthermore, the goals of the DT project must be defined. These project goals are derived in a top-down manner from the company's vision, values, and mission. The DT project is integrated into an overarching digitalization strategy, aiming to enhance the project's acceptance compared to a standalone initiative. In conjunction with the DTBMA, the benefits of the DT and the desired target state are outlined, without already presenting specific solutions (cf. section 6.2.2).

The primary goal of this step in the procedure model is to systematically gather, define, prioritize, and select use cases based on the project objectives. To achieve this, creativity methods like the use case catalog (cf. section 6.2.4), complexity methods such as cluster analysis, and decision-making methods like benefit-effort analysis are employed (cf. Figure A 30). The chosen and prioritized use cases feed into the creation of the strategy roadmap. For this purpose, the use cases need to be sequenced logically and analyzed for the best benefit-to-effort ratio. Finally, a rough collection of the required resources and the formation of the final project team take place in this step. The process from gathering use cases to developing a strategy roadmap is shown in Figure 6-5.

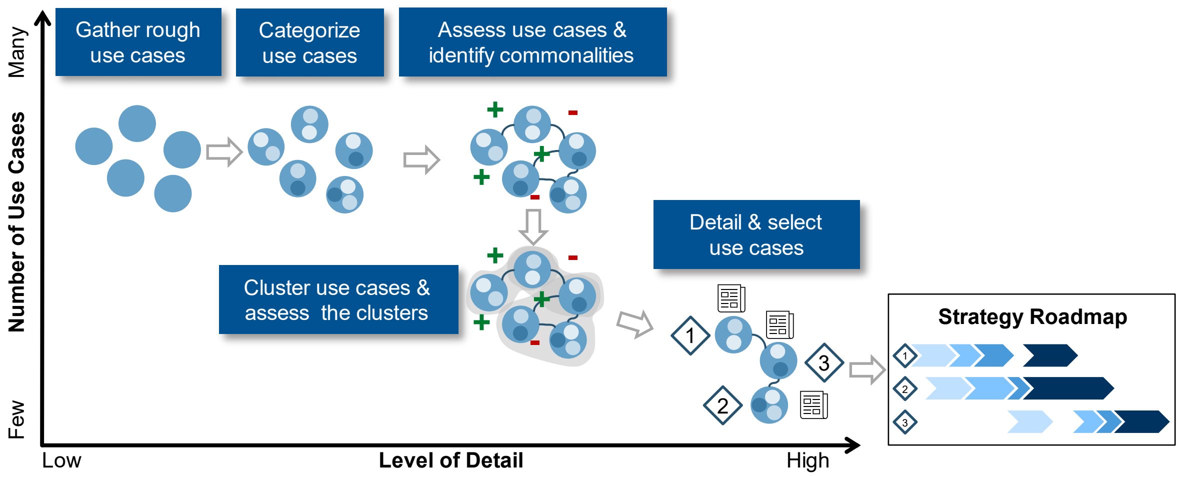


Figure 6-5: Process of Gathering, Assessing, and Selecting Use Cases to Form a Strategy Roadmap.

Step 2 – Situation Analysis

Based on the outcomes of the initial step, the subsequent stages of the procedure model are now carried out separately for each use case (as it is also sketched in Figure 6-5 on the right). In the second step, the "as-is" situation is analyzed in detail, collecting all crucial information regarding the current process within the company. Based on the analyzed current state, ideas for the desired conception are documented. The initial situation is examined from three perspectives: process environment, process flow, and associated data structure.

For the existing process environment (as described in sections 4.3, and 4.4), the architecture of the real-world system is captured covering information about the structure of the plant, facility, or product. The components of the relevant system are identified and interconnected through information, energy, and material flows. As the applications can be very diverse, no specific process modeling method is prescribed. However, the identified criteria from Trauer, Wöhr, et al. (2021) can offer assistance in selecting an appropriate method.

Next, the current process flow is documented. This step is significant for integrating the DT as the DT will induce substantial changes to the process's operation. Similar to previous case studies (cf. Chapter 4), the representation of the process follows the BPMN 2.0 standard (ISO International Organization for Standardization, 2013). Initial information about the "as-is" process's flow is collected, involved stakeholders and resources are identified, and potentially grouped. Next, the stakeholders' activities (Who performs which activity?) and the functions of the resources (What function does each component perform?) are recorded. By separately considering activities and functions, manual and automated processes differ. The activities and functions are then arranged into a logically sequential flow, considering decision points.

The activity "Document Current Data Structure", complements the preceding activities by documenting the existing IT infrastructure of the process, which is closely related to enterprise architecture management (cf. section 2.2.1, or Ziemann (2022)). Available data and information flows in the process are mapped. PDM tools are captured, and the IT-Architecture is derived from the process environment. This can for example be supported using the Cyber-Physical Systems Canvas (CPS-Canvas) by Westermann and Dumitrescu (2018). Additionally, based on the analysis of the "as-is" process and data structure, the current maturity level of the company regarding the implementation of the DT can be assessed, and a target maturity level can be determined. Comparing the current and desired maturity levels reveals the effort required to achieve the desired state. Further, untapped potential as well as threats of the current situation are uncovered and can be considered in an implementation strategy, which guides the next step.

Step 3 – Target Conception

In the third step of the procedure model, the target concept is developed based on the as-is situation and the formulated implementation strategies. In parallel, requirements for the target concept are derived and documented. In addition, as preparation for the next step, initial measures for realizing the concept are developed. The overview of this process step is shown in Figure A 32.

Same as in the previous step, this target concept is documented following the three perspectives of process flow, process environment and data structure and therefore considers integration of the use case into the legacy system (cf. Figure 6-6). To start, potential interfaces of the DT use case within the process flow are identified, focusing on parts of the as-is situation that will change with the implemented DT. The interface analysis is guided by the key question: *"Where does the DT connect in the process?"*. Additional activities of the DT are then added, and existing activities are modified if required. The focus here should be on the added value to be achieved by the DT. Based on the identified tasks of the DT, an adapted process environment and data structure will be developed. The conception of the target process environment still takes place on an abstract level, i.e., no exact specifications are given for the hardware or software to be used – the focus is only on the fulfillment of the function through a suitable solution principle. Finally, the target concept is checked for consistency and completeness. Due to the subdivision into three process perspectives, attention must be paid to a coherent overall picture of the new process.

From the developed target concept, the use case description, and the project goals from the first step, requirements and a specification sheet to the DT concept are derived. There are different approaches depending on your preferences – either conventional or agile. The conventional derivation of the requirements and the transfer to the specifications can be partially automated (cf. section 4.4.2). However, agile approaches are often more effective here because DT use cases are usually developed incrementally, similar to software products (cf. section 4.2.2).

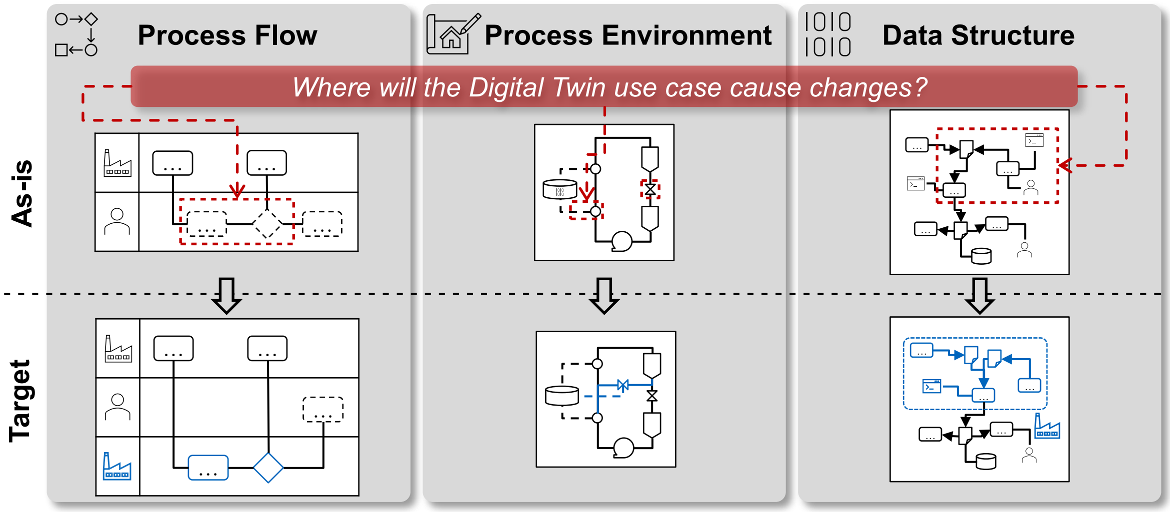


Figure 6-6: Process of Deriving the Target Concept from the As-is Situation.

Step 4 – Implementation Preparation

In preparation for implementation, a solution is developed for the previously specified desired target concept and the detailed roadmap for implementation is derived. Figure A 34 visualizes all structural elements of the "implementation preparation".

The goals of the implementation preparation include an agreed requirements specification, an elaborated roadmap of the implementation and proof of technical feasibility. The specification answers the question: *"How and with what will the requirements be realized?"*. In addition to the solution concept, test cases and acceptance criteria are documented. Test cases represent the conditions under which the solution concept will be evaluated after implementation. The implementation roadmap contains work packages and the associated responsibilities, and thus answers the question: *"Who does what, when?"*.

First, a concrete technical solution is systematically developed to realize the target concept defined in the specifications. Existing available approaches are reviewed, or a novel solution is created. The solution is selected internally or together with external providers and is documented in the requirements specification. In the case of external procurement, close cooperation with the providers is required. The selection of a suitable implementation partner is essential. For this purpose, a detailed market analysis must be carried out in coordination with DTBMA and offers must be evaluated[4].

The previously defined requirements must be agreed upon with the implementation partners. Subsequently, test cases and acceptance criteria are documented. When formulating acceptance criteria, it is important to achieve a balance between compliance and quality assurance. In addition, measurable quantities of interest for accepting test cases are to be found.

To detail the implementation roadmap, the realization of the designed solution is being planned. Based on the rough implementation roadmap, work packages are formulated, and the defined test cases are planned. The work packages are derived from implementation roadmap. Each work package is accompanied by an effort estimation. Further, roles and responsibilities are assigned to the work packages. For this purpose, the “RACI”-method[5] is suitable and useful (Smith et al., 2005).

Step 5 – Implementation

In the last step, the DT use case is implemented in accordance with the implementation roadmap. The new system is integrated into existing structures and put into operation. The implemented use case is evaluated in coordination with the DTBMA. User acceptance plays a major role in the implementation and is crucial for success. Therefore, activities to train and support users and their partners are also proposed in this step and changes are communicated within the company. The creation of lessons learned using retrospective methods concludes the development process for the use case. They are used to optimize the implementation of further use cases. Figure 4.24 shows all the structural elements of the fifth step.

The implementation of the use case takes place in two steps. First, in line with agile development, the solution concept is deployed within a pilot implementation and only transferred to operational use after successful acceptance of the requirements. If necessary, the solution is iterated further. Thus, undesired effects of the DT on the legacy system can be eliminated and user satisfaction can be increased. To ensure that the goals are achieved on time, a user story risk map can be used (Trauer, Schweigert-Recksiek, Gövert, et al., 2020).

In parallel, users and their partners are trained and resulting changes are communicated within the company. These activities should still be continued during ongoing operations. Support for employees regarding interaction with DT increases acceptance of the new system (cf. section 6.2.6). Lessons learned are created using common retrospective methods.

---

[4] *In industrial practice, this activity is highly sensible, considering the huge investments. As this requires very company-specific processes, only vague recommendations are given within DITTID.*

[5] *“RACI” stands for “Responsible – Accountable – Consulting – Informed”. Each stakeholder is assigned to one of these roles for each of the tasks. The “responsible” person or team is executing the work. “Accountable” is whoever is responsible for the success of the project or task. “Consulting” stakeholders provide valuable ideas and information, whereas “informed” stakeholders are only being kept in the loop for transparency and knowledge management. The assignment of roles can be documented in a RACI-matrix. (Smith et al., 2005)*

6.2.2 The Business Modelling Approach

Intended Use of the Business Modelling Approach

Purpose of the DT Business Modelling Approach (DTBMA) is to support engineers in effectively deriving and describing the added values of a DT solution[6]. As an output, a DT business modelling canvas will be developed. The approach is specialized for the application to DT use cases. However, it might also be applicable to other I4.0 or PSS use cases. It is intended to be used by engineers, with a basic understanding of economic analyses. Theoretically, there is no limitation regarding an industry sector, however, as it was only applied to an academic case study (cf. section 4.4). As described in the previous section, the approach is strongly intertwined with and should only be applied in combination with the procedure model of DITTID (cf. section 6.2.1). The result of DTBMA – the business modelling canvas – is documented in the DT Use Case Template (cf. section 6.2.5). Furthermore, it uses the Value Map (cf. section 6.2.3) as a supporting method. The benefit of the approach is to enable a DT project team to develop sound economic evaluations and business models for DT use cases, crucial for their success.

Development of the Business Modelling Approach

In order to develop the DTBMA, a systematic literature review was conducted, guided by a research strategy[7]. As for DTs, there is no unified definition of "business models" (Gassmann et al., 2014). In general, a business model can be defined as the way in which an *"enterprise delivers value to customers, entices customers to pay for value, and converts those payments to profit"*. However, DTs often do not lead to an increase in profit, as they are not monetarized per se. In this sense, the definition of Osterwalder and Pigneur (2010) is more suitable, as they refer to an improvement of "values" instead of "profit". According to them, a business model is *"the rationale for how an organization creates, delivers, and captures value"* (Osterwalder & Pigneur, 2010).

The main part of the literature review was to identify fundamental common elements of existing business modeling approaches. The results are presented in appendix A8.2 in Table A 11. First, *target customers,* which can be grouped in *customer segments,* play a crucial role in business models (Gassmann et al., 2014; Osterwalder & Pigneur, 2010). *Customer relationships* need to be established to manage requirements, needs, and expectations of end customers (Osterwalder & Pigneur, 2010). To interact with the customers, *channels* need to be identified to communicate, deliver, and market the value proposition and thereby influencing the customer experience (Jodlbauer, 2020; Osterwalder & Pigneur, 2010). This *value proposition* is the core element of each business model, representing the products and services offered by the company to address specific customer problems and needs, which is the key aspect a company can differ itself from competitors (de Kluyver, 2012; Jodlbauer, 2020). To realize the

---

[6] *Section 6.2.2 is based on the student theses of Matondang (2021), and Mac (2022). The theses were supervised and actively guided by the author of this thesis. Parts of the business modelling approach were already published in Trauer et al. (2023).*

[7] *The research strategy can be found in appendix A8.2.*

value proposition, *key activities*, *resources*, and *partners* are necessary (de Kluyver, 2012; Hamel, 2002; Johnson & Lafley, 2010; Osterwalder & Pigneur, 2010). Furthermore, *revenue streams* and *cost structures* need to be determined (Gassmann et al., 2014). Lastly, the *organization* needs to be adapted to the business model (Lindgardt et al., 2013).

Regarding business models for DTs only few research can be found. However, DTs offer great benefits for the business models of enterprises (cf. section 2.1.3.5). One of the few approaches including a conceptual design of marketable smart services based on DTs in the textile industries is presented by Prielipp et al. (2021). Extending the context to digital products in general, researchers and practitioners have already adapted to the different and new requirements, demanding for other organizational forms involving different stakeholders, resources, and activities that have to be considered compared to conventional business models (Wirtz, 2019). For example, Benta et al. (2017) proposed a data-enhanced business modeling canvas that considers data resources and data insights as key elements.

To sum up, digital products in general, and particularly DTs, call for unique and novel business modeling approaches due to their distinctive characteristics:

1. *Internal customers*: DTs often cater exclusively to internal customers, requiring customized strategies for customer segmentation and relationship management.
2. *Limited direct revenue*: DTs are rarely sold directly. While internal customers should be considered, they do not generate revenue, posing challenges in terms of revenue generation and cost structures.
3. *Multifaceted value proposition*: DTs offer a diverse range of value, making it difficult to identify and comprehend all the indirect effects and their interplay.
4. *Quantification complexities*: Quantifying the identified value of DTs and their associated benefits is often intricate, demanding innovative approaches for measurement and evaluation.

Taking these distinct characteristics into account, the DTBMA has been developed by identifying and adapting ten common business modeling elements. Thus, it is specifically tailored to address the requirements and challenges of DTs, providing a comprehensive framework for modeling the business aspects of DT implementation. The approach is described in the following.

Overview of the Business Modelling Approach

Figure 6-7 depicts the general structure, encompassing the nine primary process steps of the DTBMA which result in the creation of a new business model documented in an adapted business modeling canvas. The process of the approach is executed sequentially – however iterations are possible at any point in time to assure the flexibility of the approach. The process starts with *Step 1: Development Concept*, where DT use cases are identified, assessed, and prioritized. This enables the selection of the most promising DT use cases for the organization in alignment with the DT strategy, which are then incorporated into the DTBMA process. This step is closely intertwined with the procedure model. In *Step 2 – Customer Segments*, the target customers for the DT solution are identified. Two critical decision points which should be handled as milestones. The first is *Step 3: Value Proposition*, where the assumed

Value Proposition to customers is identified and validated. For this value proposition, revenue streams, or if the customer is internal values created are identified in *Step 4*. To realize the solution key activities, resources and partners need to be derived in close collaboration with the procedure model in *steps 5 – 7*. In step 8, the organization is adapted to the requirements of the DT solution. The second checkpoint is *Step 9: Cost Structure/Budget*, which unveils the profitability of the DT implementation. Finally, the new business model is documented in *step 10*.

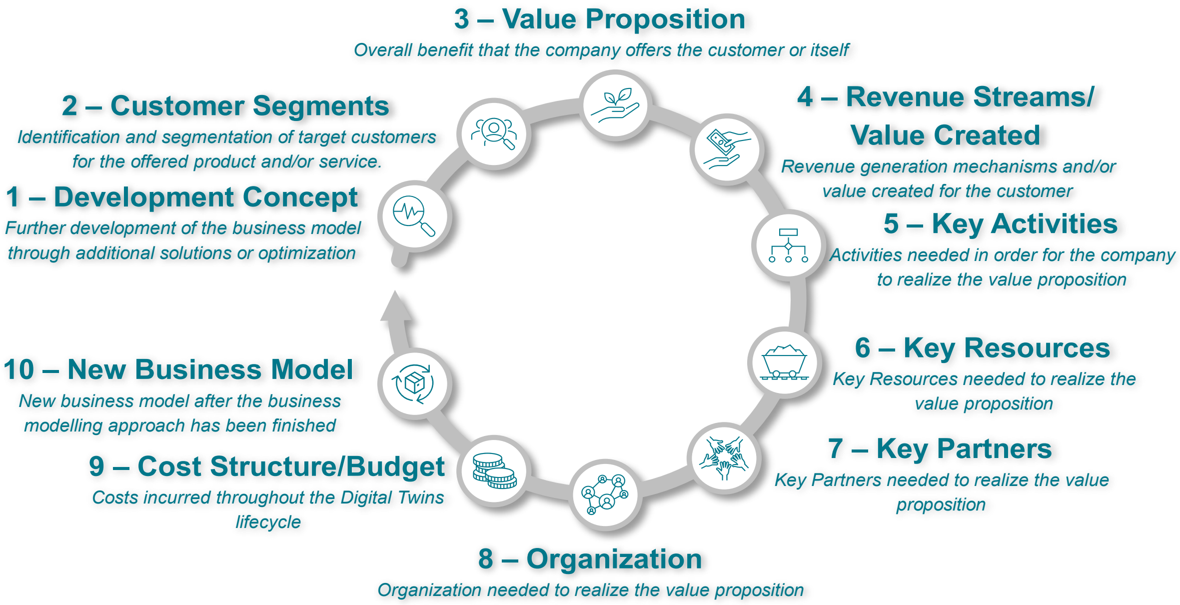


Figure 6-7: Overview of the Digital Twin Business Modelling Approach.

As for the procedure model, each step is supported by a one-pager with is exemplarily shown for step 1 in Figure 6-8. It indicates the position of the step in the DTBMA *(1)*, the aimed goal *(2)*, the required departments *(3)*, and an overall summary of the step *(4)*. Core of the one-pagers are the necessary activities *(6)*, including required competencies *(6a)*, supporting methods and tools *(6b)*, and potential links to the procedure model *(6c)*. For highest effectiveness, these activities should be conducted in collaboration with the stakeholders responsible for the execution of the procedure model. Furthermore, required inputs *(5)* and desired deliverables *(7)* of the step are shown. Lastly, key questions are provided to serve as a checklist and to help track the progress of the DTBMA. They are split into general business modelling related questions *(8)*, and DT- or data-specific questions *(9)*.

Accordingly, one-pagers for each activity, method & tools, and deliverables are provided. They are designed in the same way as the ones for the procedure model described in section 6.2.1. Their general structure is depicted in the appendix A8.2, Figure A 139. The listed methods and tools are always a suggestion and not a comprehensive list that must be applied. In the appendix, also the one-pagers of the steps can be found, which are described in the following.

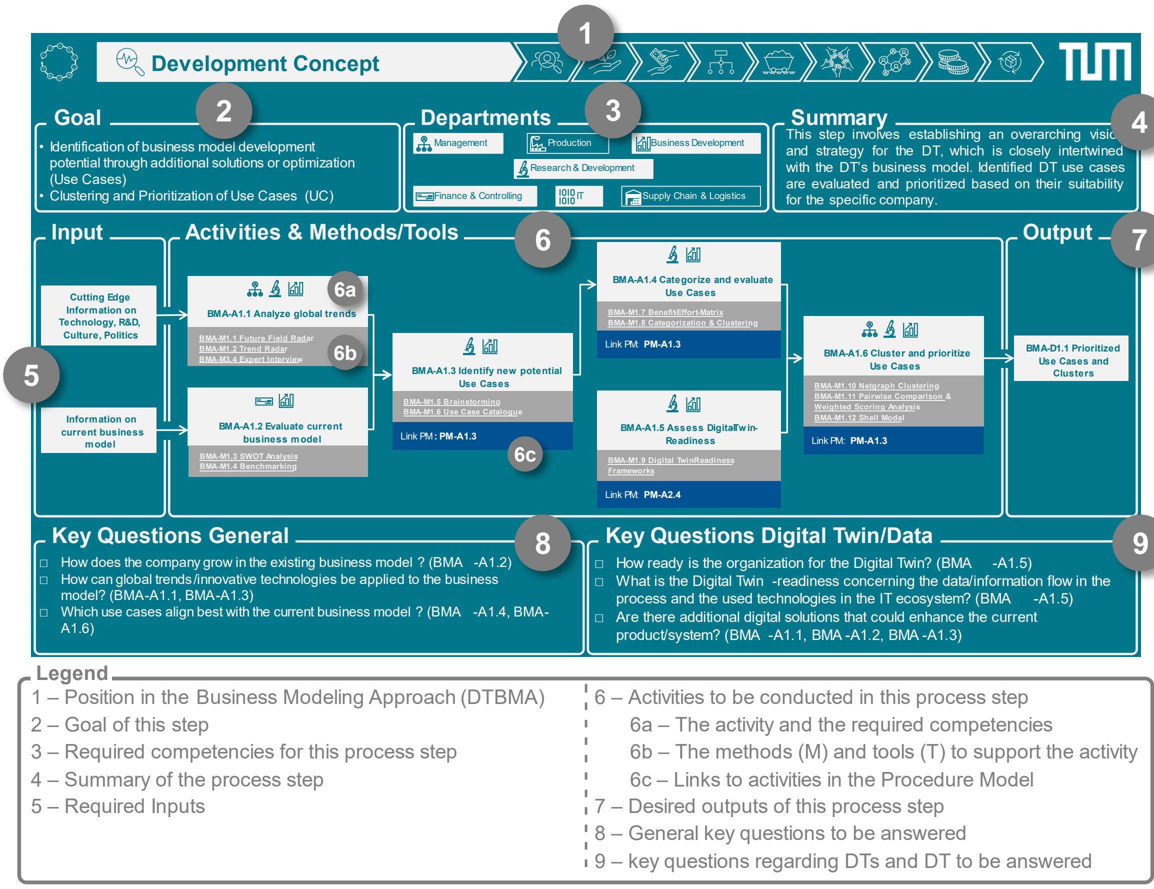


Figure 6-8: Overview of the One-Pagers for Each Step of DTBMA Shown Exemplarily for Step 1 – Development Concept.

Step 1 – Development Concept

In accordance with the DT procedure model (cf. section 6.2.1), the initial phase of any DT project involves establishing an overarching vision and strategy for the DT, which is closely intertwined with the DT's business model. Therefore, the DTBMA starts with the *"Development Concept"*, where identified DT use cases are evaluated and prioritized based on their suitability for the specific company (cf. Figure A 130). In general, a business model for the current system without a DT is already existing. Thus, the current business model and overall readiness for DT implementation are analyzed. The step aims at answering key questions, such as "Which use cases align best with the current business model?", "How prepared is the organization for the Digital Twin?", or "How can global trends/innovative technologies be applied to the business model?". Through this initial step, the company gains an overview of potential use cases, formulates a hypothesis for the business model, and already proposes potential customer segments which will be investigated in the next step of the approach. Furthermore, the identified use cases are prioritized to facilitate managerial decision-making. These activities are supported by various methods and tools. For identifying new use cases, mainly creativity enhancing methods such as brainstorming (e.g. Gericke et al., 2021; Osborn, 1957), Future Field Radar (Miecznik, 2013) or the Trend Radar (Durst et al., 2010) are incorporated. The remaining activities focus mainly on the analysis, assessment and prioritization of use case which can be supported by methods like SWOT-analysis (e.g. Thompson & Martin, 2010), Benchmarking (e.g. Passos & Haddad, 2013), or Pairwise Comparison (Lindemann, 2009).

Step 2 – Customer Segments

The next step is to define the *"Customer Segments"* to which the selected use cases are applicable. It is crucial to distinguish between internal and external customers during this process. While DTs targeting external customers may lead to increased revenue, DTs for internal customers typically do not directly generate additional income. For external customers, a comprehensive market analysis (e.g. Blake, 2000) is conducted to understand the market background and determine the customer's market size. Irrespective of the customer type, gathering pertinent information about the customer is essential. This involves identifying the activities of the target customer and comprehending the problems and needs they encounter while performing these activities. Methods such as Porter's Five Forces (Porter, 1996), customer interviews/questionnaires (Hardavella et al., 2016), or Focus Group Discussions (Nyumba et al., 2018) can be utilized to gather this valuable information. To analyze the fit between Value Proposition (step 3) and the target customer, the Value Proposition Canvas developed by Osterwalder et al. (2014) can be applied. By the end of step 2 of the DTBMA, the target customers should be clearly defined, and a comprehensive understanding of their profiles should be obtained. Figure A 131 provides an overview of this step.

Step 3 – Value Proposition

The subsequent step in the DTBMA involves formulating solutions that address customer needs and resolve customer problems (cf. Figure A 132). This is the central step of any business model. First, the company should identify the specific customer needs or problems it aims to tackle. For example, in section 4.3.2, the main problem of the case study partner was that defects in the production could not be recognized during the process. Therefore, it is not possible to take real-time actions to improve production efficiency. Consequently, the need of the customer is to get a DT solution allowing for in-situ analysis of production data and direct automated measures, based on this analysis. Next, these needs need to be matched with the applications of DTs and their values provided. Given the diverse nature of DT use cases, this can be a challenging task. Although existing literature provides an overview of DT benefits (cf. section 2.1.3.5), they are generally not specific to use cases, limiting their applicability. To address this the DT value map was developed that categorizes benefits into three main areas: increasing revenue, saving costs, and improving sustainability (cf. section 6.2.3). Based on the identified and assessed values, the use case is compared to competitor products to benchmark and determine the company's market position. The outcome of this comparison should unveil the company's unique selling proposition (Maurya, 2018). After the formulation of Value Propositions, it is crucial to validate them with the target customers. For this purpose, e.g., Validation Boards can be applied (Ardyanti et al., 2019). The validation results serve as a significant decision point in the DTBMA, determining whether a use case is accepted, needs to be reworked, or should be rejected. Thus, Step 3 represents a crucial milestone in the DTBMA.

Step 4 – Revenue Streams / Value Created

Once the value proposition for the target customer has been established, it needs to be determined how *revenue streams* will be realized or *value* will be *created* (cf. Figure A 133). The value provided to both internal and external customers can be categorized and evaluated. Identified benefits must be assessed and, ideally, quantified. Multiple metrics can be utilized for analysis, such as overall equipment effectiveness (OEE) for production use cases (e.g. Corrales et al., 2020). Additionally, it is crucial to consider how specific product or service characteristics influence customer satisfaction. Different features of a solution may have varying priorities for customers, and these desires or expectations should be integrated into the development project. While the value creation for internal customers is already known from the previous step's value creation calculation, the value creation for external customers must be translated into revenue. Key questions to address include "What pricing is assumed for the products/services?" and "How will the revenue be generated?". The revenue can for example be generated by offering the DT as a service (e.g. Aheleroff et al., 2021) or by monetizing the collected data.

Step 5 – Key Activities

To realize the identified and assessed values, the next step is to derive *"Key Activities"*. Based on the information collected about the products and services intended for the target customer, essential activities, tasks, workflows, and processes are derived (cf. Figure A 134). These activities align with the goal of delivering value to the customer, implementing, and running the DT, and generating revenue streams. Business, sales, and organizational activities are derived from the DTBMA. The technical activities required for implementing and operating the DT are determined in conjunction with the DT procedure model (cf. section 6.2.1). As described in the previous step, it is important to note that revenue streams primarily apply to external use cases. Additionally, it is crucial to identify the channels that the target customer expects for value delivery and communication (e.g., a DT platform, offering the DT as a standalone product, as part of a general consultancy, or as a cloud-based service), as well as the channels that the company intends to serve.

Step 6 – Key Resources

Additionally, the *"Key Resources"* necessary to carry out the key activities are identified in step 6 of the DTBMA (cf. Figure A 135). Examples of key resources include specialized buy-in workforce, data, and general human resources of the company such as data analysts. Data analysts play a vital role in areas such as simulation and determining the required usage data. Most of the required physical resources can be derived from the procedure model, described in the previous section. It is essential to document both the resources needed for implementation and those necessary for operating the respective use case. For instance, external customers may require additional resources for sales and marketing purposes. To support these activities, a resource inventory, or a resource requirement plan can be applied (Drews, 2021; Qi et al., 2021).

Step 7 – Key Partners

Collaboration often is a characteristic of DT projects, involving the cooperation of various stakeholders. Thus, it is important to be aware of the *"Key Partners"* involved in the project (cf. Figure A 136). The successful implementation and operation of DTs can be significantly influenced by both internal and external stakeholders. Hence, it is essential to identify all relevant stakeholders and manage them based on their characteristics. A stakeholder map can support getting an overview of all required partners (Murray-Webster & Simon, 2006). Subsequently they can be clustered using a Power-Interest-Attitude-Matrix (Murray-Webster & Simon, 2006). The previously identified key activities can be assigned to the partners using e.g., RACI-Mapping (Smith et al., 2005). Considering the novelty and ambiguous value proposition of DTs, stakeholders may exhibit caution or even resistance toward their introduction. Therefore, trust building measures should be taken (cf. section 6.2.6).

Step 8 – Organization

Once the Key Activities, Key Resources, and Key Partners have been derived, it is crucial to address the *"Organization"* (cf. Figure A 137). Given that various departments and stakeholders are involved in the implementation and operation of the DT use cases, it is essential to facilitate coordination and communication among them. This is particularly important when collaborating with external partners alongside internal departments. Furthermore, it is often not clear who the "owner" of the DT is – Engineering, IT, interdisciplinary departments, or other. Therefore, clearly defining the allocation of tasks and responsibilities helps establish a clear organizational structure and minimizes potential conflicts that could hinder the implementation and continuation of the DT use case, which can be based on the RACI-Mapping.

Step 9 – Cost Structure / Budget

In the final prescriptive step of the DTBMA, the focus is on deriving the *"Cost Structure"* for the DT use case (cf. Figure A 138). Building upon the output obtained in Step 4 regarding revenue streams and value created, the profitability of the DT use case can be calculated. The cost structure encompasses the expenses associated with establishing and maintaining the DT use case, including customer relationship management, channels, activities, resources, and partners – it consists of both fixed and variable costs[8]. The proportion of fixed and variable costs significantly depends on the nature of the DT use case. For instance, DT products aimed at external customers may lead to a higher proportion of variable costs. On the other hand, internal DT use cases focusing on process optimization may have a lesser impact on variable costs.

Step 10 – New Business Model

Finally, all gathered information and insights can be documented as a *"New Business Model"*. To visually represent these key insights and facilitate decision-making, all acquired

[8] *According to Ehrlenspiel et al. (2021), fixed costs remain constant regardless of the changes in the cost driver, while variable costs fluctuate in accordance with the changes in the cost driver. Factors such as order quantity, lot size, and the planning or accounting period length serve as cost drivers.*

information is documented in an adapted business modeling canvas, based on Osterwalder and Pigneur (2010) and Benta et al. (2017) (cf. Figure 6-9). As for this business modelling canvas, which was designed for use phase data, also for DTs data plays a central role as a core resource and a potential source of additional benefits. Therefore, "data resources" and "data insights" were included in the canvas. The data resources are identified in *step 6 – Key Resources* and the data insights are identified in *step 4 – Revenue Streams / Value Created*. Furthermore, this canvas was adjusted to fit business models for internal customers by introducing "budget" and "value created" as alternatives to "cost structure" and "revenue streams". This consideration reflects the cyber-physical nature of DTs within the DTBMA.

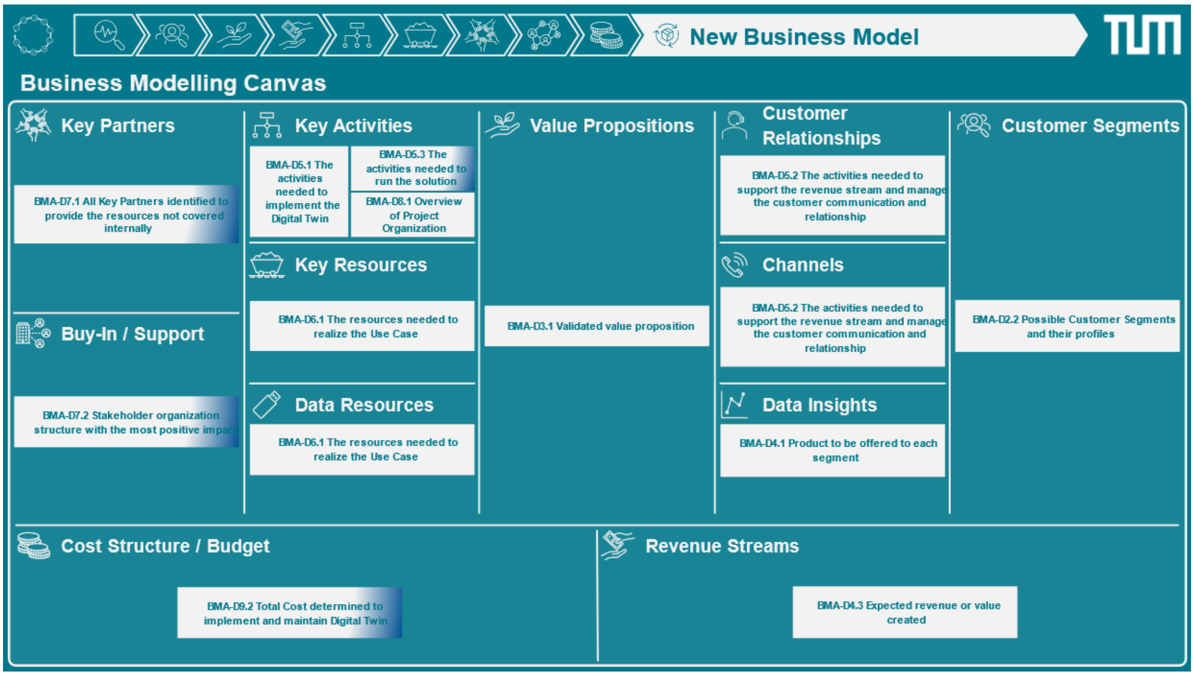


Figure 6-9: Overview of the Digital Twin Business Modelling Canvas.

6.2.3 The Value Map

Intended Use of the Value Map

The purpose of the value map[9] is twofold: on the one hand, it can be used to support the ideation of potential benefits and values of given DT use cases. In addition, it can be used as an ideation method for new use cases. Starting from a specific value a company wants to achieve, related use cases can be derived. The value map is designed for – but not limited to – use cases in the context of engineering, production, and operation of technical product-oriented industrial DT applications. It is designed to be applied in the early phases of a DT

[9] *Parts of the DT value map were already published by Christ et al. (2022) and Schweigert-Recksiek et al. (2023). The entire value map as well as examplary applications can be found in appendix A8.3.*

project to identify new use cases and later to assess the value of the use cases. Therefore, it is closely intertwined with both, the procedure model and the DTBMA (cf. sections 6.2.1 and 6.2.2). The main benefit of the value map is to enable a more holistic evaluation of the added values of a use case. It can also support a more goal-oriented identification of new use cases. It can be used without prior knowledge and as a standalone method. However, it should be moderated by an expert.

Development of the Value Map

In literature, many promising benefits of DTs can be found (cf. section 2.1.3.5). They are manifold and often hard to quantify. This large variety often makes it difficult to comprehensively describe the value of a DT – one or two primary benefits might be obvious, however that would not be sufficient to justify the high required investment to develop a DT. According to Kober et al. (2022) it is essential to define clear objectives, and to give concrete examples for the benefits of a DT. Further, even if all achievable potentials of the DT use case can be identified, it is often hard to quantify them, which is a general challenge of new technologies (Stetter, 2000). These challenges are one of the major barriers towards the implementation of DTs (cf. section 3.2). Therefore, a method is required supporting engineers to comprehensively and in the best case quantitatively describe the value of their DT solution. The goal of this research is to develop a map depicting the main achievable DT benefits, to link them to show interdependencies and to connect them to overall business values.

To achieve this goal, first a literature review was conducted. There are many papers describing the benefits of DTs (cf. section 2.1.3.5). However, only a few suggest a methodology to describe the value of a DT. Zakharchenko and Stepanets (2023) collected advantages of DTs, generalized them and clustered them in five categories: design, system interaction and integration, monitoring and diagnostic, prediction and optimization, and advanced services. It provides a good overview of the benefits of DTs, however it does neither connect them to business values or DT use cases, nor does it provide metrics to quantify them. El Bazi et al. (2023) collected benefits and clustered them according to the steps of a DT enabled value lifecycle management. Newrzella et al. (2022) on the other hand provide a methodology based on a house of quality and an “opportunity score” (Ulwick, 2005) to assess and prioritize DT use cases. While this research offers a promising framework to support the process of describing the value of DTs, no benefits are suggested that could be used to do so. In the previous empirical studies included in this thesis, the value of the DT solutions was always described based on expert interviews and was not methodologically supported. For example, in the case study on Engineering Twins for climate solutions a collection of potentials was developed. These benefits were then assigned to typical dimensions of the “project management triangle” of Atkinson (1999): improvement of quality, time reduction, and cost savings. While this is a valid clustering of benefits, these categories are still not directly related to business goals such as a quantified increase in revenue, which would be an important factor for decision makers.

Together with DT experts of the German company “:em engineering methods AG”[10] the DT

[10] *“:em engineering methods AG” is an independent German consultancy for engineering IT.*

value map was developed. The DT value map[11] is depicted in Figure 6-10. It consists of four levels. At the upper level there are the general business goals. In general, DT projects aim at increasing the profitability of a company. Profitability can be defined as a function of revenue and cost (Barbero & Zofío, 2023; Rust et al., 2002). In addition, over the last years ecological sustainability exponentially gained importance for businesses worldwide. Companies need to cope with new regulations and guidelines such as UN's sustainable development goals (United Nations Development Program, 2023), or the supply chain act of the Federal Ministry of Labour and Social Affairs (2021). Further, achieving sustainability goals is observed as a competitive advantage at the market and valued by customers (Gast et al., 2017; Kirchherr et al., 2017). By now, meeting the requirements of sustainability policies has become an essential aspect for any enterprise to operate. DTs have the potential to support companies in doing so (e.g., Edrisi & Azari, 2023). Combining these insights, the three main goals of the framework for DTs include (1) increased revenue, (2) reduced cost, and (3) improved sustainability.

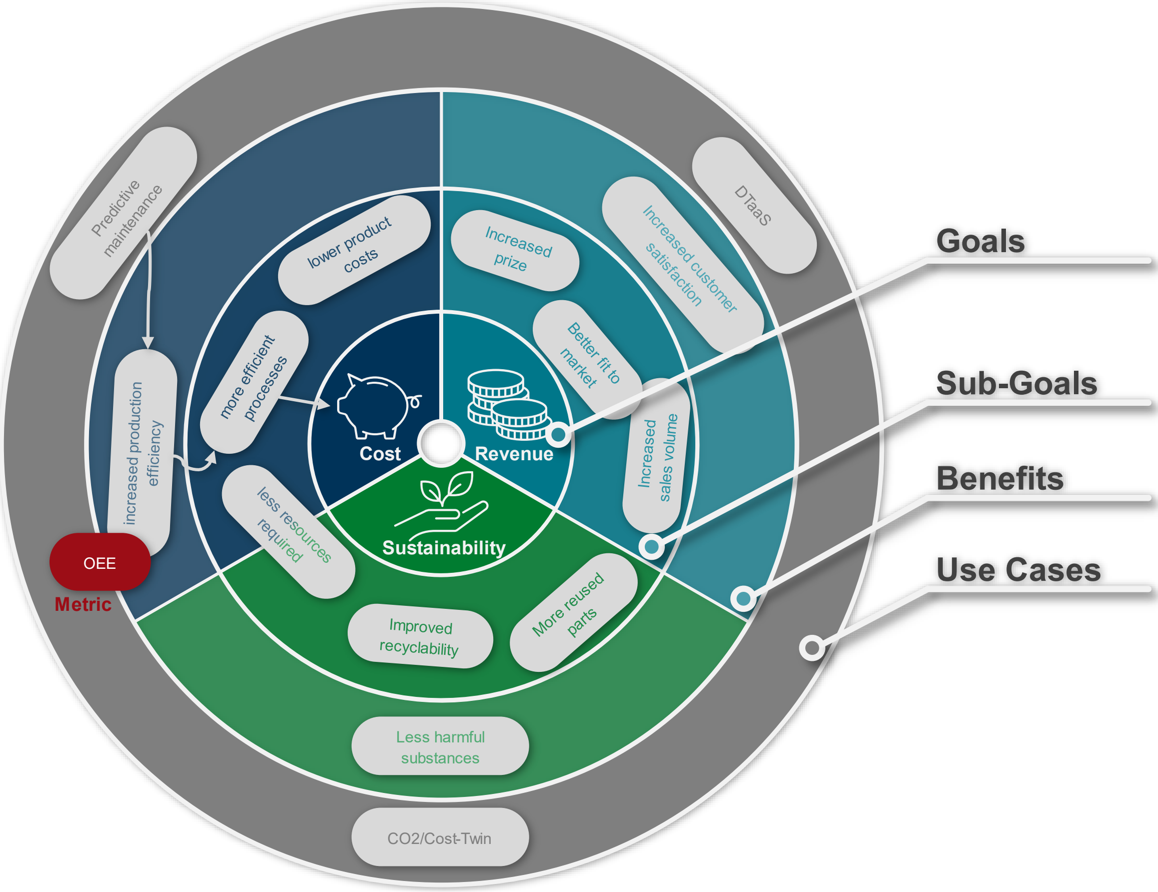


Figure 6-10: The Digital Twin Value Map with Exemplary Sub-Goals, Benefits, Use Cases, and Metrics (based on Christ et al., 2022; Schweigert-Recksiek et al., 2023).

[11] *The entire value map together with the selection matrix can be found in the appendix A8.3 and online (https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/)*

These goals can be further detailed in sub-goals. Each sub-goal can be achieved by one or several benefits of the DT solution. Further, the DT value map provides exemplary DT use cases that contribute to some of the DT benefits (cf. Figure 6-10). In addition to most of the benefits, metrics are suggested that can be used to quantify them (see Figure 6-10 in red). As an example, the case of predictive maintenance is shown. By predicting maintenance needs, downtime can be reduced, which leads to the benefit of an increased production efficiency. This benefit can be quantified using the Overall Equipment Efficiency (OEE) metric (R. Singh et al., 2013). The achievement of this benefit contributes to the sub-goal of more efficient processes and thus towards the overall goal of reducing costs.

Application Scenarios of the Digital Twin Value Map

A total of 11 subgoals and 29 benefits were included. They are connected to 17 use cases and 18 metrics (cf. Figure A 140). Due to its complexity, just from its graphical visualization, this method is not usable without software support, which is still under development at the point of time of publication of this thesis.

in the appendix depicts all elements of the value map in a matrix, showing the interdependencies between the elements. This matrix is the backbone of the selector.

There are basically two applications scenarios for the value map – a top-down and a bottom-up approach. For the former, one starts with selecting the overall goals and sub-goals that should be achieved by the DT solution. From the overall goals, the map points to specific DT benefits which are connected to use cases. The bottom-up approach refers to the possibility of comprehensively determining the value of a DT use case. Starting from a use case, which was ideated before, the map can help to identify all direct and indirect benefits that can be achieved. By deriving the subgoals and goals from the map, it can be used to put the use case at hand in relation to the overall company strategy. This can justify necessary investments, providing a means to derive further possibilities and metrics for assessing success. While the top-down scenario is focused on the ideation phases of DT projects, the latter is rather contributing to the business modelling activities and can be applied to develop the value proposition of a use case (Step 3 of DTBMA, see section 6.2.2).

As an example for the bottom-up approach, Figure A 141, Figure A 142, and Figure A 143 depict the value map applied to the case studies in sections 4.2 - 4.4. These examples highlight the potential of the value map. For instance, for the Production Twin for Aluminum Production (cf. section 4.3), the obvious benefit of the DT is to reduce costs. However, by applying the value map it becomes apparent that this use case can also lead to an improvement of sustainability and an increased revenue.

Discussion of the Digital Twin Value Map

The value map was initially evaluated and discussed with three DT experts of the :em engineering methods AG. All participants confirmed the high usefulness of the DT value map. Specifically, they emphasized that the map could be a good entry point to discuss the topic of DTs with potential customers. It is suitable to get a first impression of whether a DT would be a desirable solution to given problems. However, usability was rated low – implemented software support would be needed. Further, the map requires detailed knowledge about all elements. Therefore, it would be beneficial to develop detailed descriptions of each goal, subgoal, benefit and use case. Lastly, the value map should be combined with the DT use case catalogue (cf. section 6.2.4) to improve applicability and usefulness of both methods. Here it could complement the DT typology matrix or serve as a standalone entry ticket to identify use cases as described earlier. Further, the descriptions of the use cases involved in the catalogue should be extended by the benefits, subgoals, and goals they are contributing to. Due to time constraints, these improvements are not included in this thesis.

6.2.4 The Use Case Catalogue

Intended Use of the Use Case Catalogue

Purpose of the DT Use Case Catalogue is to enhance creativity of engineers in the conception of DT projects[12]. Similar to other analogy building methods, it provides an external perspective on DTs and should help to identify more potential applications and thus extend the solution space. This method is derived from an existing use phase data use case catalogue (cf. Wilberg, Lau, et al., 2018). Even though it has been tailored to the needs of DTs, it can also be used for the ideation phases of other data-driven engineering projects. The use case catalogue should be applied in the ideation phase of a twin project. However, it can also be used later to ideate technical solutions and to extend it. Due to time restriction, the use case catalogue is not implemented in a software application. Further, due to confidentiality issues, the use case catalogue cannot be entirely published. No specific knowledge is required for applying the catalogue and it can also be applied without DITTID.

Development and Overview of the Use Case Catalogue

Analogy building is one of the major creativity methods in design (Lindemann, 2009). As DTs are such a broad field, it is difficult to identify suitable DT solutions to given problems. Therefore, it is important to man relevant use cases as a starting point, to then cluster and prioritize them to build the final DT solution (cf. section 6.2.1). This is also true for use phase data[13] projects. Therefore, Wilberg, Lau, et al. (2018) developed a use phase data catalogue. This catalogue was developed based on literature and interviews in two industrial case studies. The overall structure of the use phase data catalogue is depicted in appendix A8.4. This catalogue already provides some filtering options: (1) Functions, (2) keywords, (3) usage data, and (4) expected benefits.

Additionally, these use cases can be filtered according to 20 uncategorized industries

---

[12] *Using the results of the use phase data catalogue of Wilberg, Lau, et al. (2018) the thesis of Schwarzburg (2021) the content of this chapter was developed. The thesis was closely supervised by the author. Due to confidentiality reasons, the catalogue itself cannot be published.*

[13] *"use phase data is the data that is generated during the use phase by the product itself (e.g., by sensors or microprocessors) or by related services (e.g., Apps, maintenance reports, or repair reports)." (Wilberg et al., 2017).*

sectors[14]. While these filters serve their purpose to function as entry tickets to IoT-use cases, they are not suitable for accessing DT use cases due to the specific characteristics of DTs. Therefore, the following novel entry tickets were developed to access the use cases of the catalogue, which are specifically suitable for DT solutions a DT Quick Check (1), a DT Typology Matrix (2), and a DT Maturity Assessment (3) (cf. Figure 6-11). The first one is the most holistic one, asking specific questions about industry sector, product lifecycle phase application area, expected benefit, and enabling data (cf. Figure A 144). The DT Typology Matrix offers the user the possibility to select use cases only based on life cycle phase and expected benefits (cf. Figure A 145). Thus, it enables a selection based on the DT topology described in section 2.1.3.2. Lastly, the Maturity Assessment sheds light on the existing or targeted capabilities of the company (cf. Figure A 146). Here, the selection is made based on the characteristics and related terms discussed in section 2.1.3.2.

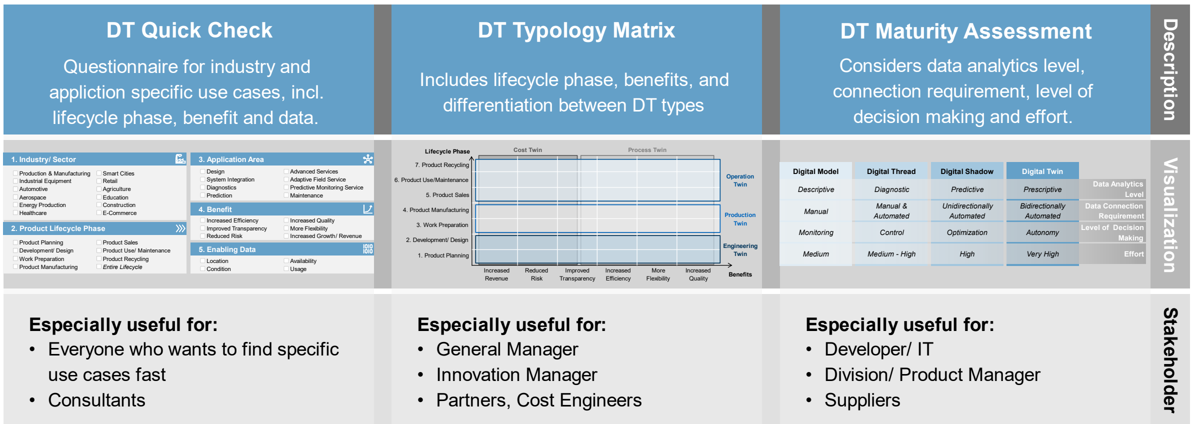


Figure 6-11: Overview of Entry Tickets of the Digital Twin Use Case Catalogue.

The industry sectors were derived from the existing clustering of Wilberg, Lau, et al. (2018) and the applications identified in industry (cf. section 2.1.3.4). For the lifecycle phases, the terms of Eigner and Stelzer (2009) were used. The application areas were selected according to Raj and Surianarayanan (2020). The benefits are only exemplary and based on literature (cf. section 2.1.3.5). In future, they should be combined with the DT value map (cf. section 6.2.3). The enabling data categories are taken from the previous use phase data catalogue (Wilberg, Lau, et al., 2018). In the maturity assessment, the related terms of DTs and their characteristics were combined with the data analytics levels described in Trauer, Schweigert-Recksiek, Onuma Okamoto, et al. (2020) and a simple effort estimation.

[14] These sectors include healthcare, agriculture, insurance, automotive, retail, manufacturing, aviation and security, to logistics, mining, energy, services, consumer goods, human, public sector, worksites, transportation environment, and marketing.

These entry tickets are used to identify the use cases in the existing use phase data use case catalogue, that are suitable for DT projects – as long as they are associated to one of the aspects covered by the entry tickets, they are considered as suitable. To identify these use cases the contribution of a use case to the beforementioned aspects, together with several industrial DT experts their connection was assessed on a progressive 1-3-9 scale (low, medium, high applicability. If a criterion is not applicable, a zero is entered. The assessment of ten exemplary use cases is shown in appendix A8.4. The concept was realized using Excel. For a given entry ticket, the user first selects the relevant dimensions, or areas. For each selection the specific values, indicating the applicability, are summed up for each use case. Thus, a score can be calculated for each use case, leading to a ranking of use cases[15].

In an implemented catalogue, this total score should not be displayed as it could convey a misleading sense of accuracy. Instead, an ABC analysis could be integrated which ranks the use cases according to their approximate significance. This ABC analysis is a practical method to simplify complexity and offers a pragmatic approach for prioritizing data (Flores & Clay Whybark, 1986). Consequently, the outcomes are categorized as highly significant (a), significant (b), and applicable (c).

Workshop Concept for the Application of the Use Case Catalogue

The DT use case catalog can be effectively implemented through a workshop. The workshop's recommended duration is approximately five to six hours. Its main audience should be specialist departments overseeing DTs, as well as other stakeholders. The inclusion of diverse stakeholders from relevant departments can enhance diversity and mitigate bias (cf. section 4.2.3). The layout of the workshop is depicted in Figure 6-12. Each agenda point includes necessary input, potential tools and methods, required materials, and involved participants.

General Information	Participants/ Guests
Time frame: 5-6 hours Objective: Empowerment of the users, application of the use case catalogue Format: preferably as a onsite event, remote should also be possible	Specialist departments Persons who can be classified as stakeholders

Agenda & Input	Time	Tools/ Methods	Materials	People
1. Digital Twins- Setting the scene Definition, characteristics, use cases	**1 h**	Pentagenda	Flip Charts	Moderator
2. The Digital Twin Use Case Catalogue Previous work, development, DT procedure model Entry tickets, digital twin frameworks	**4 h**	GAP analysis from the corporate perspective	Digital Twin Use Case Catalogue	Participants and Moderator
Break for discussion and interaction Use case selection, prototype application	*0,5 h*	Working in teams	Notebooks and Internet	Teams of 2-4 people
Use case prioritization and user journey		Action plan		
3. Q&A Session General and technical feedback	**0,5 h**	Discussion	KANBAN board	Participants and Moderator
4. Summary Conclusion, management summary, outlook	**0,5 h**	Check-Out-Questions	Pens and Sticky Notes	Moderator

Figure 6-12: Workshop Concept for the Implementation of the Digital Twin Use Case Catalogue.

[15] *Examples of this assessment can be found in appendix A8.4 as well.*

To initiate the workshop, the first agenda point introduces DTs and their context. Next, the DT use case catalogue is applied – within a four-hour time frame, four primary modules can be presented. The initial module encompasses previous work on DTs, contextual information about the catalogue's development, and an introduction to the DT procedure model. Module two outlines DT frameworks, emphasizing the characteristics of DTs and presenting the entry points of the DT catalog. Following a brief 30-minute break, fostering discussions, interactions, and team collaborations, the third module continues with use case selection within the entry points. The prioritization of use cases, as described in section 6.2.1, concludes the second agenda point. For these activities, methods like GAP analysis (Bens, 2017), or KANBAN boards (Corona & Pani, 2013) can be applied. Finally, a 30-minute question and answer session is conducted, feedback is collected, and the key takeaways and tasks are summarized.

Discussion of the Digital Twin Use Case Catalogue

An initial expert-based evaluation engaged six individuals with expertise in the development, consultation, and research of DTs. Within this group, two participants are industry experts, two are consultants, one is a co-founder of a data-driven innovation launchpad, and the sixth participant is a research associate at a German university. Overall, two evaluators rated the use case catalogue together with the entry tickets as “very good”, three as a “good”, and one as “satisfactory”. This indicates general applicability and usefulness of the approach. The entry tickets’ applicability was rated with five out of six points. Here, especially the quick check was rated as very useful, while the typology matrix received the lowest score, due to the relatively few included benefits. Concerning the conceptualization of the workshop, experts mentioned the significance of maintaining a generic structure to ensure general applicability. Nonetheless, it is noteworthy that two experts expressed concerns about the workshop’s duration, suggesting a 90-minute format instead of the initially proposed five hours. In future, the catalogue should be implemented in a software tool. Further, it should be combined with the value map as described in section 6.2.3. Lastly, the catalogue should be extended by further use cases, which are openly available (cf. section 2.1.3.4).

6.2.5 The Use Case Template

Overview and Intended Use of the Use Case Template

As presented in previous sections, a standardized documentation of DT use cases is rather beneficial (cf. sections 4.2.2, 4.3.2, and 4.5.2). Therefore, the purpose of the DT Use Case Template is to support engineers in documenting DT use cases in a comparable form[16]. Thus, it supports the application of the DITTID framework. The template should be applied for each identified use case. Its structure is designed in resemblance of the phases of the DT procedure model and is therefore closely intertwined with the procedure model (cf. section 6.2.1). Based

---

[16] *The use case template is partly based on the master theses of Mahlau (2018) and D. Fischer (2022). Previous versions of the template have been published by Schweigert-Recksiek et al. (2020) and Trauer, Pfingstl, et al. (2021).*

on the insights of the conducted case studies, the template is adapted to the needs of Engineering, Production, and Operation Twins. Therefore, it is suitable for different types of twins. Even though, it is not limited to specific industries or environments, claims can only be made about the application areas of the case studies described in Chapter 4. No specific knowledge is required for applying the catalogue and theoretically it can also be applied without DITTID. Since the instructions on how to use the template and what to enter are documented in the DT procedure model, these elements should be applied together. Furthermore, the DT business model canvas of the DTBMA is part of the template. The major benefit of the template is to enable a comparison of different use cases. Besides making use cases more comprehensible, supporting to keep the entire team informed, and helping not to forget an important aspect, it can also be used to improve trust in the DT solution (cf. section 6.2.6). Figure 6-13 depicts an overview of the DT use case template[17], which is described in detail in the following.

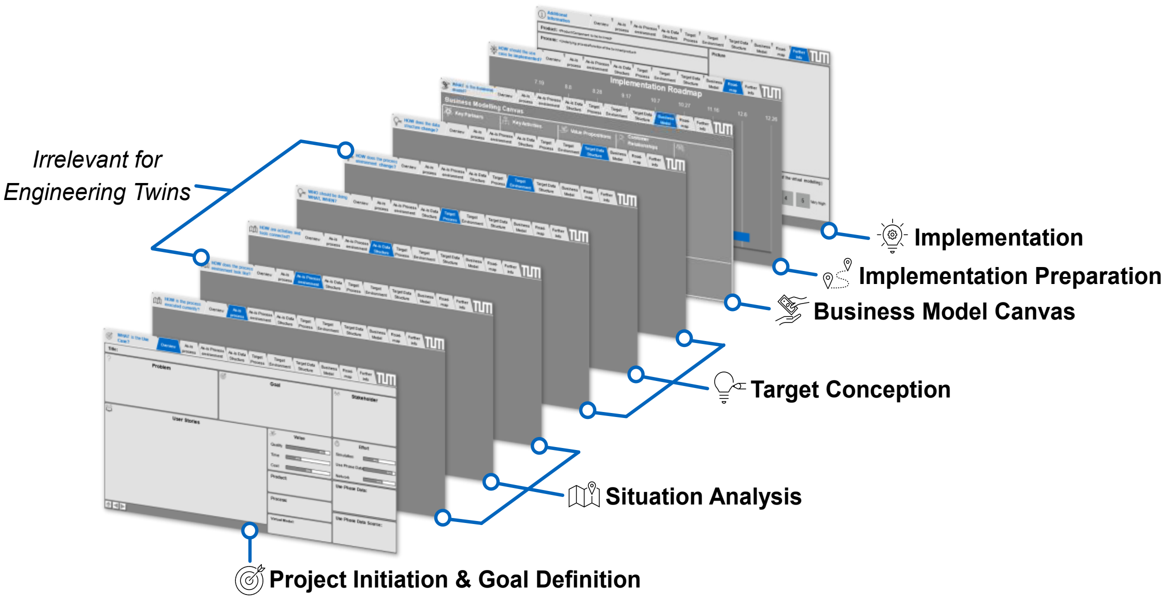


Figure 6-13: Overview of the Digital Twin Use Case Template.

Detailed Description of the Use Case Template

The DT use case template was initially developed in the case study on climate solutions (cf. section 4.2) based on a literature review, expert interviews, as well as observations from the case study. In further case studies, it was adapted to be suitable to Engineering, Production, and Operation Twins. As already mentioned, the main purpose of the template is to document all relevant information and knowledge of a use case as well as to support communication between involved stakeholders. Therefore, it was made sure to closely connect the template with the procedure

[17] *The Use Case Template is shown in appendix A8.5. As well as the other parts of DITTID, it is also published online: https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/*

model. As shown in Figure 6-13, the structure of the template resembles the main steps of the procedure model (cf. section 6.2.1). Thus, it captures the most important deliverables of the procedure model.

As a result of the first step of the procedure model *"project initiation & goal definition"*, the *"overview"* page of the template is filled for each of the identified use cases (cf. Figure 6-14). This page is valid for each type of DT. Next to the *"title" (1),* it captures the answers to the "Why?", "What?", and "Who?" in the sections *"problem" (2)*, *"goal" (3)*, and *"stakeholder" (4).* For the stakeholders it is important to include all required stakeholders, but also the stakeholders this use case originated from. The goals are further detailed in the form of *"user stories" (5)*. These user stories should cover expectations on the DT use case from all different perspectives. Based on these descriptions, the team can roughly estimate the *"value and effort" (6)* of the use case. Value is estimated in the categories: quality improvement, time savings, and cost reduction. Effort is sub-structured in effort related to the required simulations, the gathering of use phase data, and providing a suitable network for data exchange. As already described in section 6.2.1, these values do not have to be based on exact quantitative analyses but should enable to compare different use case in early stages. Lastly, additional important information such as involved products and processes, required virtual models and use phase data, as well as the source of the data are documented (7).

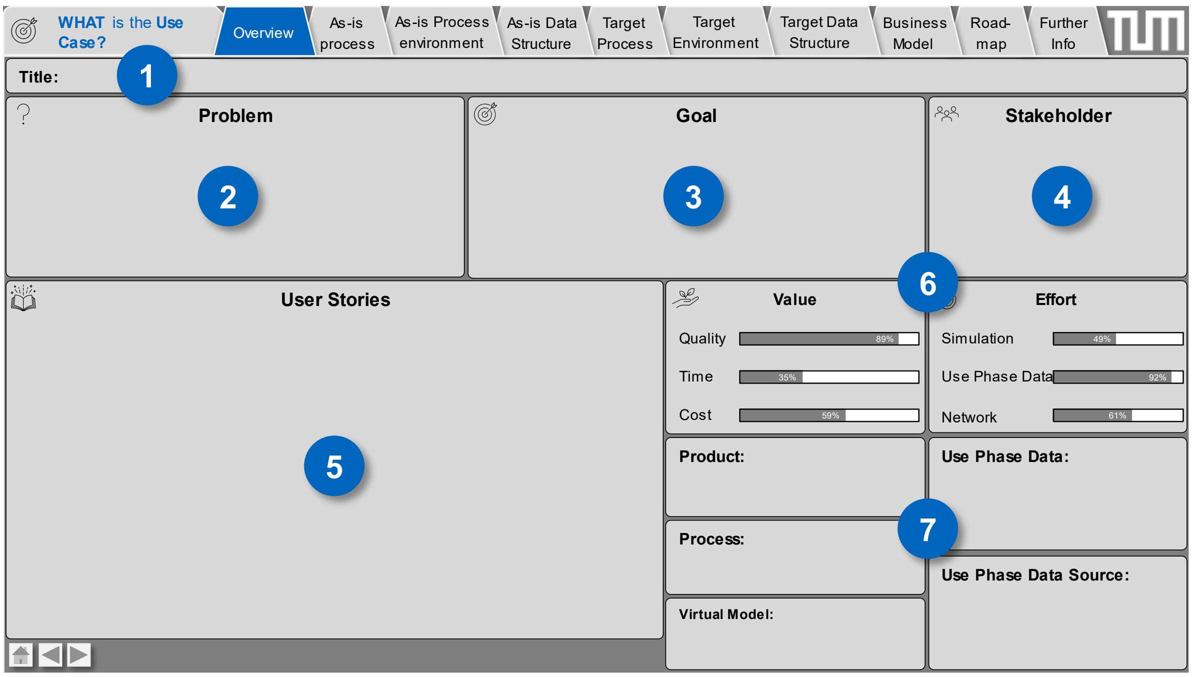


Figure 6-14: First Page of the Digital Twin Use Case Template Showing the General Overview of a Use Case. All Pages of the Use Case Template can be Found in Appendix A8.5.

Moving on to the second step of the procedure model, *"situation analysis"*, the template documents the as-is process, its environment, as well as the current data structure (cf. Figure 6-13). The process environment is especially important, when not only the real-world twin is of relevance, but also connected product, people, or processes. As engineering twins occur in the early development phases, the physical twin usually is not yet embedded in its real-life environment (e.g., the factory, or at the end customer). Therefore, the process environment can be skipped for Engineering Twin use cases and is only relevant for Production and Operation Twin use cases. The processes and structural overviews of these parts are modelled according to the procedure model (cf. section 6.2.1). The target conception is documented in the same manner as the situation analysis, including the target process, its environment, and the target data structure. Also here, the process environment can be skipped for Engineering Twins.

Before implementing the use case, its profitability has to be proven and agreed upon by the relevant decision makers. This is the main objective of the DTBMA (cf. section 6.2.2). The outcome of the DTBMA should also be incorporated in the template. Therefore, the DT business model canvas[18], is included in the tab *"Business Model"* (cf. Figure 6-13). The implementation is executed according to the implementation roadmap, which is included in the template as well as further relevant information. This last tab includes details about existing models, descriptions of the tools to be used as well as the needed parameters and properties of the desired virtual model.

Discussion of the Digital Twin Use Case Template

Clear communication of DT solutions is crucial to their success (Kober et al., 2022). The developed and presented template proved its applicability and usefulness in all conducted empirical studies. The use case template was described as "very clear" by the involved project partners (cf. sections 4.2.3 and 4.3.3). As intended, two experts explicitly described that the use case template in its structured form helped them "very much" during the ongoing sessions of the expert interviews to quickly think their way back into the DT project. This indicates the success of the template. But, as for all parts of DITTID, claims can only be made about the actually conducted applications. Therefore, general applicability of the template to any DT use case can only be assumed.

A similar "use case canvas" is presented by Saari et al. (2023). However, it focusses more on the high-level business goals and covers implementation related information in less detail. A more extensive framework form of documentation is presented by Newrzella et al. (2022) based on a house of quality for DT use cases. Although this framework seems to be suitable for the prioritization of use cases and the technical features to be implemented, it lacks specific documentation standards for the use cases.

[18] *The canvas is depicted in Figure 6-9.*

6.2.6 The Trust Framework

Overview and Intended Use of the Trust Framework

As described in section 3.2, *"setting realistic expectations and trust"* was ranked as one of the ten most problematic challenges in the implementation of DTs. Therefore, this DT Trust Framework is intended to support companies in building trustworthy relationships with their partners, and to increase perceived trustworthiness of their own DT solutions[19]. It is specifically designed for the needs of DT use cases – it considers the different parties of DT projects and the situations in which they are collaborating. Thus, the framework shows its full potential in scenarios where all stakeholders are present but is also applicable to smaller projects. Theoretically, there is no limitation regarding application scenarios. It is applicable during the development of a DT as well as after its deployment. However, it has not been tested in real life use cases. Companies applying the trust framework mainly benefit from the hands-on recommendations that help to increase the trustworthiness of their DT solutions, which is a competitive advantage. No prior knowledge is required for applying the framework and it can be used as a standalone method but is designed to be compatible with DITTID.

As described in section 4.5, the DT Trust Framework was developed based on a literature review and an interview study. An overview of the framework is shown in Figure 6-15. It consists of detailed descriptions of the stakeholders interacting in DT projects, the situations in which they collaborate as well as solution elements that can help to increase the trustworthiness of DT solutions. To increase usefulness of the framework, also concrete, executable measures were derived and assigned to the solution elements as a starting point.

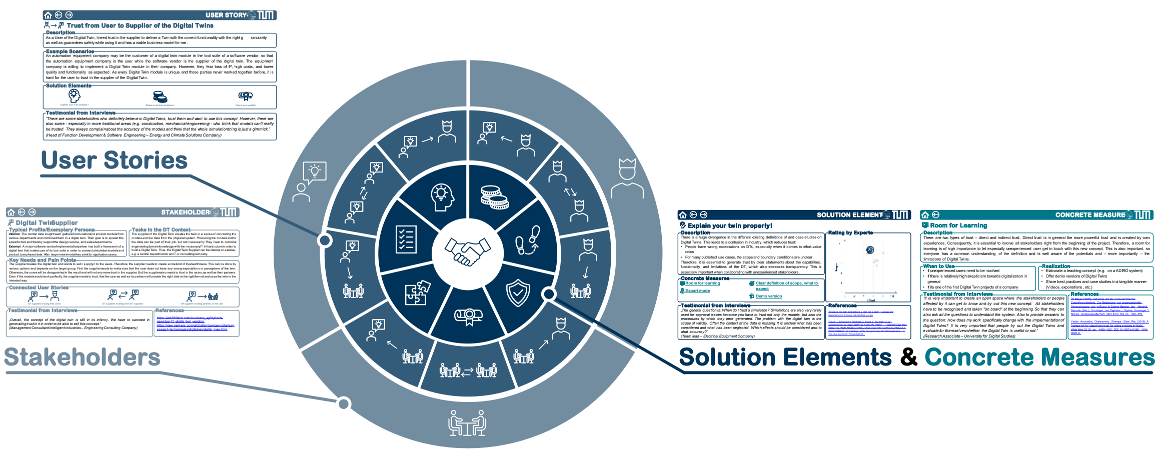


Figure 6-15: Overview and One-Pagers[20] of the Digital Twin Trust Framework (adapted from Trauer, Schweigert-Recksiek, et al., 2022).

---

[19] *Parts of this framework were already published by Trauer, Schweigert-Recksiek, et al. (2022).*

[20] *The one-pagers are exemplarily shown in appendix A8.3. Due to confidentiality reasons, the entire framework cannot be published. A reduced, approved version of the framework can be found online: https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/*

Stakeholders of Digital Twin Projects

As already stated in section 4.5.2, in the context of Digital Twins (DT), there exist three fundamental stakeholder categories: The DT Supplier, the User, and the User's Partners. All of these roles can be either internal, involving various departments or teams within the same organization, or external, including business collaborators from different companies (cf. Figure 6-16).

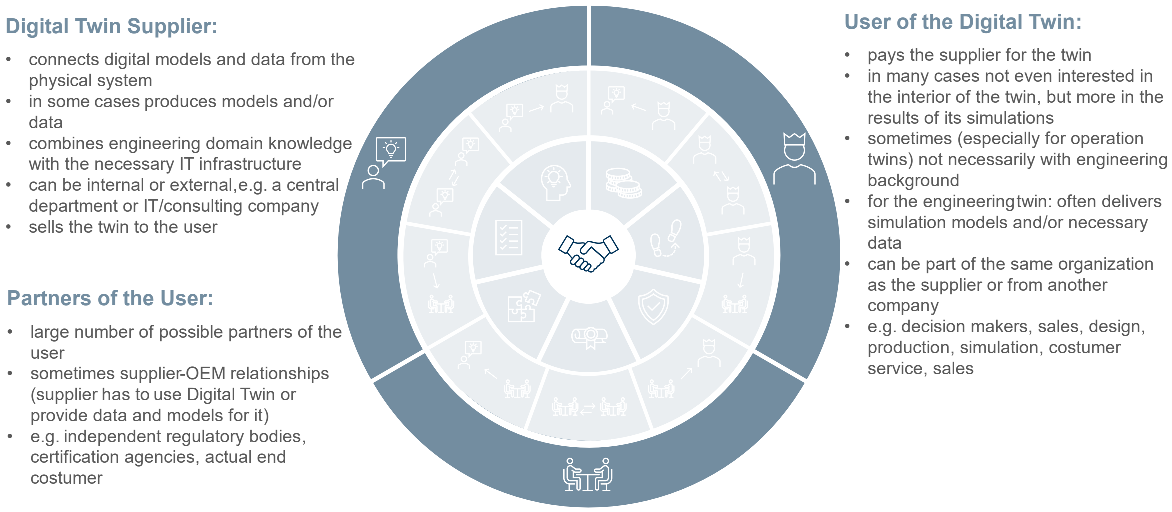


Figure 6-16: Typical Stakeholders in Digital Twin Projects.

A **Digital Twin Supplier** is responsible for constructing the twin by connecting physical system models and data. Their job might include creating model types and/or data, yet this isn't always a requirement. They need a blend of engineering domain knowledge and IT infrastructure to build and offer the DT to users. The supplier's origin can be internal or external, spanning from an in-house department to an IT or consulting company. For example, an *internal* supplier could be the central data insight team gathering simulation and product models from various departments and combining them in a DT. Their goal is to spread this powerful tool and thereby support the design, service, and sales departments. An *external* supplier on the other hand could be a major software vendor/implementation partner offering a framework of a DT that makes use of its tool suite in order to connect simulation models and product (use phase) data.

Regarding trust, the supplier creates the DT and wants to sell / supply it to the users. Therefore, the supplier needs to create some kind of trustworthiness. This can be done by various options and depends on the target group. First the supplier needs to make sure that the user does not have any wrong expectations or perceptions of the DT. Otherwise, the users will be disappointed in the result and will not any more trust in the supplier. But the supplier also needs to trust in the users, as well as their partners. Even if the models would work perfectly, the supplier needs to trust that the user as well as its partners will provide the right data in the right format and uses the twin in the intended way.

The **User of the Digital Twin** is the buyer of the DT who pays for its benefits. Often, users are primarily concerned with the results of the DT's simulations rather than its internal workings. This is particularly true for operation twins. For engineering twins, the user might need to provide simulation models or necessary data to the supplier, as these are part of their domain expertise. The user can be part of the same organization as the supplier or from an external company. Their roles could include decision-makers, salespeople, or professionals in design, production, and simulation. An exemplary user could be the head of the R&D of an automation equipment company approaching a software vendor to build a DT of their products. He/She has informed himself/herself about the possibilities of DTs and has a basic understanding of the (data) models, IT infrastructure, and use phase data. He/She wants to know how the DT works in principle, but at a certain point in the project, once trust has been built, he/she focusses on the use cases and leaves the implementation to the software vendor.

In both the creation and implementation as well as during the usage of the DT, the user has to share a lot of unique know-how and domain knowledge with their partners and especially the supplier. This leaves them vulnerable to know-how loss and IP theft. Therefore, next to the functionality of the DT, a major need of the user is data safety. This also affects collaboration with partners, as suppliers have to deliver models in the right granularity, with the right functionality and with clear and safe interfaces for the DT to work as well as to ensure data safety to the user.

Partners of the User can encompass various entities. They might include independent regulatory bodies, certification agencies, or the end customers (consumers) utilizing the system mirrored by the DT. These partners are of particular relevance in supplier-OEM (Original Equipment Manufacturer) relationships. Once the OEM decides to use a DT, next to the products the partners of the OEM have delivered to their customer for years, they are now also asked to deliver CAD and simulation models as well to feed the DT.

In such a constellation, the main concern of partners of the DT User is data security and the threat of losing knowhow – often, the building of the required models and the generation and analysis of the respective data are the core know-how of the supplier. This is especially true as the partners do not make data and models available to the user, but also to the supplier of the DT and other partners, enlarging the associated risks.

User Stories of Situations in which Stakeholders are Collaborating

Trust-building among the beforementioned stakeholders is crucial across various scenarios. To develop situation specific trust enhancing solutions, user stories were formulated covering all possible combinations of stakeholder (cf. Figure 6-17). One of the most common and relevant user stories in this context covers situations in which the users of the DT need to trust the suppliers of the DT. Here, one of the industry partners stated for example: *"[...] there are also some [...] who think that models can't really be trusted. They always complain about the accuracy of the models and think that the whole simulation thing is just a gimmick."* (Vice President Methods, Analyses & Materials – Aerospace & Defense Company). All interview statements clustered by stakeholders, user stories, and solution element can be found in appendix A6.3.

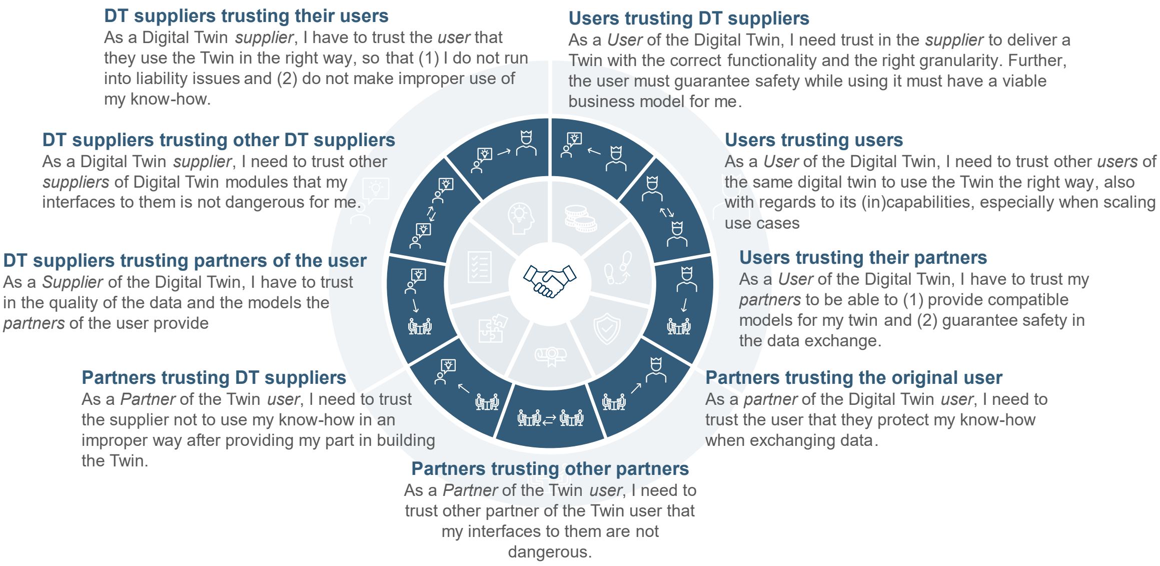


Figure 6-17: User Stories of Situations in which the Different Stakeholders have to Trust each other (adapted from Trauer, Schweigert-Recksiek, et al., 2022).

Solution Elements and Concrete Measures to Develop Trust

At the core of the framework are the solution elements with concrete measures that can be taken to achieve these (cf. Figure 6-18). As described in section 4.5.2, seven elements were identified based on literature, an interview and a market study.

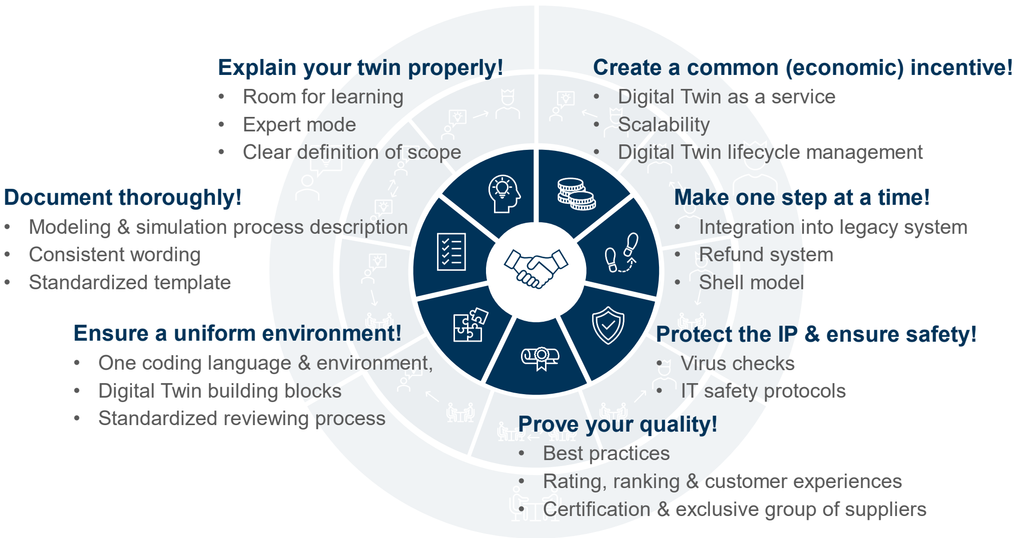


Figure 6-18: Solution Elements with their Respective Concrete Measures to Create Trust in Digital Twins (Trauer, Schweigert-Recksiek, et al., 2022).

Explain your twin properly! As described earlier, the ambiguity of definitions and case studies about DTs, leading to confusion and misinterpretations, is still present. This ambiguity affects trust, particularly regarding the value proposition of the DT. Therefore, establishing trust requires clear communication of a DT's capabilities, limitations, and functionality. This is especially important when dealing with inexperienced stakeholders. To achieve this, transparency can be enhanced by offering room for learning, an expert mode, allowing users to delve into the DT's source code, or a clear definition of scope. These concrete measures enhance trust by demonstrating openness.

Create a common (economic) incentive! Based on the insights of the market analysis, a shared economic incentive is an effective strategy for building trust – If there is doubt in the equal motivation of the stakeholders to further drive the DT project even after implementation, trust will be reduced. With a common incentive it is ensured that stakeholders will invest resources throughout the life cycle of the DT, benefiting all parties. As one of the interview partners stated: *"[...] In the end, it is important to have a community that shares the same intentions. This improves trust."* (General Manager - Automation Engineering Company). This solution element can be achieved e.g., by offering a "DT as a Service" (Aheleroff et al., 2021) instead of a "single-use" product. Also a complementary DT Lifecycle Management (Durão, Luiz Fernando C. S. et al., 2018; S. Singh et al., 2020) embodies this concept. Saari et al. (2023) suggest a "joint offering" business model for DT use cases.

Make one Step at a time! Due to the broad and complex nature of DTs, stakeholders often struggle in its realization, which increases mistrust. As the Vice President for methods, analyses and materials of a large aerospace and defense company stated, *"Incremental development. Demonstrate capabilities, first do compact small projects at the beginning where you can look at very defined topics and show benefits and added values very quickly."* Addressing this, incremental steps are crucial to reduce risks and enhance stakeholder understanding. This approach also facilitates consistent feedback, promptly addressing emerging concerns. The previously presented shell model (Trauer, Schweigert-Recksiek, Engel, et al., 2020) or implementing refund systems, as it is done by Steam (Valve Corporation, 2023), are potential strategies.

Protect intellectual property (IP) & ensure safety! Given the extensive data exchange required for DT operation, robust IT security and IP protection are paramount. Failing to address these aspects may reduce trust. Early adoption of measures such as IT safety protocols and virus checks, in alignment with modern data security practices (Rasheed et al., 2020), are exemplary concrete measures to contain trust.

Prove your quality! *"[...] Because trust can only develop if you have experiences."* (Project Lead Digital Manufacturing – Digital Industries Company). As the DT landscape evolves, stakeholders, users, and third-party partners will collaborate extensively. In this competitive environment, trust is cultivated through consistent demonstration of reliability. Transparency is essential, and showcasing best practices, ratings, rankings, and customer experiences can help to increase trust. Notably, as Utz et al. (2012) investigated, credible customer reviews have a stronger impact on trustworthiness than assurance seals. Also, Schwarzburg et al. (2024) found out, that in the area of modelling and simulation, trust in the modeler is more important than trust in the model.

Ensure a uniform environment! As DTs rely on diverse models and data from various sources, a lack of transparency can lead to mistrust in the DT's capabilities and security. Yet, when a foundational level of trust exists in the environment, it naturally extends to the DT module itself. This concept draws parallels from appstores, where a standardized (development) environment ensures a basic quality level among developers. Therefore, stakeholders should adopt a unified coding language and environment, establish a standardized review process, and ideally offer DT building blocks.

Document thoroughly! Given the complexity of DTs involving multiple stakeholders, comprehensive documentation becomes imperative. This is particularly crucial for stakeholders joining later stages or utilizing existing twin modules. Thorough documentation aids in understanding the DT's functionality, enables maintenance, and fosters transparency. Here, the DT Use Case template (cf. section 6.2.5) could serve as a standard for documenting DTs.

To connect these elements with the user stories, a pairwise comparison was conducted in collaboration with the research project partners. Each element was compared to the others in terms of its usefulness for a specific user story. The three highest-ranks elements for each user story were selected and are presented in Figure 6-19a[21]. Additionally, the impact of a solution element on trust and the effort required for its implementation was assessed by the interview partners. The findings are depicted in Figure 6-19b.

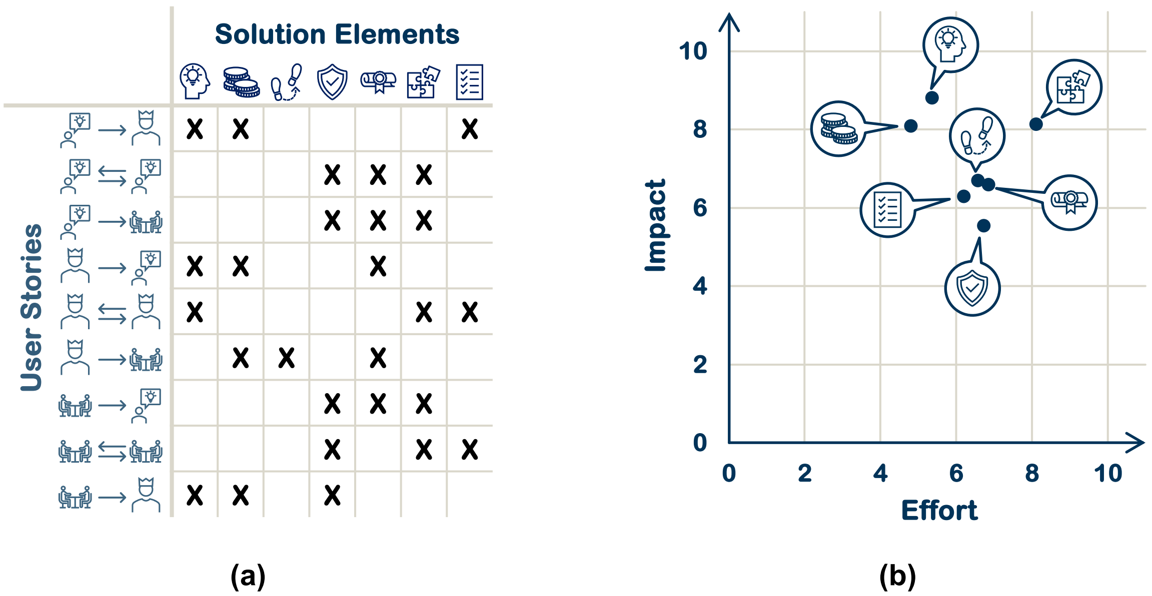


Figure 6-19: (a) Assignment solution elements to user stories. (b) Estimated impact and effort of the solution elements as rated by the interview partners. (Trauer, Schweigert-Recksiek, et al., 2022).

[21] *The pairwise comparison is shown in appendix A8.3.*

7 Evaluation of the Systematic Support

7.1 Application of the Systematic Approach in a Student Course

7.1.1 Design of the Practical Student Course

Each part of DITTID was initially evaluated throughout the empirical studies. However, these evaluations never covered the final versions of all methods and approaches. Additionally, they have never been applied together. Therefore, no assumptions about the contribution of DITTID towards lowering the challenges identified in Chapter 5 could be made. Therefore, a practical student course was developed and conducted in order to initially evaluate the contribution of DITTID[1].

The course took place in February 2023 and eight students from different departments of the Technical University of Munich participated. The course was part of their curriculum and they received credits for participating. Motivation for this course was not only to transfer the technical knowledge of DTs but also the practical engineering design knowledge for practical work. For such objectives the format of project-based learning (PbL) is suitable (Frank et al., 2003; Hagedorn et al., 2023). Especially the work of Hagedorn et al. (2023) inspired the layout of this DT course.

The two-week course was structured as follows (cf. Figure 7-1). On the first day, a general introduction to DTs was given, accomplished by two keynotes on DT-driven design and IT-Architectures for DTs. At the end of the first day, a short hackathon was conducted to get to know the participants, their way of working, strengths, and weaknesses. In addition, as proposed by Hagedorn et al. (2023), an online survey was conducted to get a detailed view on the initial knowledge of the students (cf. appendix A9.2). At the second day, the task description for the practical course was communicated and the students received an introduction to the demonstrator and the IoT platform. As this course was meant to evaluate DITTID, the students were split into four teams of two, based on the results of the pre-test and the hackathon[2]. Care was taken to distribute the students as evenly as possible regarding prior knowledge and performance in the hackathon to ensure comparability of the teams. Then two teams were randomly selected to receive DITTID with all associated methods as input. The other two teams only received a general introduction to the high-level procedure model described in section 6.2.1. Thus, it was possible to track the progress of all four teams according

[1] The course material can be found online: https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/

[2] They were assigned to the teams based on semester, experience with DTs, technical, and social skills. Therefore, all teams were equally capable of succeeding in the course.

to the phases of the procedure model, while still being able to observe the effect of DITTID on the two selected teams. The task description was derived from the previously developed case study scenario described in section 4.4.2. The students were provided with a general description of a fictional company "Zwillingsbräu GmbH" (cf. appendix A9.1). Further, they received the personas of four exemplary stakeholders, who all have their own pain points and needs, regarding the implementation of a DT. The teams were asked to act as a taskforce at the company with the objective of developing a DT strategy matching the needs of the company and the stakeholders and showcasing its value in minimum one implemented use case.

Over the following eight working days the students did not receive any more additional input. However, the author of this thesis supported all teams in all technical and conceptional questions. At the end of each day a daily standup meeting was conducted to track the progress of the teams and to solve urgent technical problems. These standups replaced the interims test, suggested by Hagedorn et al. (2023). On the last day of the course each team presented their DT solution for the given objective in front of seven experts who assessed the teams[3]. The assessment was based on the factors (1) business value, (2) technical feasibility (i.e. the feasibility of the solution in a real world setting), (3) extent of implementation, (4) innovativeness, and (5) overall value. Finally, the students were asked to fill a "post-test" (cf. appendix A9.3), matching the online survey they filled at the beginning of the course. Thus, it was possible to track their learning progress and to ask for feedback regarding DITTID.

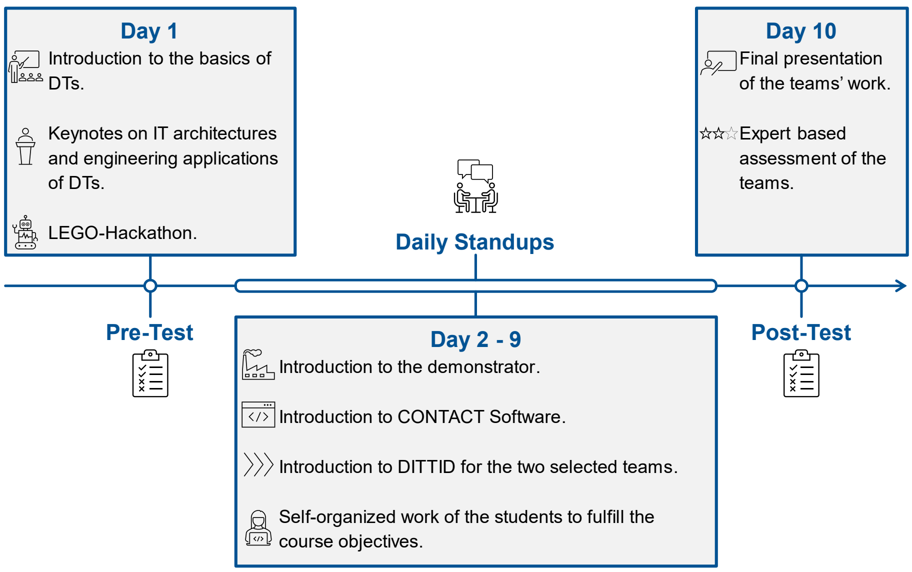


Figure 7-1: Structure of the Practical Student Course on the Conception and Implementation of Digital Twins.

[3] *These DT experts consisted of a professor for product development, two research associates in the field of DTs, an sales representative of a software vendor, a consultant for DTs of the company :em engineering methods AG, as well as two experts from ADIRO Automatisierungstechnik GmbH.*

7.1.2 Demonstrator for the Practical Student Course

As a demonstrator, the model bottle filling plant, described in section 4.4.1 was used. However, based on the results of the first empirical study, several modifications had to be made. Figure 7-2 depicts the modified demonstrator. To fulfill the criterion of bidirectionality, a 3/2-way solenoid ball valve was implemented. Thus, it is possible to automatically switch the filling mode from upper to lower, if needed[4]. Further, an energy monitoring system was implemented to also gather data on energy consumption of the system. Finally, more manual valves were implemented to allow the simulation of clogged pipes at different positions in the circuit.

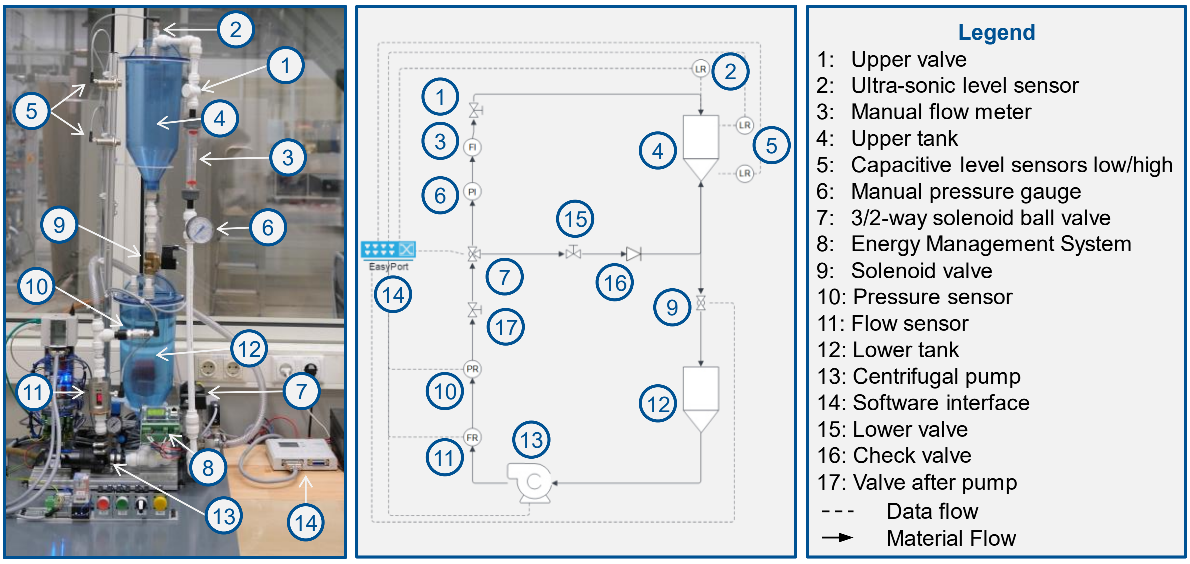


Figure 7-2: Overview of the Modified Demonstrator for the Practical Student Course.

The data collected by the EasyPort (number 14 in Figure 7-2) is converted on a Raspberry Pi in a JSON[5] format and transmitted using MQTT[6] to a database. Connected to the database is the CONTACT Software IoT platform (CONTACT Software GmbH, 2023), which is used to depict the data in dashboards and to develop and execute the DT modules. The system as well as the results of the student teams are not described in detail, as they are not relevant to the evaluation of DITTID and the course.

---

[4] *The filling modes are described in section 4.4.2.*

[5] *According to Bray (2014), JSON (JavaScript Object Notation) is a lightweight and text-based format for exchanging data, independent of any specific programming language. It includes a concise set of formatting rules to portray structured data in a portable manner.*

[6] *According to Atmoko et al. (2017), the MQTT (Message Queuing Telemetry Transport) protocol enables seamless communication between machines. One of its key characteristics is its efficiency in terms of data packet size, reducing the energy consumption required. The protocol is characterized by its utilization of a publish/subscribe model, which differs from the traditional client-server approach.*

7.1.3 Results of the Evaluation of DITTID and the Practical Student Course

As mentioned before, the purpose of this student course was twofold – (1) providing an effective teaching concept for DTs based on PbL and (2) evaluating the effect of DITID on the development process of DTs. In order to assess the success of the first objective, the self-assessment of the students in the pre- and post-test were compared. Here, the students were asked about how familiar they are with DTs (conceptual knowledge), and to what extend they think, they would know what must be done to develop a DT (procedural knowledge). The results are shown in Figure 7-3. The red marks depict the average of the students votes. Based on this analysis, the effectiveness of the course format in teaching basic concepts of DTs and approaches to develop DTs, can be confirmed. In open feedback, the students especially emphasized the practical project-based format and open task description as helpful for the learning effect.

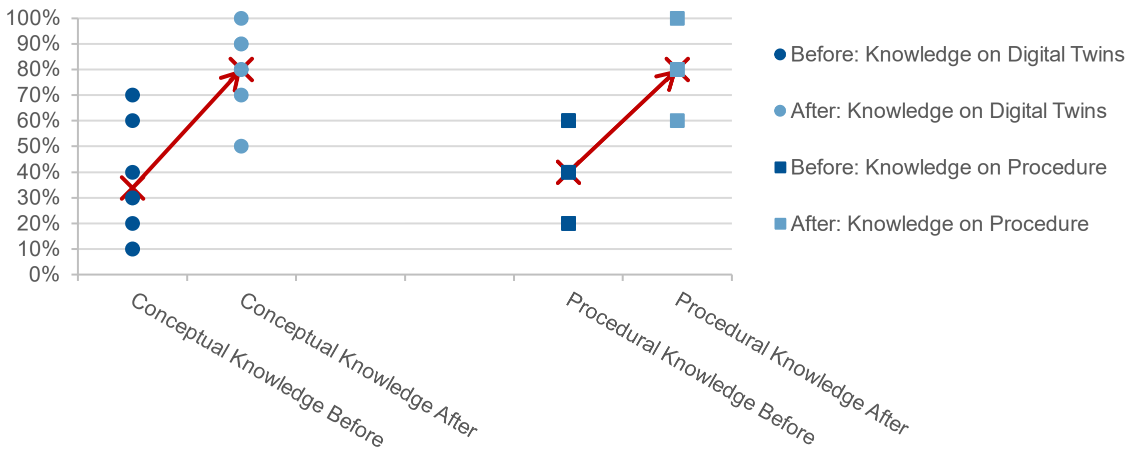
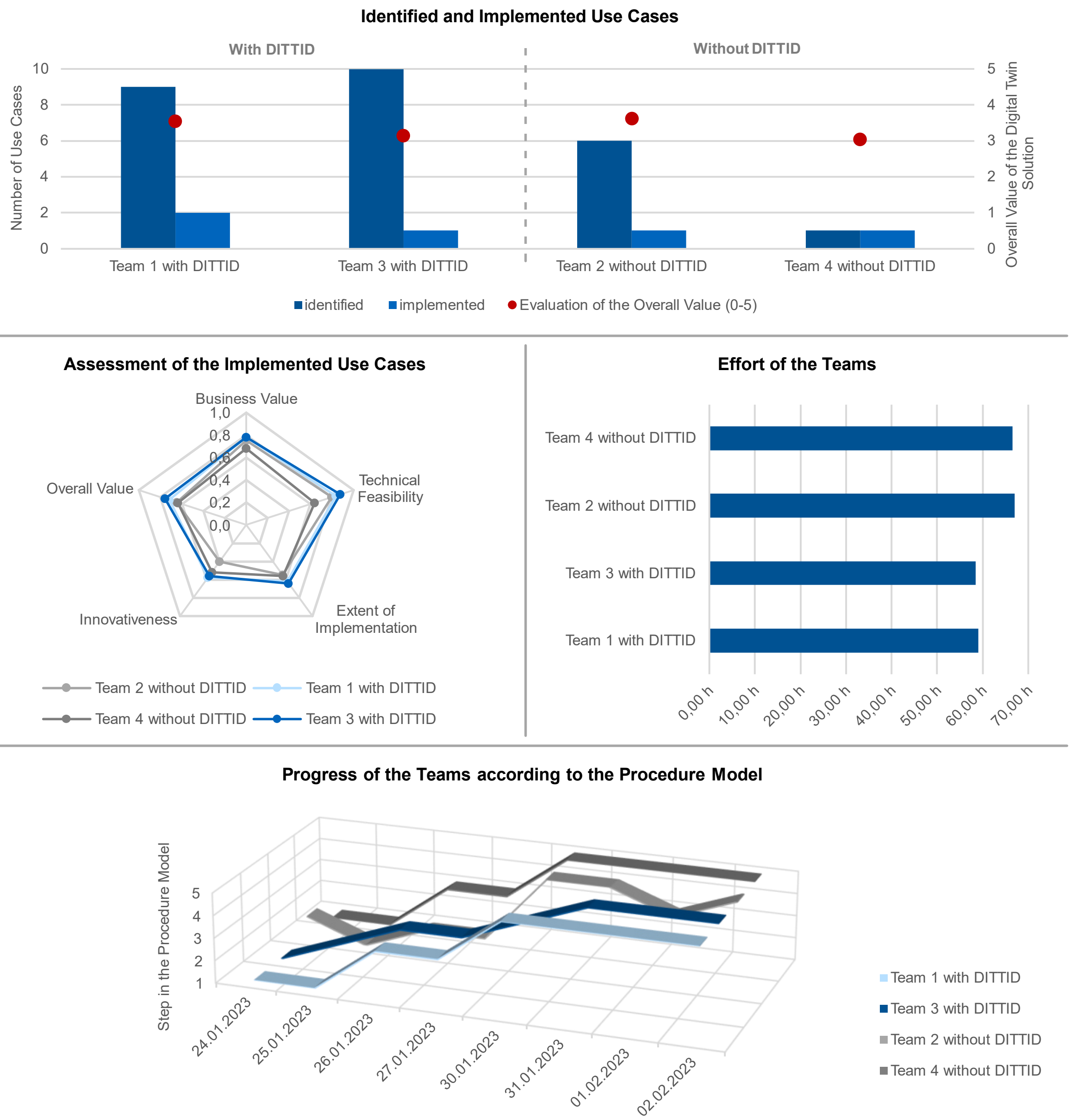


Figure 7-3: Teaching Effect of the Practical Course based on the Questions "How familiar are you with Digital Twins?" and "To what extent do you think, you would know what must be done to develop a Digital Twin?". The Red Marks Depict the Average Values.

To get an initial understanding of the effect of DITTID on the performance of the teams, three basic metrics were derived in accordance with the objectives of this thesis described in section 1.4.. DITTID is supposed to support engineers in order to develop DTs with (1) a higher overall value, (2) in less time, and (3) with less iterations. For the first goal, the assessments of DT use cases made by the experts were analyzed. As shown in Figure 7-4 in the top and on the left, the teams who applied DITTID, received higher rankings for the overall value of their solution. Especially in terms of technical feasibility and innovativeness, they succeeded their competitors, as they were considering integration in the legacy system more thoroughly but at the same time came up with more surprising solutions. Interestingly, the teams with DITTID also identified more suitable DT use cases and were able to implement more use cases which also leads to the next objective. Regarding the development time, the effort of the teams was tracked by using a time tracking tool. Here, the teams who used DITTID required on average 12 % less development time. To keep track of iterations, the progress of the teams regarding the steps of the procedure model was captured (bottom of Figure 7-4). This analysis is made based on the daily standups, and the Kanban boards used by the teams. While team 2, who did not use DITTID had two small drawbacks at the beginning and the end, all other teams proceeded without any iterations. Therefore, no effect of DITTID regarding iterations could be observed.



	24.01.2023	25.01.2023	26.01.2023	27.01.2023	30.01.2023	31.01.2023	01.02.2023	02.02.2023
Team 1 with DITTID	1	1	3	3	5	5	5	5
Team 3 with DITTID	1	2	3	3	4	5	5	5
Team 2 without DITTID	2	1	2	2	5	5	4	5
Team 4 without DITTID	1	1	3	3	5	5	5	5

Figure 7-4: Effect of DITTID on the Performance of the Student Teams. Top: Identified and Implemented Use Cases per Team and the Overall Assessment of the Use Cases. Middle Left: Assessment of the Digital Twin Use Cases by the Experts. Middle Right: Effort Spent by the Teams to Develop their Digital Twin Solution. Bottom: Progress of the Teams according to the Steps of the Digital Twin Procedure Model (cf. section 6.2.1).

In addition to these metrics, in the post-test the teams applying DITTID were directly asked to provide feedback on the included methods and approaches (Figure 7-5). First, the students were asked to generally and subjectively rate the usefulness of the elements of DITTID on a scale from 1 (not at all) to 6 (absolutely). The average values are depicted on the left of Figure 7-5. Here, the Procedure Model and the Business Modelling Approach are ranked highest, whereas the usefulness of the Trust Framework and the Value Map are rated low. However, no team applied the Trust Framework in the course, and the Value Map was provided without the selection support, described in section 6.2.3.

Additionally, six specific statements were presented to the students, and their agreement with the statements was recorded (cf. Figure 7-5, right). All elements indicate a high usefulness of the methods of DITTID[7]. Only, the statement "the methods are useful to develop better DT use cases" received medium acceptance, which contrasts with the previously presented metrics indicating higher quality of the use cases developed with DITTID (cf. Figure 7-4). In open feedback, students particularly praised the clear approach and procedural support offered by DITTID (cf. appendix A9.4). In addition, the templates for the methods were considered helpful. On the other hand, it was criticized that some of the methods and approaches were too complex and that some were not applicable or assessable in the short period of the internship.

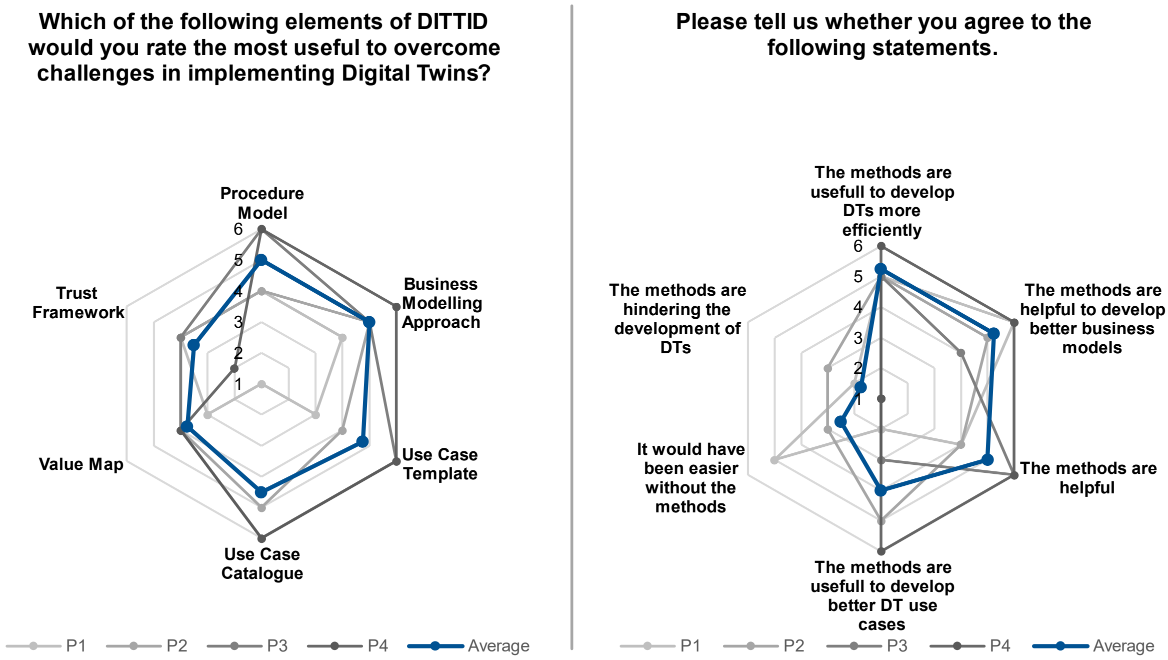


Figure 7-5: Feedback Gathered from the Students who Used DITTID on the Usefulness of the Provided Methods and Approaches. The Blue Line Indicates the Average Rating.

[7] *Also here, the participants were able to indicate their agreement on a scale from 1 (not at all) to 6 (absolutely). To check for random answering, two of the six options were formulated negatively. Here, a disagreement confirms usefulness of the solution.*

7.2 Discussion of the Systematic Approach

The purpose of the practical student course was to get initial indications of the success of DITTID. In this section, the evaluation as well as the systematic approach for the conception and implementation of DTs is discussed. Overall, the practical application in the student course showed the general **usefulness** of DITTID. Teams who applied DITTID developed their DT solution in less time while achieving better assessment results.

The time reduction of the teams with DITTID compared to the ones without as measured within the course (cf. Figure 7-4) supports the assumption made in Chapter 5 that having a clear **procedure model** with associated methods and tools will lead to an improvement of the identified challenge *“Development and deployment time and resources required”*. While all teams followed the five steps of the procedure model, only the teams with DITTID received the model with complete descriptions and methods. Regarding unnecessary iterations no effect could be observed, as all teams progressed in similar ways. Only team two started with a detailed analysis of the current demonstrator before identifying suitable use cases. This might be the case due to the short timeframe of the course and the academic setting, where the procedure was relatively clear. In large industrial projects, this might be different, which would underscore the importance of a clear glidepath. Additionally, the procedure model should be flexible enough to be applied in various situations (cf. Chapter 5). This cannot be confirmed directly by the evaluation results. However, over the course of the empirical studies and the practical course, the procedure model was applied and adapted to Engineering, Production, and Operation Twins in various industries (heating systems, aluminum production, and process industry). In all these applications, the procedure model showed its positive effects – i.e. a guidance for novices, time reductions, and few iterations. Therefore, it can be assumed, that it is suitable to these situations and might also be adaptable to other types of DTs.

Analyzing the assessment results in Figure 7-4 (middle, left), it is noticeable that the teams that used DITTID outperformed the other teams, especially regarding technical feasibility. The technical feasibility was assessed in the final presentation by the DT experts and referred to the potential of the suggested solution to work in a real-world setting. This supports the assumption that deriving a target concept based on a detailed analysis of the as-is situation, as proposed in the procedure model, improves feasibility of the solution. Further, it supports the overall usefulness of the **use case template**, which is also designed to support *“integration of the DT in the legacy system”*.

Also, in terms of innovativeness, the students applying DITTID outperformed the others (cf. Figure 7-4, mid-left). This indicates the effectiveness of the creativity enhancing elements of DITTID. Especially, in the identification of use cases. The DITTID teams identified more use cases by applying the **use case catalogue** to the course scenario. As shown in Figure 7-4 (top), this also led to a higher overall performance of the proposed DT solution. Consequently, the number of identified use cases appears to have an influence on the quality of the solution – Team 4 identified only one use case and received lowest rankings in the assessment. This is a reasonable assumption. Team 4 focused on the realization of the one use cases in detail from the start, before laying out an overall strategy or comprehensively assessing the suitability and value of the use case.

Lastly, the strong performance of the DITTID teams in terms of business value and overall value shows the usefulness of the **business modelling approach** and the **value map**. *"Identifying clear and valid value propositions associated to the DT"* was identified as one of the major challenges in previous studies. In the course of this evaluation however, the experts underscored the understandable and convincing description of the added value of the DT solution based on the DTBMA.

Nevertheless, the usefulness of the **value map** was rated low by the students themselves (cf. Figure 7-5, left). The value map was also considered to be too complicated, and not applicable, as no tool and selection support was provided. However, the value map was further developed after the course to improve its applicability, which is not included in this thesis. Further, the usefulness could already be confirmed in other industrial projects. For example, it is actively being applied in industrial projects, for example by Mahle GmbH (Humpa, 2023).

Same accounts for the **trust framework** – based on the students' feedback, usefulness cannot be confirmed (cf. Figure 7-5, left). However, the trust framework was not actively applied in the evaluation, because it was too complicated, and a lack of trust was no pain point of the exemplary personas. Further, the trust framework is designed for large DT projects including several industrial stakeholders from different companies, which was not part of the practical course and would be difficult to achieve. Nonetheless, the initial evaluation conducted in the empirical study with Siemens (cf. section 4.5.3) confirms the usefulness of the framework. Siemens further stated that they are actively applying the framework in their projects.

Applicability and **usability** were not directly analyzed within the evaluation. Nonetheless, some observations could be made. The applicability of the elements of DITTID have already been confirmed in previous empirical studies, with regard to the application scenarios mentioned before. Within the evaluation study, the compatibility of the elements among each other could be observed. Further, for the first time, DITTID was applied by DT novices and was still applicable – this confirms that there are no restrictions regarding previous experience. However, two students suggested including more specific examples for each element of DITTID, to support applicability. So far, there are no indications contradicting general applicability of DITTID.

The general usability of DITTID could not be confirmed. For the student course a prototype of software support was developed and applied. However, many templates and tools were not directly usable, or had to be adapted before use. For example, one student stated, *"The structuring in the app was not quite intuitive for me and the individual pages [are] also very full at first glance."*. Therefore, usability is the strongest limitation of the approach.

Finally, as a result of the evaluation study, the conducted practical course could be confirmed as a suitable and effective **teaching concept** for DTs. The students especially emphasized the positive effects of the project-based format with the hands-on demonstrator. Further, the daily standup meetings, the hands-on demonstrator and the open task were complimented. For an application of the teaching format in an industrial setting, it would be necessary to shorten the format to a one- or two-day workshop with limited practical aspects. Further, it would be beneficial to use demonstrators related to the operating field of the company at hand.

Limitations of the Evaluation

While the initial evaluation was successful, there are some limitations to the results. First and foremost, the significance of the results is strongly limited by the small sample of participants. Only eight students participated. Therefore, only four teams could be built and observed. This hinders any significant statistical analysis. Consequently, only first indications could be observed, and assumptions based on these observations be made.

Another limitation lays in the missing experience of the students. While all students were in their masters, and half of them already had experiences with DTs in their studies, there is still a difference compared to experienced industry experts. According to Atman et al. (2007), the most significant difference between students and experts in engineering design projects, is that experts spent way more time in problem scoping and defining activities, than student teams. Also, within this practical course, the student teams spent approximately half of the time on implementing their use case and only one or two days on problem scoping (cf. Figure 7-4, bottom). Thus, in an industrial setting this might look differently and might lead to more iterations in the process (Atman et al., 2007). Another finding of Atman et al. (2007) is that experts tend to gather more information than students, and build a more comprehensive and divers information model to develop their designs. However, within this practical course, the students still were able to develop convincing technical and business concepts. This shows that one of the major strengths of DITTID is to guide even unexperienced engineers in DT projects.

The format of the student course is also a limitation to the evaluation. Due to the limited timeframe of two weeks and the academic setting, DITTID could not reach its full potential. For example, the DT trust framework was not applied by the student teams. Also, in the procedure model and the DTBMA some activities were skipped by the student teams. While this demonstrates the flexibility of these approaches, it reduces significance and scope of the evaluation. This was even exaggerated as many unexpected failures of the IoT system occurred during the course. Therefore, the students had to spend a lot of time on unnecessary troubleshooting or could not test because of downtimes of the system.

8 Conclusion

8.1 Summary

The overall objective of this thesis was to develop a solution approach including processes and methods to **support engineering companies to design and implement DTs more efficiently and with a higher quality**. DTs are one of the major trends in engineering design and a fast growing research field (Isaksson & Eckert, 2020). Even though the concept is known for more than two decades, there are relatively few industrial applications known to date. This implies a certain barrier to the implementation of DTs and a lack of support, which was the motivation for this thesis.

Starting point for this research was a **literature review on the theoretical background (cf. section 2.1) and related work (cf. section 2.2)**. In the theoretical background an overview on related concepts was given, including Digital Transformation, Big Data, Artificial Intelligence, Industry 4.0, CPS, Smart Factories, and IoT. Further, PLM was outlined as the background of DTs. Based on these findings the basics of DTs were presented. Starting from a short overview of the origins of DTs a terminology valid for this thesis was presented to avoid misunderstandings. In the course of this thesis a DT is *"a dynamic virtual representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange."* This is important as there is large ambiguity in the terminology and many terms are mistakenly used as synonyms to DTs. Next, applications, benefits, and challenges of DTs were discussed. The findings showed that beneath technical challenges, literature lists also non-technical challenges. However, most research only focusses on solving technical issues. This was even more emphasized by the analysis of related work. Neither approaches for related concepts, nor for DTs specifically provide sufficient support to tackle technical and non-technical challenges holistically. However, based on this analysis insights for the development of a suitable approach could be derived.

To further analyze the challenges in the conception and implementation of DTs, an **online survey** including 61 industrial experts was conducted (cf. Chapter 3). The survey results confirmed the existence of non-technical challenges and emphasized the need of a solution approach considering both technical and non-technical aspects. Even more, the result showed, that by now, non-technical problems are at least as problematic as the technical ones.

In line with these findings four **empirical studies on the conception and implementation of DTs were conducted** (cf. Chapter 4). Each of them focused on a different aspect. In the first one on engineering twins for climate solutions an initial version of a procedure model and a use case template for the implementation of DTs was developed. These elements were further developed and adapted to production twins in the second industrial case study. These elements were further developed in an academic case study to adapt them to the characteristics of operation twins. Further, a DT business modelling approach was developed, and a DT use case catalogue further developed. Lastly, a case study on trust in DTs was conducted.

Combining findings from literature, online survey, and the empirical case studies, the final **Digital Twin Toolbox for Implementation and Design – DITTID** – was presented (cf. Chapter 5). It consists of a procedure model which is supported by several methods and tools including a DT business modelling approach, a DT value map, a DT use case catalogue, a DT use case template, and a DT trust framework. The procedure model is a five step process, which is intended to reduce development time and to increase quality by ensuring a value driven approach. The business model with its ten steps aims at enabling DT developers to model the business value of their DT use cases and support the DT procedure model. One of the most difficult tasks in business modelling is the derivation of a value proposition. This is supported by the DT value map connecting DT use cases with specific benefits and business goals. It can also be used to identify suitable use cases regarding desired outcomes. Thus, it aligns well with the DT use cases catalogue that offers different "entry tickets" to support the creativity process of identifying suitable DT use cases. To keep track of the overall process and to streamline documentation efforts, a DT use case template was developed. Finally, the DT trust framework lists relevant stakeholders in DT projects, in which situations they need to collaborate, and how trust in these situations between those stakeholders can be created.

DITTID was **initially evaluated in an academic student course** (c.f. Chapter 7). Here, a practical course was conceptualized in which student teams were able to experience the challenges in designing and implementing a DT and to learn about methodologies how to overcome these issues based on project-based learning. The teams were split up into two groups. Two teams received the entire DITTID toolbox for their project, the other two teams only got minor methodological support. The comparison of the two teams indicates the general usefulness of the developed approach. Teams with DITTID required less development effort, derived more use cases with a higher business value and a better technical feasibility. There are also indications for applicability and useability, however as for the usefulness, the student course does not hold as scientific proof for any of these effects. Nevertheless, in all empirical studies and in the feedback from the student course, DITTID was positively evaluated.

8.2 Contribution

Contribution for Academia

The scientific contribution of this thesis lays in contributing to closing the research gap of a holistic and operational design support for the development of DTs. Starting point for this research, was an analysis of the current situation. Therefore, the state of the art was elaborated, different concepts and terminologies were compared, and combined. Thus, this thesis also contributes to lowering the ambiguity in terminology, as a consistent definition of DTs was derived. Further, suitable subtypes of DTs were suggested which serve as a basis for future research (e.g. Kos et al., 2024; Vogel-Heuser et al., 2023).

Furthermore, the online survey contributes to the state of the art, by quantitatively assessing the effect of known challenges in implementing DTs. The key finding is that non-technical challenges are just as critical as technical challenges. This is an important observation which inspires future research and in depths analysis of the effects (e.g. D'Amico et al., 2023).

The theoretical observations of the literature review and the online survey were combined with empirical findings from industrial case studies. Therefore, the thesis provides practical aspects that should be considered in the development of DTs. Thus, the derived insights, requirements, and needs (cf. Chapter 5) provide a sound basis for the development of DT related methods.

Finally, the developed student course proved to be a suitable application of project-based learning. A positive learning effect could be observed, and the feedback of the students regarding the course design was very positive. Hence, this course format can be adopted for other DT teaching formats, but it can also be modified for related topics such as IoT, CPS, digital shadows, or PLM.

Contribution for Industry

The objective of this thesis was focused on improving current industrial practice. Therefore, the main contribution for industry is the toolbox supporting companies in designing and implementing DTs more successfully. Companies often struggle in starting DT projects, as they do not know how to start, how to proceed, and what to do. Here, the procedure model is a strong contribution as it provides a clear, executable process with detailed descriptions of required inputs, necessary tasks, and desired outcomes, as well as checklists to track progress. The use case catalogue and the value map contribute to the ideation phases of DT projects. Even when projects start, responsible stakeholders often struggle in modelling and communicating the business value of their DT solution, leading to budget cuts or failure of the project. Here the DT business modelling approach together with the value map comes in play, offering an understandable, useable process and methodology to holistically describe and quantify the value of the DT solution. Finally, the trust framework is a suitable support for many industrial stakeholders. It supports DT suppliers in building trust in their DT solutions, so companies will buy them. Further, it supports DT users by convincing their partners to collaborate with the DT. In addition, it provides measures to assess the trustworthiness of DT suppliers or other DT users.

DITTID provides hands-on, useable support for various companies in different industries for multiple DT subtypes. No software demonstrator has been developed, however all elements of DITTID despite the DT use case catalogue are available online and should be applicable without prior knowledge.

8.3 Outlook

As described in section 7.2, this research has several limitations which require further investigation. The main limitation lays in the usability of the developed systematic support. So far, the elements have only been developed document-based. An initial software application was developed, however, due to time constraints it could not be finished. However, with a suitable tool to support the application of DITTID, the effort for using it could significantly be lowered and consequently its value be improved. This especially holds true for the DT use case catalogue and the value map. As stated in the evaluation, to date, the methods are too complex to be usable to the full extent. Additionally, so far DITTID is not self-explanatory –

unexperienced users will still need support from an expert to fully gain all benefits of the methodology. This could also be resolved by an extensive software support.

Further, the applicability of DITTID could not entirely be investigated. The methods were applied for engineering twins, production twins, and operation twins in various engineering companies. However, the conditions for implementing DTs strongly vary depending on the companies' size, the type of product, the market, geographical region and the industry branch. Therefore, general applicability cannot be claimed based on the evaluation. In addition, DITTID has never been used as a whole in any of the projects. The evaluation combined all elements but the trust framework. Consequently, a more comprehensive evaluation would be needed. DITTID needs to be applied for other subtypes of DTs, in more companies and over a longer time period to finally assess the value of the approach.

Lastly, while DITTID covers most of the identified non-technical challenges, technical challenges are not fully covered. Here, further research would be required extending DITTID by further methods and tools to improve usefulness of the toolbox. One key requirement in the development of DITTID was interdisciplinarity. But, as the author of this thesis has a background in mechanical engineering, IT aspects would need to be strengthened in the approach. This includes methods for supporting the development of suitable IT architectures, support for the selection and design of data exchange methods and techniques, or even guidelines for IT security related aspects. Here, DITTID could profit from the advancements and standardization, which are currently under development by the industrial associations like the Digital Twin Consortium, or the Industrial Digital Twin Association.

9 References

Adamenko, D., Kunnen, S., & Nagarajah, A. (2020a). Comparative Analysis of Platforms for Designing a Digital Twin. In *Advances in Design, Simulation and Manufacturing III* (pp. 3–12). Springer, Cham. https://doi.org/10.1007/978-3-030-50794-7_1

Adamenko, D., Kunnen, S., & Nagarajah, A. (2020b). Digital Twin and Product Lifecycle Management: What Is the Difference? In *Product Lifecycle Management Enabling Smart X* (pp. 150–162). Springer, Cham. https://doi.org/10.1007/978-3-030-62807-9_13

ADIRO Automatisierungstechnik GmbH (2023a). ADIRO Automatisierungstechnik GmbH - EduKit PA for Festo Didactic. Retrieved from https://www.adiro.com/en/didactic/hardware/edukit-pa.php

ADIRO Automatisierungstechnik GmbH (2023b). ADIRO Automatisierungstechnik GmbH - IoT-Kit PA. Retrieved from https://www.adiro.com/en/didactic/hardware/IoT-Kit.php

ADIRO Automatisierungstechnik GmbH (2023c, July 3). DC-Wattmeter for energy monitoring. Retrieved from https://www.adiro.com/en/didactic/hardware/dc-wattmeter-energiemonitoring.php

Aheleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. [Yuqian] (2021). Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model. *Advanced Engineering Informatics*, *47*, 101225. https://doi.org/10.1016/j.aei.2020.101225

Alnowaiser, K. K., & Ahmed, M. A. (2023). Digital Twin: Current Research Trends and Future Directions. *Arabian Journal for Science and Engineering*, *48*(2), 1075–1095. https://doi.org/10.1007/s13369-022-07459-0

Alt, R., & Zimmermann, H.-D. (2001). Preface: Introduction to Special Section - Business Models. *Electronic Markets*, *11*(1), 3–9. https://doi.org/10.1080/713765630

Andrade, M. A. N. de, Lepikson, H. A., & Machado, C. A. T. (2021). A New Framework and Methodology for Digital Twin Development. In *2021 14th IEEE International Conference on Industry Applications (INDUSCON)*.

Ardyanti, A. A. A. P., Wibawa, I. P. P. S., & Putra, I. G. J. E. (2019). Evaluation and efficient measurement I-Canang digital startup in Bali with questionnaire user experience and lean startup machine validation board. *Journal of Physics: Conference Series*, *1402*(2), 22070. https://doi.org/10.1088/1742-6596/1402/2/022070

Atkinson, R. (1999). Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. *International Journal of Project Management*, *17*(6), 337–342. https://doi.org/10.1016/S0263-7863(98)00069-6

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering Design Processes: A Comparison of Students and Expert Practitioners. *Journal of Engineering Education*, *96*(4), 359–379. https://doi.org/10.1002/j.2168-9830.2007.tb00945.x

Atmoko, R. A., Riantini, R., & Hasin, M. K. (2017). IoT real time data acquisition using

MQTT protocol. *Journal of Physics: Conference Series*, *853*, 12003. https://doi.org/10.1088/1742-6596/853/1/012003

Attaran, M., & Celik, B. G. (2023). Digital Twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, *6*, 100165. https://doi.org/10.1016/j.dajour.2023.100165

Aurich, J. C., Koch, W., Kölsch, P., & Herder, C. (2019). *Entwicklung datenbasierter produkt-service systeme ein ansatz zur*. [Place of publication not identified]: MORGAN KAUFMANN. https://doi.org/10.1007/978-3-662-59643-2

Azangoo, M., Sorsamaki, L., Sierla, S. A., Matasniemi, T., Rantala, M., Rainio, K., & Vyatkin, V. (2022). A Methodology for Generating a Digital Twin for Process Industry: A Case Study of a Fiber Processing Pilot Plant. *IEEE Access*, *10*, 58787–58810. https://doi.org/10.1109/ACCESS.2022.3178424

Ba, S., & Pavlou, P. A. (2002). Evidence of the Effect of Trust Building Technology in Electronic Markets: Price Premiums and Buyer Behavior. *MIS Quarterly*, *26*(3), 243. https://doi.org/10.2307/4132332

Bajaj, M., Cole, B., & Zwemer, D. (2016). Architecture To Geometry - Integrating System Models With Mechanical Design. In. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2016-5470

Baltes, G., & Freyth, A. (2017). *Veränderungsintelligenz*. Wiesbaden: Springer Fachmedien Wiesbaden: Springer Fachmedien Wiesbaden.

Bamberg, A., Urbas, L., Bröcker, S., Bortz, M., & Kockmann, N. (2021). The Digital Twin – Your Ingenious Companion for Process Engineering and Smart Production. *Chemical Engineering & Technology*, *44*(6), 954–961. https://doi.org/10.1002/ceat.202000562

Banerjee, A., Dalal, R., Mittal, S., & Joshi, K. P. (2017). Generating Digital Twin Models using Knowledge Graphs for Industrial Production Lines. In. ACM. https://doi.org/10.1145/3091478.3162383

Barbero, J., & Zofío, J. L. (2023). The measurement of profit, profitability, cost and revenue efficiency through data envelopment analysis: A comparison of models using BenchmarkingEconomicEfficiency.jl. *Socio-Economic Planning Sciences*, *89*, 101656. https://doi.org/10.1016/j.seps.2023.101656

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. *IEEE Access*, *7*, 167653–167671. https://doi.org/10.1109/ACCESS.2019.2953499

Bens, I. (2017). *Facilitating with ease! Core skills for facilitators, team leaders and members, managers, consultants, and trainers / Ingrid Bens* (Fourth edition). Hoboken, New Jersey: John Wiley & Sons.

Benta, C., Wilberg, J., Hollauer, C., & Omer, M. (2017). PROCESS MODEL FOR DATA-DRIVEN BUSINESS MODEL GENERATION. In *21st International Conference on Engineering Design*. Retrieved from https://bit.ly/3LSHia5

Bieger, T., & Reinhold, S. (2011). Das wertbasierte Geschäftsmodell – Ein aktualisierter Strukturierungsansatz. In T. Bieger, D. zu Knyphausen-Aufseß, & C. Krys (Eds.), *Innovative Geschäftsmodelle* (pp. 13–70). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-18068-2_2

Binz, H., Keller, A., Kratzer, M., Messerle, M., & Roth, D. (2011). Increasing Effectiveness and Efficiency of Product Development - A Challenge for Design Methodologies and Knowledge Management. In H. Birkhofer (Ed.), *The future of design methodology* (pp. 79–90). London: Springer. https://doi.org/10.1007/978-0-85729-615-3_7

Blake, D. (2000). *Financial market analysis* (2. ed.). Chichester: Wiley.

Blessing, L., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. London: Springer London. https://doi.org/10.1007/978-1-84882-587-1

BMW Group (2022). BMW Group Technology Trend Radar. Retrieved from https://www.bmwgroup.com/en/innovation/company/technology-trend-radar.html

Boschert, S., & Rosen, R. (2016). Digital Twin—The Simulation Aspect. In P. Hehenberger & D. Bradley (Eds.), *Mechatronic Futures* (pp. 59–74). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-32156-1_5

Boureanu (2017). *Out-thinking organizational communications: The impact of digital transformation / Joachim Klewes, Dirk Popp, Manuela Rost-Hein, editors, Management for Professionals, Vol.*

Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, *101*, 1–12. https://doi.org/10.1016/j.compind.2018.04.015

Braun, T. E. (2005). *Methodische Unterstützung der strategischen Produktplanung in einem mittelständisch geprägten Umfeld* (Dissertation). Technical University of Munich, Munich, Germany. Retrieved from https://mediatum.ub.tum.de/601955

Bray, T. (2014). *The JavaScript Object Notation (JSON) Data Interchange Format*. Retrieved from Google Inc. website: https://greenbytes.de/tech/webdav/rfc7159.pdf

Brossard, M., Chaigne, S., Corbo, J., Mühlreiter, B., & Stein, J. P. (2022). Digital twins: The art of the possible in product development and beyond. Retrieved from https://www.mckinsey.com/capabilities/operations/our-insights/digital-twins-the-art-of-the-possible-in-product-development-and-beyond

Chesbrough, H. (2010). Business Model Innovation: Opportunities and Barriers. *Long Range Planning*, *43*(2-3), 354–363. https://doi.org/10.1016/j.lrp.2009.07.010

Christ, A., Koch, P., Krastel, M., Schweigert-Recksiek, S., & Trauer, J. (2022). Ready or not – the Digital Twin is coming! How can companies prepare for it? In prostep ivip e.V. (Ed.), *ProductData Journal* (2022-2, pp. 12–17). Darmstadt, Germany. Retrieved from https://prostep.epaper-pro.org/pdj2-2022_english/#12

CONTACT Software GmbH (2023, August 26). Digital Twin: Use the virtual representation of devices in the field for product and process improvements. Retrieved from https://www.contact-software.com/en/elements/smart-product-factory/digital-twin

Cornwall, A., & Jewkes, R. (1995). What is participatory research? *Social Science & Medicine*, *41*(12), 1667–1676. https://doi.org/10.1016/0277-9536(95)00127-S

Corona, E., & Pani, F. E. (2013). A review of lean-kanban approaches in the software development. In K. Ntalianis, L. Sztandera, & M. Poulos (Eds.), *WSEAS Transactions on Information Science and Applications* (Vol. 10). Retrieved from https://wseas.com/journals/isa/2013/5709-110.pdf

Corrales, L. d. C. N., Lambán, M. P., Hernandez Korner, M. E., & Royo, J. (2020). Overall Equipment Effectiveness: Systematic Literature Review and Overview of Different Approaches. *Applied Sciences*, *10*(18), 6469. https://doi.org/10.3390/app10186469

Crespi, N., Drobot, A. T., & Minerva, R. (2023). The Digital Twin: What and Why? In N. Crespi, A. T. Drobot, & R. Minerva (Eds.), *The Digital Twin* (1st ed., pp. 3–20). Cham: Springer International Publishing AG. https://doi.org/10.1007/978-3-031-21343-4_1

D'Amico, R. D., Addepalli, S., & Erkoyuncu, J. A. (2023). Industrial Insights on Digital Twins in Manufacturing: Application Landscape, Current Practices, and Future Needs. *Big Data and Cognitive Computing*, *7*(3), 126. https://doi.org/10.3390/bdcc7030126

Danilovic, M., & Browning, T. R. (2007). Managing complex product development projects with design structure matrices and domain mapping matrices. *International Journal of Project Management*, *25*(3), 300–314. https://doi.org/10.1016/j.ijproman.2006.11.003

De Kluyver, C. A. (2012). *Fundamentals of global strategy*. *Open textbook library*. Arlington, Virginia, Minneapolis: Saylor Academy; Open Textbook Library.

Digital Twin Consortium (2023). Digital Twin Consortium. Retrieved from https://www.digitaltwinconsortium.org/

Dillman, D. A., Smyth, J. D., & Christian, L. M. (2014). *Internet, phone, mail, and mixed-mode surveys: The tailored design method* (4th edition). Hoboken: Wiley.

Dimitrijević, S., Jovanović, J., & Devedžić, V. (2015). A comparative study of software tools for user story management. *Information and Software Technology*, *57*, 352–368. https://doi.org/10.1016/j.infsof.2014.05.012

Dohrmann, K., Gesing, B., & Ward, J. (2022). Digital Twins in Logistics: A DHL perspective on the impact of digital twins on the logistics industry. Retrieved from https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf

Drews, G. (2021). *Praxishandbuch Projektmanagement - inkl. Arbeitshilfen online* (3. Auflage 2020). Freiburg: Haufe-Lexware GmbH & Co. KG. Retrieved from https://www.wiso-net.de/document/HAUF,AHAU,VHAU__9783648144053684

Durão, Luiz Fernando C. S., Haag, S., Anderl, R., Schützer, K., & Zancul, E. (2018). Digital Twin Requirements in the Context of Industry 4.0. In P. Chiabert, A. Bouras, F. Noël, & J. I. Rios (Eds.), *IFIP Advances in Information and Communication Technology: Vol. 540. Product Lifecycle Management to Support Industry 4.0. PLM 2018*. Cham:

Springer. https://doi.org/10.1007/978-3-030-01614-2_19

Durst, M., Stang, S., Stößer, L., & Edelmann, F. (2010). Kollaboratives Trendmanagement. *HMD Praxis Der Wirtschaftsinformatik*, *47*(3), 78–86. https://doi.org/10.1007/BF03340476

Edrisi, F., & Azari, M. S. (2023). Digital Twin for Sustainability Assessment and Policy Evaluation: A Systematic Literature Review. In *2023 IEEE/ACM 7th International Workshop on Green And Sustainable Software (GREENS)*.

Ehrlenspiel, K., Kiewert, A., Lindemann, U., & Mörtl, M. (2021). *KOSTENGNSTIG ENTWICKELN UND KONSTRUIEREN: Kostenmanagement bei der*. [S.l.]: MORGAN KAUFMANN. https://doi.org/10.1007/978-3-662-62591-0

Ehrlenspiel, K., & Meerkamm, H. (2017). Sachgebundene Methoden für die Entwicklung und Konstruktion. In K. Ehrlenspiel & H. Meerkamm (Eds.), *Integrierte Produktentwicklung* (pp. 433–680). München: Carl Hanser Verlag GmbH & Co. KG. https://doi.org/10.3139/9783446449084.007

Eigner, M. (2021). *System Lifecycle Management*. [S.l.]: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-33874-9

Eigner, M., & Stelzer, R. (2009). Produktdaten-Management und Product Lifecycle Management. In M. Eigner & R. Stelzer (Eds.), *Produktdatenmanagement-Systeme: Ein Leitfaden für Product Development und Life Cycle Management* (2nd ed., pp. 27–45). Berlin: Springer-Verlag GmbH & Co. KG. https://doi.org/10.1007/b93672_3

El Bazi, N., Mabrouki, M., Laayati, O., Ouhabi, N., El Hadraoui, H., Hammouch, F.-E., & Chebak, A. (2023). Generic Multi-Layered Digital-Twin-Framework-Enabled Asset Lifecycle Management for the Sustainable Mining Industry. *Sustainability*, *15*(4), 3470. https://doi.org/10.3390/su15043470

Ergün, M. M., Kocabay, A., Yesilcimen, Y. M., & Turanli Parlaktuna, M. (2023). Digital Twin and Its Applications. In A. Azizi (Ed.), *Emerging Trends in Mechatronics. Industry 4. 0 : Technologies, Applications, and Challenges* (pp. 151–170). Singapore: Springer. https://doi.org/10.1007/978-981-19-2012-7_7

Erikstad, S. O. (2017). Merging Physics, Big Data Analytics and Simulation for the Next-Generation Digital Twins. In V. Bertram (Ed.), *Schriftenreihe Schiffbau, Proceedings of the 11th Symposium on High-Performance Marine Vehicles: HIPER'17* (pp. 139–149). Hamburg, Germany: Technische Universität Hamburg-Harburg. Retrieved from http://data.hiper-conf.info/Hiper2017_Zevenwacht.pdf

Erkoyuncu, J. A., Del Amo, I. F., Ariansyah, D., Bulka, D., Vrabič, R., & Roy, R. (2020). A design framework for adaptive digital twins. *CIRP Annals*, *69*(1), 145–148. https://doi.org/10.1016/j.cirp.2020.04.086

Eyre, J. M., Hyde, S., Walker, D., Ojo, S., Hayes, O., Hartley, R., . . . Bray, J. (2020). *Untangling the requirements of a Digital Twin*. Sheffield. Retrieved from The University of Sheffield - AMRC Factory 2050 website: https://www.amrc.co.uk/files/document/406/1605271035_1604658922_AMRC_Digital_Twin_AW.pdf

Fang, X., Wang, H. [Honghui], Liu, G., Tian, X., Ding, G., & Zhang, H. [Haizhu] (2022). Industry application of digital twin: From concept to implementation. *The International Journal of Advanced Manufacturing Technology*, *121*(7-8), 4289–4312. https://doi.org/10.1007/s00170-022-09632-z

Federal Ministry of Labour and Social Affairs (Ed.). *Act on Corporate Due Diligence Obligations in Supply Chains*. Berlin, Germany: Federal Law Gazette: Federal Law Gazette.

Finsterer, M. (2021). *Analysis and Detection of Anomalies of the Extrusion Parameters on an Extrusion Press with Artificial Intelligence* (Master's Thesis). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Fischer, D. (2022). *Further Development of a Procedure Model for the Implementation of Digital Twins - A Scientific Case Study* (Master's Thesis). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Fischer, T., Biskup, H., & Müller-Luschnat, G. (1998). Begriffliche Grundlagen für Vorgehensmodelle. In R. Kneuper, G. Müller-Luschnat, & A. Oberweis (Eds.), *Vorgehensmodelle für die betriebliche Anwendungsentwicklung* (pp. 13–31). Wiesbaden: Vieweg+Teubner Verlag. https://doi.org/10.1007/978-3-663-05994-3_1

Flores, B. E., & Clay Whybark, D. (1986). Multiple Criteria ABC Analysis. *International Journal of Operations & Production Management*, *6*(3), 38–46. https://doi.org/10.1108/eb054765

Follath, A., Bross, F., & Galka, S. (2022). Vorgehensmodell zur Erstellung Digitaler Zwillinge für Produktion und Logistik. *Zeitschrift Für Wirtschaftlichen Fabrikbetrieb*, *117*(10), 691–696. https://doi.org/10.1515/zwf-2022-1127

Franciosi, C., Miranda, S., Veneroso, C. R., & Riemma, S. (2022). Improving industrial sustainability by the use of digital twin models in maintenance and production activities. *IFAC-PapersOnLine*, *55*(19), 37–42. https://doi.org/10.1016/j.ifacol.2022.09.215

Frank, M., Lavy, I., & Elata, D. (2003). Implementing the Project-Based Learning Approach in an Academic Engineering Course. *International Journal of Technology and Design Education*, *13*(3), 273–288. https://doi.org/10.1023/A:1026192113732

Friederici, G. (2019). Digitaler Zwilling im Wasserkraftwerk für prädiktive Diagnosen. Retrieved from https://www.cadfem.net/de/de/cadfem-informiert/media-center/cadfem-journal/digitaler-zwilling-im-wasserkraftwerk-fuer-praediktive-diagnosen.html

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

Furnham, A. (2000). The Brainstorming Myth. *Business Strategy Review*, *11*(4), 21–28. https://doi.org/10.1111/1467-8616.00154

Gassmann, O., Frankenberger, K., & Choudury, M. (2014). *The business model navigator: 55 models that will revolutionise your business* (1st ed.). FT Publishing International. Retrieved from https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=5833827

Gast, J., Gundolf, K., & Cesinger, B. (2017). Doing business in a green way: A systematic review of the ecological sustainability entrepreneurship literature and future research directions. *Journal of Cleaner Production*, *147*, 44–56. https://doi.org/10.1016/j.jclepro.2017.01.065

Gericke, K., Bender, B., Feldhusen, J., & Grote, K.-H. (2021). Entwickeln von Wirkstrukturen. In B. Bender & K. Gericke (Eds.), *Pahl/Beitz Konstruktionslehre* (pp. 255–306). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-57303-7_10

Gericke, K., & Blessing, L. (2012). An ANALYSIS OF DESIGN PROCESS MODELS ACROSS DISCIPLINES. *DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia*, 171–180. Retrieved from https://www.designsociety.org/publication/31984/AN+ANALYSIS+OF+DESIGN+PROCESS+MODELS+ACROSS+DISCIPLINES

Gericke, K., Eckert, C., & Stacey, M. (2017). What do we need to say about a design method? *DS 87-7 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 7: Design Theory and Research Methodology, Vancouver, Canada, 21-25.08.2017*, 101–110. Retrieved from https://www.designsociety.org/publication/39810/What+do+we+need+to+say+about+a+design+method%3F

Gericke, K., Eckert, C., & Stacey, M. (2022). Elements of a design method – a basis for describing and evaluating design methods. *Design Science*, *8*, e29. https://doi.org/10.1017/dsj.2022.23

German, S. E., & Rhodes, D. H. (2018). Model-Centric Decision-Making: Exploring Decision-Maker Trust and Perception of Models. In *Disciplinary Convergence in Systems Engineering Research* (pp. 813–827). Springer, Cham. https://doi.org/10.1007/978-3-319-62217-0_57

Göbel, J. C., & Eickhoff, T. (2020). Konzeption von Digitalen Zwillingen smarter Produkte. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *115*(s1), 74–77. https://doi.org/10.3139/104.112301

Gogineni, S., Tanrikulu, C., Brünnhäußer, J., Lindow, K., & Witte, H. (2023). Capability Building Blocks for Digital Twin Development. In E. Alfnes, A. Romsdal, J. O. Strandhagen, G. von Cieminski, & D. Romero (Eds.), *IFIP Advances in Information and Communication Technology. ADVANCES IN PRODUCTION MANAGEMENT SYSTEMS. PRODUCTION MANAGEMENT SYSTEMS FOR* (Vol. 691, pp. 154–168). [S.l.]: SPRINGER INTERNATIONAL PU. https://doi.org/10.1007/978-3-031-43670-3_11

Göllner, D., Klausmann, T., Rasor, R., & Dumitrescu, R. (2022). Use Case Driven Digital Twin Generation. In *2022 IEEE 5th International Conference on Industrial Cyber-Physical Systems (ICPS)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICPS51978.2022.9816907

Golovina, T., Polyanin, A., Adamenko, A., Khegay, E., & Schepinin, V. (2020). Digital Twins as a New Paradigm of an Industrial Enterprise. *International Journal of Technology*, *11*(6), 1115. https://doi.org/10.14716/ijtech.v11i6.4427

Gong, C., & Ribiere, V. (2021). Developing a unified definition of digital transformation. *Technovation*, *102*, 102217. https://doi.org/10.1016/j.technovation.2020.102217

Grafe, M. (2023). Blog article: "Digital twins: a central pillar of industry 4.0&quot. Retrieved from https://blogs.zeiss.com/digital-innovation/en/digital-twins-pillar/

Graner, M. (2013). *Der Einsatz von Methoden in Produktentwicklungsprojekten: Eine empirische Untersuchung der Rahmenbedingungen und Auswirkungen*. *Schriften zum europäischen Management*. Wiesbaden: Springer Gabler. https://doi.org/10.1007/978-3-658-01278-6

Gräßler, I. (2018). Competitive engineering in the age of Industry 4.0 and beyond. In *Tools and Methods of Competitive Engineering (TMCE),* Las Palmas de Gran Canaria.

Gräßler, I., Wiechel, D., Roesmann, D., & Thiele, H. (2021). V-model based development of cyber-physical systems and cyber-physical production systems. *Procedia CIRP*, *100*, 253–258. https://doi.org/10.1016/j.procir.2021.05.119

Graupner, T.-D. (2010). *A procedure model for the development of web-based services for mechanical engineering, plant engineering and construction* (Dissertation). University of Stuttgart, Stuttgart, Germany. Retrieved from https://elib.uni-stuttgart.de/handle/11682/4310?locale=en https://doi.org/10.18419/opus-4293

Grieves, M. W. (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. W. (2022). Physical Twins, Digital Twins, and the Apollo Myth | LinkedIn. Retrieved from https://www.linkedin.com/pulse/physical-twins-digital-apollo-myth-michael-grieves/

Grieves, M. W. (2023). Digital Twins: Past, Present, and Future. In N. Crespi, A. T. Drobot, & R. Minerva (Eds.), *The Digital Twin* (1st ed., pp. 97–121). Cham: Springer International Publishing AG. https://doi.org/10.1007/978-3-031-21343-4_4

Grieves, M. W., & Vickers, J. (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), *Transdisciplinary Perspectives on Complex Systems* (pp. 85–113). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-38756-7_4

Haberfellner, R., Weck, O. de, Fricke, E., & Vössner, S. (2019). *Systems engineering: Fundamentals and applications / Reinhard Haberfellner, Olivier de Weck, Ernst Fricke, Siegfried Vössner*. Cham: Birkhäuser. https://doi.org/10.1007/978-3-030-13431-0

Hagedorn, L., Riedelsheimer, T., & Stark, R. (2023). PROJECT-BASED LEARNING IN ENGINEERING EDUCATION – DEVELOPING DIGITAL TWINS IN A CASE STUDY. *Proceedings of the Design Society*, *3*, 2975–2984. https://doi.org/10.1017/pds.2023.298

Hamel, G. (2002). *Leading the revolution: How to thrive in turbulent times by making innovation a way of life* (Rev. and updated hardcover ed.). [Boston, Mass.]: Harvard Business

School Press.

Hardavella, G., Aamli Gagnat, A., Xhamalaj, D., & Saad, N. (2016). How to prepare for an interview. *Breathe (Sheffield, England)*, *12*(3), e86-e90. https://doi.org/10.1183/20734735.013716

Heindl, W., & Stary, C. (2022). Structured Development of Digital Twins—A Cross-Domain Analysis towards a Unified Approach. *Processes*, *10*(8), 1490. https://doi.org/10.3390/pr10081490

Hermann, M., Pentek, T., & Otto, B. (2016). Design Principles for Industrie 4.0 Scenarios. In H. 2. :. (. Annual Hawaii International Conference on System Sciences Kauai (Ed.), *Proceedings of the 49th Annual Hawaii International Conference on System Sciences : 5-8 January 2016, Kauai, Hawaii* (pp. 3928–3937). IEEE. https://doi.org/10.1109/HICSS.2016.488

Hoff, K. A., & Bashir, M. (2014). Trust in Automation. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *57*(3), 407–434. https://doi.org/10.1177/0018720814547570

Holt, J., Perry, S. A., & Brownsword, M. (2012). *Model-based requirements engineering*. *IET Professional applications of computing series: Vol. 9*. London: The Institution of Engineering and Technology. https://doi.org/10.1049/PBPC009E

Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? *Technological Forecasting and Social Change*, *146*, 119–132. https://doi.org/10.1016/j.techfore.2019.05.021

Human, C., Basson, A. H., & Kruger, K. (2023). A design framework for a system of digital twins and services. *Computers in Industry*, *144*, 103796. https://doi.org/10.1016/j.compind.2022.103796

Humpa, M. (2023, June 14). *Der Weg und das Ziel der digitalen Transformation im Engineering Umfeld: Die Gestaltungsaspekte und Methoden des Veränderungsprozesses.* :em engineering methods AG. Engineering Process Day 2023, Darmstadt, Germany. Retrieved from https://www.em.ag/epd2023/

IDC Research, Inc. (2022). *Digital Twins: Potential of Constant Optimization in the Consumer Product Industry* (An IDC Whitepaper). Retrieved from Sponsored by Siemens AG website: https://resources.sw.siemens.com/en-US/white-paper-product-optimization-consumer-goods-digital-twin?token=eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJleGVjdXRpb25JZCI6ImJkMjhlOTg2ZDRl-MmFhZjg1NTQ5ZWZhNjI2ZDc1NWQ4LWNjZmEzZjU4NTg3OGQ3ODd-lYjJmMjhjZjVhNTBmYzg5LTE2Nzg2ODc5MzUwNTgiLCJpYXQi-OjE2Nzg2ODc5MzUsImV4cCI6MTcxMDIyMzkzNX0.vbooYFU5zYioU3fdz6kAnn50BGHxWcmqHEMVo4efM7I

IDC Research, Inc., & Statista (2021). Volume of data/information created, captured, copied, and consumed worldwide from 2010 to 2020, with forecasts from 2021 to 2025 (in zettabytes) [Graph]. Retrieved from https://www.statista.com/statistics/871513/world-wide-data-created/

Industrial Digital Twin Association e.V. (2023). IDTA – working together to promote the Digital Twin. Retrieved from https://industrialdigitaltwin.org/en/

Isaksson, O., & Eckert, C. (2020). *Product Development 2040: Technologies are just as good as the designer's ability to integrate them* (Design Society Report No. DS107). Glasgow, United Kingdom: The Design Society. https://doi.org/10.35199/report.pd2040

ISO International Organization for Standardization (2005). *Graphical symbols for diagrams*. (Standard, ISO 14617).

ISO International Organization for Standardization (2013). *Information technology*. (Standard, ISO/IEC 19510:2013).

ISO International Organization for Standardization (2021). *Automation systems and integration - Digital twin framework for manufacturing - Part 1: Overview and general principles*. (International Standard, ISO 23247-1:2021(E)). Technical Committee ISO/TC 184: Technical Committee ISO/TC 184.

Jodlbauer, H. (2020). *Geschäftsmodelle erarbeiten: Modell zur digitalen Transformation etablierter Unternehmen* (1. Aufl. 2020). Wiesbaden: Springer Gabler. https://doi.org/10.1007/978-3-658-30455-3

Johnson, M. W., & Lafley, A. G. (2010). *Seizing the white space: Business model innovation for growth and renewal*. Boston: Harvard Business Press.

Jones, D. E., Snider, C., Kent, L., & Hicks, B. (2019). Early Stage Digital Twins for Early Stage Engineering Design. *Proceedings of the Design Society: International Conference on Engineering Design*, *1*(1), 2557–2566. https://doi.org/10.1017/dsi.2019.262

Jones, D. E., 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

Josifovska, K., Yigitbas, E., & Engels, G. (2019). Reference Framework for Digital Twins within Cyber-Physical Systems. In *2019 IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS)*.

Kagermann, H., & Winter, J. (2018). The Second Wave of Digitalisation: Germany's Chance. In D. Messner, L. Meyer, & S. Mair (Eds.), *Germany and the world 2030: What will change ; how we must act* (pp. 201–208). Berlin: Econ.

Kasote, S., Das, S., & Rao, S. (2017). *Adoption of Structural Analysis Capabilities in an IOT Based Scenario for Connected Assets* (Human-Computer Interaction – INTERACT 2017). Springer International Publishing: Springer International Publishing, *10516*, pp. 332–335.

Katal, A., Wazid, M., & Goudar, R. H. (2013). Big data: Issues, challenges, tools and Good practices. In *2013 Sixth International Conference on Contemporary Computing (IC3)*.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kober, C., Fette, M., & Wulfsberg, J. P. (2022). Challenges of Digital Twin Application in Manufacturing. In *2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*.

Koch, Y., Husung, S., Röhnert, F., Mahboob, A., Frank, M. G., & Kirchner, E. (2022). A Method for the Support of the Design for Digital Twin Solution and Its Application on a Gearbox System. *Proceedings of the Design Society*, *2*, 1609–1618. https://doi.org/10.1017/pds.2022.163

Kos, J., Schröder, P., Trauer, J., Mörtl, M., & Zimmermann, M. (2024). Improving Sustainability of Additive Manufacturing Processes Based on Digital Twins - A Case Study. In *Design Conference Proceedings, Proceedings of the DESIGN 2024*. Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia; The Design Society, Glasgow, UK.

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

Krosnick, J. A. (2017). Questionnaire Design. In D. L. Vannette & J. A. Krosnick (Eds.), *The Palgrave Handbook of Survey Research* (1st ed., pp. 439–455). [s.l.]: Springer International Publishing AG. https://doi.org/10.1007/978-3-319-54395-6_53

Krosnick, J. A., Narayan, S., & Smith, W. R. (1996). Satisficing in surveys: Initial evidence. *New Directions for Evaluation*, *1996*(70), 29–44. https://doi.org/10.1002/ev.1033

Kumar, V., Leng, J., Akberdina, V., & Kuzmin, E. (Eds.) (2022). *Digital Transformation in Industry: Digital Twins and New Business Models*. : Vol. *54*. Cham: Springer: Springer.

LaBerge, L., O'Toole, C., Schneider, J., & Smaje, K. (October 2020). *How COVID-19 has pushed companies over the technology tipping point - and transformed business forever*. Retrieved from McKinsey & Company website: https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/how-covid-19-has-pushed-companies-over-the-technology-tipping-point-and-transformed-business-forever#/

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business & Information Systems Engineering*, *6*(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

Laudon, K. C., & Traver, C. G. (2014). *E-commerce: Business, technology, society* (Tenth edition). Upper Saddle River, New Jersey: Pearson.

Lee, J., Jin, C., & Liu, Z. [Zongchang] (2017). Predictive Big Data Analytics and Cyber Physical Systems for TES Systems. In L. Redding, R. Roy, & A. Shaw (Eds.), *Decision engineering, 1619-5736. Advances in through-life engineering services* (pp. 97–112). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-49938-3_7

Lee, J. D., & See, K. A. (2004). Trust in Automation: Designing for Appropriate Reliance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *46*(1), 50–80. https://doi.org/10.1518/hfes.46.1.50.30392

Legner, C., Eymann, T., Hess, T., Matt, C., Böhmann, T., Drews, P., . . . Ahlemann, F. (2017). Digitalization: Opportunity and Challenge for the Business and Information Systems Engineering Community. *Business & Information Systems Engineering*, *59*(4), 301–308. https://doi.org/10.1007/s12599-017-0484-2

Li, X., Cao, J., Liu, Z. [Zhenggang], & Luo, X. (2020). Sustainable Business Model Based on Digital Twin Platform Network: The Inspiration from Haier's Case Study in China. *Sustainability*, *12*(3), 936. https://doi.org/10.3390/su12030936

Lindemann, U. (2009). *Methodische Entwicklung technischer Produkte*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-01423-9

Lindemann, U., Maurer, M., & Braun, T. E. (2008). Deduction of indirect dependencies. In U. Lindemann, M. Maurer, & T. E. Braun (Eds.), *Structural Complexity Management* (pp. 99–117). Berlin: Springer-Verlag Berlin and Heidelberg GmbH & Co. KG. https://doi.org/10.1007/978-3-540-87889-6_7

Lindgardt, Z., Reeves, M., Stalk, J., & Deimler, M. (2013). Business Model Innovation: When the Game Gets Tough, Change the Game. In M. Deimler, R. Lesser, D. Rhodes, & J. Sinha (Eds.), *Own the future: 50 ways to win from the Boston Consulting Group* (pp. 291–298). https://doi.org/10.1002/9781119204084.ch40

Liu, L., & Loper, M. (2018). Trust as a Service: Building and Managing Trust in the Internet of Things. In *2018 IEEE International Symposium on Technologies for Homeland Security (HST): Crowne Plaza Boston - Woburn15 Middlesex Canal Park Road, Woburn, Massachusetts 01801 United States, 23-24 October 2018* (pp. 1–6). [Piscataway, NJ]: IEEE. https://doi.org/10.1109/THS.2018.8574169

Liu, M., Fang, S., Dong, H., & Xu, C. (2021). Review of digital twin about concepts, technologies, and industrial applications. *Journal of Manufacturing Systems*, *58*, 346–361. https://doi.org/10.1016/j.jmsy.2020.06.017

Liu, Y., Peng, Y., Wang, B., Yao, S., & Liu, Z. [Zihe] (2017). Review on cyber-physical systems. *IEEE/CAA Journal of Automatica Sinica*, *4*(1), 27–40. https://doi.org/10.1109/JAS.2017.7510349

Lu, Y. [Yuqian], Liu, C., Wang, K. I.-K., Huang, H., & Xu, X. (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing*, *61*, 101837. https://doi.org/10.1016/j.rcim.2019.101837

Lucassen, G., Dalpiaz, F., van der Werf, J. M. E. M., & Brinkkemper, S. (2016). The Use and Effectiveness of User Stories in Practice. In M. Daneva & O. Pastor (Eds.), *Lecture Notes in Computer Science: Volume 9619. Requirements Engineering: Foundation for Software Quality: 22nd International Working Conference, REFSQ 2016, Gothenburg, Sweden, March 14-17, 2016, Proceedings* (1st ed., Vol. 9619, pp. 205–222). Cham:

Springer International Publishing. https://doi.org/10.1007/978-3-319-30282-9_14

Lünnemann, P., Lindow, K., & Goßlau, L. (2023). Implementing digital twins in existing infrastructures. *Forschung Im Ingenieurwesen*, *87*(1), 421–429. https://doi.org/10.1007/s10010-023-00639-w

Mac, D. P. (2022). *Further Development of a Digital Twin Business Modelling Approach* (Master's Thesis). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Mahlau, L. (2018). *Conception and Introduction of a Digital Twin in Mechanical Engineering – A Case Study in Technical Product Development* (Master's Thesis). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Maier, A., Oehmen, J., & Vermaas, P. E. (2023). Introducing Engineering Systems Design: A New Engineering Perspective on the Challenges of Our Times. In *Handbook of Engineering Systems Design* (pp. 1–30). Springer, Cham. https://doi.org/10.1007/978-3-030-46054-9_1-3

Mankins, J. C. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica*, *65*(9-10), 1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058

Matondang, N. R. U. (2021). *Business Modelling Approach for Digital Twin Use Cases* (Master's Thesis). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Maurya, A. (2018). *Running lean: Iterate from plan A to a plan that works* (Second Edition). *The lean series: 2018: 1*. Beijing: O'Reilly. Retrieved from https://books.google.de/books?id=j4hXPn233UYC

Mayer, R. C., Davis, J. H., & Schoorman, F. D. (1995). An Integrative Model of Organizational Trust. *The Academy of Management Review*, *20*(3), 709. https://doi.org/10.2307/258792

Menold, N., Kaczmirek, L., Lenzner, T., & Neusar, A. (2014). How Do Respondents Attend to Verbal Labels in Rating Scales? *Field Methods*, *26*(1), 21–39. https://doi.org/10.1177/1525822X13508270

Miecznik, B. (2013). Ideenmanagement. In T. Abele (Ed.), *Suchfeldbestimmung und Ideenbewertung* (pp. 143–168). Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-02184-9_7

Minerva, R., Lee, G. M., & Crespi, N. (2020). Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models. *Proceedings of the IEEE*, *108*(10), 1785–1824. https://doi.org/10.1109/JPROC.2020.2998530

Möhring, M., Keller, B., Radowski, C.-F., Blessmann, S., Breimhorst, V., & Müthing, K. (2022). Empirical Insights into the Challenges of Implementing Digital Twins. In *Human Centred Intelligent Systems* (Vol. 310, pp. 229–239). Springer, Singapore. https://doi.org/10.1007/978-981-19-3455-1_18

MSCI Inc. (2021). GICS - Global Industry Classification Standard. Retrieved from https://www.msci.com/our-solutions/indexes/gics

Murray-Webster, R., & Simon, P. (2006). Making sense of stakeholder mapping. *PM World Today Tips and Techniques - "Connecting the World of Project Management"*, *8*(11). Retrieved from https://www.researchgate.net/publication/265653139_Making_Sense_of_Stakeholder_Mapping

Mutschler, M. (2021). *Impediments in Implementing Digital Twins* (Term Paper). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Nardelli, P. H. J. (2022). *Cyber-physical Systems: Theory, Methodology, and Applications* (1st ed.). Newark: Wiley-IEEE Press.

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

Neligan, A., Baumgartner, R. J., Geissdoerfer, M., & Schöggl, J.-P. (2022). Circular disruption: Digitalisation as a driver of circular economy business models. *Business Strategy and the Environment.* Advance online publication. https://doi.org/10.1002/bse.3100

Neto, A. A., Deschamps, F., Da Silva, E. R., & Lima, E. P. de (2020). Digital twins in manufacturing: an assessment of drivers, enablers and barriers to implementation. *Procedia CIRP*, *93*, 210–215. https://doi.org/10.1016/j.procir.2020.04.131

Newrzella, S. R., Franklin, D. W., & Haider, S. (2022). Methodology for Digital Twin Use Cases: Definition, Prioritization, and Implementation. *IEEE Access*, *10*, 75444–75457. https://doi.org/10.1109/ACCESS.2022.3191427

Nyumba, O. T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and Evolution*, *9*(1), 20–32. https://doi.org/10.1111/2041-210X.12860

O'Leary, D. E. (2013). Artificial Intelligence and Big Data. *IEEE Intelligent Systems*, *28*(2), 96–99. https://doi.org/10.1109/MIS.2013.39

The Open Group (2023). The TOGAF Standard, 10th Edition: Supporting Agility in the Digital Enterprise. Retrieved from https://www.opengroup.org/togaf

Osborn, A. (1957). *Applied Immagination: Principles and Procedures of Creative Problem Solving*. New York, NY: Charles Scribner's Sons.

Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: A handbook for visionaries, game changers, and challengers*. New York: Wiley & Sons.

Osterwalder, A., Pigneur, Y., Bernarda, G., & Smith, A. (2014). *Value proposition design: How to create products and services customers : Get started with*. *Strategyzer series*. Hoboken, New Jersey: John Wiley & Sons, Inc. Retrieved from http://ebooks.ciando.com/book/index.cfm?bok_id/1862474

Ozcan, Mustafa, Bugra, Konuk, B., & Yesilcimen, Y. M. (2023). Big Data Analytics in Industry 4.0. In A. Azizi (Ed.), *Emerging Trends in Mechatronics. Industry 4. 0 :*

Technologies, Applications, and Challenges (pp. 171–199). Singapore: Springer. Retrieved from https://doi.org/10.1007/978-981-19-2012-7_8

Parnianifard, A., Jearavongtakul, S., Sasithong, P., Sinpan, N., Poomrittigul, S., Bajpai, A., . . . Wuttisittikulkij, L. (2022). Digital-Twins towards Cyber-Physical Systems: A Brief Survey. *Engineering Journal*, *26*(9), 47–61. https://doi.org/10.4186/ej.2022.26.9.47

Passos, C. A., & Haddad, R. B. (2013). Benchmarking: A tool for the improvement of production management. *IFAC Proceedings Volumes*, *46*(24), 577–581. https://doi.org/10.3182/20130911-3-BR-3021.00003

Perno, M., Hvam, L., & Haug, A. (2021). Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers. *Computers in Industry*, *134*, 103558. https://doi.org/10.1016/j.compind.2021.103558

Pfingstl, S. (2023). *Gaussian Processes for Prognostics* (Dissertation). Technical University of Munich, Munich, Germany. Retrieved from https://mediatum.ub.tum.de/1661754

Piccolo, S. A., Trauer, J., Wilberg, J., & Maier, A. (2018). Understanding TASK EXECUTION TIME IN RELATION TO THE MULTILAYER PROJECT STRUCTURE: Empirical EVIDENCE. In *20th International Dependency and Structure Modelling Conference (DSM 2018)*. Retrieved from https://www.designsociety.org/publication/40982/understanding+task+execution+time+in+relation+to+the+multilayer+project+structure%3a+empirical+evidence

Pires, F., Cachada, A., Barbosa, J., Moreira, A. P., & Leitao, P. (2019). Digital Twin in Industry 4.0: Technologies, Applications and Challenges. In *2019 IEEE 17th International Conference on Industrial Informatics (INDIN): Aalto University, Helsinki-Espoo, Finland, 22-25 July, 2019 : proceedings* (pp. 721–726). Piscataway, NJ: IEEE. https://doi.org/10.1109/INDIN41052.2019.8972134

Pohl, K., & Rupp, C. (2021). *Basiswissen Requirements Engineering: Aus- und Weiterbildung nach IREB-Standard zum Certified Professional for Requirements Engineering Foundation Level* (5. Auflage). Heidelberg: dpunkt.verlag. Retrieved from https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=2913478

Ponn, J. (2007). *Situative Unterstützung der methodischen Konzeptentwicklung technischer Produkte* (Dissertation). Technical University of Munich, Munich, Germany. Retrieved from https://mediatum.ub.tum.de/644219

Porter, M. E. (1996). How Competitive Forces Shape Strategy. In D. Asch (Ed.), *Readings in strategic management* (pp. 133–143). Houndmills, Basingstoke: Macmillan. https://doi.org/10.1007/978-1-349-20317-8_10

Prielipp, R., Bojko, M., Göhlert, N., & Pelliccia, L. (2021). Business models based on digital twins and digital shadows in the textile industry. *Wt Werkstattstechnik Online*, *111*(07-08), 531–535. https://doi.org/10.37544/1436-4980-2021-07-08-63

Qamsane, Y., Moyne, J., Toothman, M., Kovalenko, I., Balta, E. C., Faris, J., . . . Barton, K.

(2021). A Methodology to Develop and Implement Digital Twin Solutions for Manufacturing Systems. *IEEE Access*, *9*, 44247–44265. https://doi.org/10.1109/ACCESS.2021.3065971

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., . . . Nee, A. Y. C. (2021). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems*, *58*, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001

Radziwon, A., Bilberg, A., Bogers, M., & Madsen, E. S. (2014). The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions. *Procedia Engineering*, *69*, 1184–1190. https://doi.org/10.1016/j.proeng.2014.03.108

Raj, P., & Surianarayanan, C. (2020). Chapter Twelve - Digital twin: The industry use cases. In P. Raj & P. Evangeline (Eds.), *Advances in Computers : The Digital Twin Paradigm for Smarter Systems and Environments: The Industry Use Cases* (Vol. 117, pp. 285–320). Elsevier. https://doi.org/10.1016/bs.adcom.2019.09.006

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital Twin: Values, Challenges and Enablers From a Modeling Perspective. *IEEE Access*, *8*, 21980–22012. https://doi.org/10.1109/ACCESS.2020.2970143

Rathore, M. M., Shah, S. A., Shukla, D., Bentafat, E., & Bakiras, S. (2021). The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and Opportunities. *IEEE Access*, *9*, 32030–32052. https://doi.org/10.1109/ACCESS.2021.3060863

Rayes, A., & Salam, S. (2019). Internet of Things (IoT) Overview. In A. Rayes & S. Salam (Eds.), *Internet of Things from hype to reality: The road to digitization / Ammar Rayes, Samer Salam* (pp. 1–35). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-99516-8_1

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., . . . Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, *90*(5), 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001

Riedelsheimer, T., Gogineni, S., & Stark, R. (2021). Methodology to develop Digital Twins for energy efficient customizable IoT-Products. *Procedia CIRP*, *98*, 258–263. https://doi.org/10.1016/j.procir.2021.01.040

Riesener, M., Schuh, G., Dölle, C., & Tönnes, C. (2019). The Digital Shadow as Enabler for Data Analytics in Product Life Cycle Management. *Procedia CIRP*, *80*, 729–734. https://doi.org/10.1016/j.procir.2019.01.083

Rosário, A. T., & Dias, J. C. (2023). How Industry 4.0 and Sensors Can Leverage Product Design: Opportunities and Challenges. *Sensors (Basel, Switzerland)*, *23*(3), 1165. https://doi.org/10.3390/s23031165

Rosen, R., Fischer, J., & Boschert, S. (2019). Next Generation Digital Twin: an Ecosystem for Mechatronic Systems? *IFAC-PapersOnLine*, *52*(15), 265–270. https://doi.org/10.1016/j.ifacol.2019.11.685

Rust, R. T., Moorman, C., & Dickson, P. R. (2002). Getting Return on Quality: Revenue Expansion, Cost Reduction, or Both? *Journal of Marketing*, *66*(4), 7–24. Retrieved from http://www.jstor.org/stable/3203355

Saaksvuori, A., & Immonen, A. (2008). *Product lifecycle management* (3rd ed.). Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-540-78172-1

Saari, L., Räikkönen, M., Hytönen, E., & Valkokari, K. (2023). Joint Offering Evaluation Framework for Assessing the Feasibility and Business Value of a Digital Twin Use Case. *Systems Engineering.* Advance online publication. https://doi.org/10.1002/sys.21713

Saha, P. K. (2000). *Aluminum extrusion technology*. Materials Park, OH: ASM International. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=395820

Saporiti, N., Cannas, V. G., Pozzi, R., & Rossi, T. (2023). Challenges and countermeasures for digital twin implementation in manufacturing plants: A Delphi study. *International Journal of Production Economics*, *261*, 108888. https://doi.org/10.1016/j.ijpe.2023.108888

Saygin, M. (2019). *Further Development of a Concept for a Digital Twin in Technical Product Development* (Master's Thesis). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Schaeffer, N. C., & Dykema, J. (2020). Advances in the Science of Asking Questions. *Annual Review of Sociology*, *46*(1), 37–60. https://doi.org/10.1146/annurev-soc-121919-054544

Schmitt, L., & Copps, D. (2023). The Business of Digital Twins. In N. Crespi, A. T. Drobot, & R. Minerva (Eds.), *The Digital Twin* (1st ed., pp. 21–63). Cham: Springer International Publishing AG. https://doi.org/10.1007/978-3-031-21343-4_2

Schneider, A. (2012). *Geschäftsmodellwandel durch disruptive Innovationen: Fallstudie zum Elektrofahrzeug in Automobilindustrie und Energiewirtschaft*. *Driesen Wirtschaftswissenschaften*. Taunusstein: Driesen.

Schroeder, G., Steinmetz, C., Rodrigues, R., Henriques, R. V. B., Rettberg, A., & Pereira, C. E. (2021). A Methodology for Digital Twin Modeling and Deployment for Industry 4.0. *Proceedings of the IEEE*, *109*(4), 556–567. https://doi.org/10.1109/JPROC.2020.3032444

Schumacher, A., Sihn, W., & Erol, S. (2016). Automation, digitization and digitalization and their implications for manufacturing processes. In *International Scientific Conference "Innovation and Sustainability 2016",* Bucharest. Retrieved from https://www.researchgate.net/profile/Andreas-Schumacher-3/publication/318877006_Automation_digitization_and_digitalization_and_their_implications_for_manufacturing_processes/links/5982ed4daca272a370f5a2e4/Automation-digitization-and-digitalization-and-their-implications-for-manufacturing-processes.pdf

Schwarzburg, J. (2021). *Use Case Catalogue for Digital Twins* (Term Paper). Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Schwarzburg, J., Trauer, J., & Rebentisch, E. (2024). On the Factors Influencing Confidence in Models and Simulations for Decision-Making: A Survey. *Design Science*.

Schweigert-Recksiek, S. (2022). *Enhancing the Collaboration of Design and Simulation - Bridging Barriers in Technical Product Development*. *Produktentwicklung*. München: Dr. Hut.

Schweigert-Recksiek, S., Hagenow, N., & Lindemann, U. (2021). EVALUATION OF IMPROVEMENT OPPORTUNITIES FOR THE COLLABORATION OF DESIGN AND SIMULATION - AN INDUSTRIAL MULTI-METHOD STUDY. *Proceedings of the Design Society*, *1*, 1421–1430. https://doi.org/10.1017/pds.2021.142

Schweigert-Recksiek, S., & Lindemann, U. (2020). CHOOSING THE RIGHT MEASURES TO IMPROVE COLLABORATION BETWEEN DESIGN AND SIMULATION DEPARTMENTS. *Proceedings of the Design Society: DESIGN Conference*, *1*, 727–736. https://doi.org/10.1017/dsd.2020.57

Schweigert-Recksiek, S., Trauer, J., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). CONCEPTION OF A DIGITAL TWIN IN MECHANICAL ENGINEERING – A CASE STUDY IN TECHNICAL PRODUCT DEVELOPMENT. *Proceedings of the Design Society: DESIGN Conference*, *1*, 383–392. https://doi.org/10.1017/dsd.2020.23

Schweigert-Recksiek, S., Trauer, J., & Krastel, M. (2023, August 15). Wie der digitale Zwilling Mehrwert schafft – eine Nutzensystematik. *Konstruktionspraxis*. Retrieved from https://www.konstruktionspraxis.vogel.de/digitale-zwilling-einfuhrung-mehrwert-a-f000072016006493b2806b0946aafd34/

Schweigert-Recksiek, S., Trauer, J., Wilberg, J., Stöhr, B., Mahlau, L., Saygin, M., . . . Zimmermann, M. (2022). *Einführung eines digitalen Zwillings in die technische Produktentwicklung*. Unpublished. https://doi.org/10.13140/RG.2.2.34190.23365

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., & Wang, L. [Lui] (2010). Modeling, Simulation, Information Technology and Processing Roadmap. Retrieved from https://www.nasa.gov/pdf/501321main_TA11-MSITP-DRAFT-Nov2010-A1.pdf

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital Twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration*, *30*, 100383. https://doi.org/10.1016/j.jii.2022.100383

Siedlak, D. J. L., Pinon, O. J., Schlais, P. R., Schmidt, T. M., & Mavris, D. N. (2018). A digital thread approach to support manufacturing-influenced conceptual aircraft design. *Research in Engineering Design*, *29*(2), 285–308. https://doi.org/10.1007/s00163-017-0269-0

Singh, M., Fuenmayor, E., Hinchy, E., Qiao, Y., Murray, N., & Devine, D. (2021). Digital Twin: Origin to Future. *Applied System Innovation*, *4*(2), 36. https://doi.org/10.3390/asi4020036

Singh, R., Shah, D. B., Gohil, A. M., & Shah, M. H. (2013). Overall Equipment Effectiveness (OEE) Calculation - Automation through Hardware & Software Development. *Procedia Engineering*, *51*, 579–584. https://doi.org/10.1016/j.proeng.2013.01.082

Singh, S., Shehab, E., Higgins, N., Fowler, K., Reynolds, D., Erkoyuncu, J. A., & Gadd, P. (2020). Data management for developing digital twin ontology model. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *235*(14), 2323–2337. https://doi.org/10.1177/0954405420978117

Singh, S., Shehab, E., Higgins, N., Fowler, K., Tomiyama, T., & Fowler, C. (2018). Challenges of Digital Twin in High Value Manufacturing. In *SAE Technical Paper Series, SAE Technical Paper Series*. SAE International400 Commonwealth Drive, Warrendale, PA, United States. https://doi.org/10.4271/2018-01-1928

Singh, Y. K. (2006). *Fundamental of research methodology and statistics*. New Delhi: New Age International.

Smith, M. L., Erwin, J., & Diaferio, S. (2005). Role & responsibility charting (RACI). In *Project Management Forum (PMForum)*. Retrieved from https://www.workfront.com/sites/default/files/imported/pdfs/raci_r_web3_1.pdf

Spath, D., Gausemeier, J., Dumitrescu, R., Winter, J., Steglich, S., & Drewel, M. (2023). Digitalisation of Society. In *Handbook of Engineering Systems Design* (pp. 1–27). Springer, Cham. https://doi.org/10.1007/978-3-030-46054-9_5-2

Stark, J. (2022). Product Lifecycle Management (PLM). In *Product Lifecycle Management (Volume 1)* (pp. 1–32). Springer, Cham. https://doi.org/10.1007/978-3-030-98578-3_1

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., Kind, S., & Neumeyer, S. (2017). Innovations in digital modelling for next generation manufacturing system design. *CIRP Annals*, *66*(1), 169–172. https://doi.org/10.1016/j.cirp.2017.04.045

Stetter, R. (2000). *Method Implementation in Integrated Product Development* (Dissertation). Technical University of Munich, Munich, Germany. Retrieved from https://mediatum.ub.tum.de/1192137

Stetter, R., Rauchenberger, J., Spiegelberger, B., Müller, T., Pfeifer, G., Witzel, O., & Gideon, F. (2009). *Betriebliche Einführungsstrategie für ein anwendungsorientiertes Vorgehensmodell für die Entwicklung zuverlässigerer mechatronischer Systeme im Maschinen- und Anlagenbau: Projektabschlussbericht des Forschungsprojekts BESTVOR*. Research Report. ITQ GmbH. Retrieved from https://publica.fraunhofer.de/handle/publica/294738

Steward, D. V. (1981). The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management*, *EM-28*(3), 71–74. https://doi.org/10.1109/TEM.1981.6448589

Stjepandić, J., Sommer, M., & Stobrawa, S. (2021a). Digital Twin: A Conceptual View. In J. Stjepandić, M. Sommer, & B. Denkena (Eds.), *Springer Series in Advanced Manufacturing. DigiTwin: An Approach for Production Process Optimization in a Built Environment* (pp. 31–49). Cham: Springer. https://doi.org/10.1007/978-3-030-77539-1_3

Stjepandić, J., Sommer, M., & Stobrawa, S. (2021b). Digital Twin: Conclusion and Future Perspectives. In J. Stjepandić, M. Sommer, & B. Denkena (Eds.), *Springer Series in Advanced Manufacturing. DigiTwin: An Approach for Production Process Optimization in a Built Environment*. Cham: Springer. https://doi.org/10.1007/978-3-030-77539-1_11

Stöhr, B. (2018). *Konzeption und Einführung eines Digital-Twin-Ansatzes in der industriellen Praxis* (Master's Thesis). Friedrich-Alexander-Universität Erlangen-Nürnberg, Nuremberg, Germany.

Stupar, S., Bičo Ćar, M., & Šestić, M. (2023). Challenges and Benefits of Using Digital Twin Technology. In I. Karabegovic, A. Kovačević, & S. Mandzuka (Eds.), *Lecture Notes in Networks and Systems: Vol. 687. NEW TECHNOLOGIES, DEVELOPMENT AND APPLICATION VI* (Vol. 687, pp. 585–595). [S.l.]: SPRINGER INTERNATIONAL PU. https://doi.org/10.1007/978-3-031-31066-9_66

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H. [He], & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, *94*(9-12), 3563–3576. https://doi.org/10.1007/s00170-017-0233-1

Tao, F., Qi, Q., Wang, L. [Lihui], & Nee, A. Y. C. (2019). Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. *Engineering*, *5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., . . . Nee, A. Y. C. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935–3953. https://doi.org/10.1080/00207543.2018.1443229

Tao, F., Zhang, H. [He], Liu, A., & Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, *15*(4), 2405–2415. https://doi.org/10.1109/TII.2018.2873186

Tekkaya, A. E., & Chatti, S. (2019). Bar Extrusion. In S. Chatti, L. Laperrière, G. Reinhart, & T. Tolio (Eds.), *Springer Reference. CIRP Encyclopedia of production engineering* (pp. 115–118). Berlin: Springer. https://doi.org/10.1007/978-3-662-53120-4_20

Theil, M. (2002). The role of translations of verbal into numerical probability expressions in risk management: a meta-analysis. *Journal of Risk Research*, *5*(2), 177–186. https://doi.org/10.1080/13669870110038179

Thelen, A., Zhang, X., Fink, O., Lu, Y. [Yan], Ghosh, S., Youn, B. D., . . . Hu, Z. (2022). A comprehensive review of digital twin — Part 1: Modeling and twinning enabling technologies. *Structural and Multidisciplinary Optimization*, *65*(12), 1–55. https://doi.org/10.1007/s00158-022-03425-4

Thielsch, M. T., Meeßen, S. M., & Hertel, G. (2018). Trust and distrust in information systems at the workplace. *PeerJ*, *6*, e5483. https://doi.org/10.7717/peerj.5483

Thompson, J. L., & Martin, F. (2010). *Strategic management: Awareness & change* (6th ed.). Andover: Cengage Learning.

Trauer, J., Mac, D. P., Mörtl, M., & Zimmermann, M. (2023). A Digital Twin Business Modelling Approach. In *Proceedings of the Design Society: International Conference on Engineering Design* (Vol. 3, pp. 121–130). Cambridge University Press. https://doi.org/10.1017/pds.2023.13

Trauer, J., Mutschler, M., Mörtl, M., & Zimmermann, M. (2022). Challenges in Implementing Digital Twins – a Survey. In *Volume 2: 42nd Computers and Information in Engineering Conference (CIE)*. American Society of Mechanical Engineers. https://doi.org/10.1115/detc2022-88786

Trauer, J., Pfingstl, S., Finsterer, M., & Zimmermann, M. (2021). Improving Production Efficiency with a Digital Twin Based on Anomaly Detection. *Sustainability*, *13*(18), 10155. https://doi.org/10.3390/su131810155

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). What Is a Digital Twin? – Definitions and Insights from an Industrial Case Study in Technical Product Development. *Proceedings of the Design Society: DESIGN Conference*, *1*, 757–766. https://doi.org/10.1017/dsd.2020.15

Trauer, J., Schweigert-Recksiek, S., Gövert, K., Mörtl, M., & Lindemann, U. (2020). Combining Agile Approaches and Risk Management for Mechatronic Product Development – a Case Study. *Proceedings of the Design Society: DESIGN Conference*, *1*, 767–776. https://doi.org/10.1017/dsd.2020.16

Trauer, J., Schweigert-Recksiek, S., Onuma Okamoto, L., Spreitzer, K., Mörtl, M., & Zimmermann, M. (2020). Data-Driven Engineering – Definitions and Insights from an Industrial Case Study for a New Approach in Technical Product Development. In *Balancing Innovation and operation*. The Design Society. https://doi.org/10.35199/NORDDESIGN2020.46

Trauer, J., Schweigert-Recksiek, S., Schenk, T., Baudisch, T., Mörtl, M., & Zimmermann, M. (2022). A Digital Twin Trust Framework for Industrial Application. *Proceedings of the Design Society*, *2*, 293–302. https://doi.org/10.1017/pds.2022.31

Trauer, J., Wöhr, F., Eckert, C., Kannengiesser, U., Knippenberg, S., Sankowski, O., & Zimmermann, M. (2021). Criteria for Selecting Design Process Modelling Approaches. *Proceedings of the Design Society*, *1*, 791–800. https://doi.org/10.1017/pds.2021.79

Tzachor, A., Sabri, S., Richards, C. E., Rajabifard, A., & Acuto, M. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nature Sustainability*, *5*(10), 822–829. https://doi.org/10.1038/s41893-022-00923-7

Uhlemann, T. H.-J., Lehmann, C., & Steinhilper, R. (2017). The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. *Procedia CIRP*, *61*, 335–340. https://doi.org/10.1016/j.procir.2016.11.152

Ulwick, A. W. (2005). *What customers want: Using outcome-driven innovation to create breakthrough products and services*. New York: McGraw-Hill.

United Nations Development Program (2023, August 16). Sustainable Development Goals. Retrieved from https://www.undp.org/sustainable-development-goals?gclid=CjwKCAjw5_GmBhBIEiwA5QSMxNrq5HmQxRutu9Wf7xGJNi5Yy6Ul2is1U_sGr5S0BPcuiitM-Xj4lhoCIqcQAvD_BwE

Utz, S., Kerkhof, P., & van den Bos, J. (2012). Consumers rule: How consumer reviews influence perceived trustworthiness of online stores. *Electronic Commerce Research and Applications*, *11*(1), 49–58. https://doi.org/10.1016/j.elerap.2011.07.010

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0 – A Glimpse. *Procedia Manufacturing*, *20*, 233–238. https://doi.org/10.1016/j.promfg.2018.02.034

Vajna, S., & Burchardt, C. (2014). Modelle und Vorgehensweisen der Integrierten Produktentwicklung. In S. Vajna (Ed.), *Integrated Design Engineering: Ein interdisziplinäres Modell für die ganzheitliche Produktentwicklung* (pp. 3–50). Dordrecht: Springer Vieweg. https://doi.org/10.1007/978-3-642-41104-5_1

Valve Corporation (2023, January 10). Steam Refunds. Retrieved from https://store.steampowered.com/steam_refunds/?l=english

Van der Valk, H., Haße, H., Möller, F., & Otto, B. (2021). Archetypes of Digital Twins. *Business & Information Systems Engineering.* Advance online publication. https://doi.org/10.1007/s12599-021-00727-7

VanDerHorn, E., & Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. *Decision Support Systems*, *145*, 113524. https://doi.org/10.1016/j.dss.2021.113524

VDI Verein Deutscher Ingenieure e.V. (2014, April 1). *System requirement/specification for planning and design of automation systems*. (Standard, VDI/VDE 3694:2014-04). Beuth Verlag GmbH: Beuth Verlag GmbH.

VDI Verein Deutscher Ingenieure e.V. (2016). *Informationsverarbeitung in der Produktentwicklung - Einführung und Betrieb von PDM-Systemen*. (Standard, VDI 2219:2016-09).

VDI Verein Deutscher Ingenieure e.V. (2021). *Development of mechatronic and cyber-physical systems*. (Standard, VDI 2206:2021-11).

Voelpel, S. C., Leibold, M., & Tekie, E. B. (2004). The wheel of business model reinvention: how to reshape your business model to leapfrog competitors. *Journal of Change Management*, *4*(3), 259–276. https://doi.org/10.1080/1469701042000212669

Vogel-Heuser, B., Bi, F., Wittemer, M., Zhao, J., Mayr, A., Fleischer, M., . . . Wudy, K. (2023). Digital Twins in Engineering: Applications, Challenges, Integration, and Beyond. *Computers in Industry*, *151*.

Vrana, J. (2021). The Core of the Fourth Revolutions: Industrial Internet of Things, Digital Twin, and Cyber-Physical Loops. *Journal of Nondestructive Evaluation*, *40*(2), 1–21. https://doi.org/10.1007/s10921-021-00777-7

Wang, R., & Krosnick, J. A. (2020). Middle alternatives and measurement validity: a recommendation for survey researchers. *International Journal of Social Research Methodology*, *23*(2), 169–184. https://doi.org/10.1080/13645579.2019.1645384

Wellner, L., & Pierce-Friedman, K. (2019). The Types of Case Studies in Research and Career-Based Endeavors. In A. Baron & K. McNeal (Eds.), *Advances in Higher Education and Professional Development. Case Study Methodology in Higher Education* (pp. 83–108). IGI Global. https://doi.org/10.4018/978-1-5225-9429-1.ch005

West, S., Stoll, O., Meierhofer, J., & Züst, S. (2021). Digital Twin Providing New Opportunities for Value Co-Creation through Supporting Decision-Making. *Applied Sciences*, *11*(9), 3750. https://doi.org/10.3390/app11093750

Westermann, T., & Dumitrescu, R. (2018). MATURITY MODEL-BASED PLANNING OF CYBER-PHYSICAL SYSTEMS IN THE MACHINERY AND PLANT ENGINEERING INDUSTRY. In *Design Conference Proceedings, Proceedings of the DESIGN 2018 15th International Design Conference* (pp. 3041–3052). Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia; The Design Society, Glasgow, UK. https://doi.org/10.21278/idc.2018.0260

Wichmann, R. L., Eisenbart, B., & Gericke, K. (2019). The Direction of Industry: A Literature Review on Industry 4.0. *Proceedings of the Design Society: International Conference on Engineering Design*, *1*(1), 2129–2138. https://doi.org/10.1017/dsi.2019.219

Wilberg, J. (2020). *From data to value: facilitating strategy development for connected products* (Dissertation). Technical University of Munich, Munich, Germany. Retrieved from https://mediatum.ub.tum.de/1468778

Wilberg, J., Fahrmeier, L., Hollauer, C., & Omer, M. (2018). Deriving a Use Phase Data Strategy for Connected Products: a Process Model. In *Design Conference Proceedings, Proceedings of the DESIGN 2018 15th International Design Conference* (pp. 1441–1452). Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia; The Design Society, Glasgow, UK. https://doi.org/10.21278/idc.2018.0213

Wilberg, J., Lau, K., Nützel, T., Hollauer, C., & Omer, M. (2018). Development OF A CATALOGUE SUPPORTING IDEA GENERATION FOR INTERNET OF THINGS USE CASES. In *DESIGN 2018 - 15th International Design Conference*. Retrieved from https://www.designsociety.org/publication/40550/DEVELOPMENT+OF+A+CATALOGUE+SUPPORTING+IDEA+GENERATION+FOR+INTERNET+OF+THINGS+USE+CASES

Wilberg, J., Triep, I., Hollauer, C., & Omer, M. (2017). Big Data in Product Development: Need for a Data Strategy. In D. F. Kocaoglu & T. R. Anderson (Eds.), *PICMET '17: Portland International Conference on Management of Engineering and Technology : proceedings : Technology Management for the Interconnected World* (pp. 1–10). Portland, OR: PICMET, Portland State University, Dept. of Engineering and Technology Management. https://doi.org/10.23919/PICMET.2017.8125460

Wirth, R., & Hipp, J. (2000). CRISP-DM: Towards a Standard Process Model for Data Mining. In *International Conference and Exhibition on the Practical Application of Knowledge Discovery and Data Mining.* Symposium conducted at the meeting of Practical Application Company, Manchester, UK.

Wirtz, B. W. (2019). *Digital Business Models*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-13005-3

Wirtz, B. W. (2020). *Business Model Management: Design - Process - Instruments* (2nd ed.). *Springer Texts in Business and Economics*. Springer Cham. https://doi.org/10.1007/978-3-030-48017-2

Wright, L., & Davidson, S. (2020). How to tell the difference between a model and a digital twin. *Advanced Modeling and Simulation in Engineering Sciences*, *7*(1), 1–13. https://doi.org/10.1186/s40323-020-00147-4

Xiong, M., & Wang, H. [Huawei] (2022). Digital twin applications in aviation industry: A review. *The International Journal of Advanced Manufacturing Technology*, *121*(9-10), 5677–5692. https://doi.org/10.1007/s00170-022-09717-9

Yin, R. K. (2018). *Case study research and applications: Design and methods* (Sixth edition). Los Angeles, Calif.: SAGE.

Zakharchenko, A., & Stepanets, O. (2023). DIGITAL TWIN VALUE IN INTELLIGENT BUILDING DEVELOPMENT. *Advanced Information Systems*, *7*(2), 75–86. https://doi.org/10.20998/2522-9052.2023.2.11

Ziemann, J. (2022). *Fundamentals of Enterprise Architecture Management: Foundations for Steering the Enterprise-Wide Digital System*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-96734-5

LIST OF STUDENT THESES

The research project of this dissertation set the context for the following, chronologically listed student theses. The theses were closely mentored by the author and delivered valuable content. In weekly meetings the author of this thesis contributed to all student theses. The students consented to the laboratory and its staff members to use content from their theses for publications, project reports, lectures, seminars, dissertations, and postdoctoral lecture qualifications.

Chebbi, S. (2022). *Literature Review on Digital Twins* [Bachelor's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Dekaluk, A. (2019). *Deriving Use Cases in the Context of Predictive Maintenance for the Innovative Usage of Use Phase Data* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Engelbrecht, J. (2020). *Development of a Concept for Partner Management to Support Sourcing in the Context of Digital Ecosystems* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Finsterer, M. (2021). *Analysis and Detection of Anomalies of the Extrusion Parameters on an Extrusion Press with Artificial Intelligence* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Fischer, D. (2022). *Further Development of a Procedure Model for the Implementation of Digital Twins - A Scientific Case Study* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Lender, B. (2019). *Framework for the systematic development of system architecture processes – a case study in the development of heating systems* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Mac, D. P. (2022). *Further Development of a Digital Twin Business Modelling Approach* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Mahlau, L. (2018). *Conception and Introduction of a Digital Twin in Mechanical Engineering – A Case Study in Technical Product Development* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Matondang, N. R. U. (2021). *Business Modelling Approach for Digital Twin Use Cases* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Mutschler, M. (2021). *Impediments in Implementing Digital Twins* [Term Paper]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Oliverio, F. (2019). *Entwicklung eines Workshopkonzeptes für die Ableitung konkreter Handlungsempfehlungen zur Einführung agiler Methoden in der mechatronischen Produktentwicklung* [Bachelor's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Onuma Okamoto, L. (2020). *Case Study-Based Definition and Conception of Data-Driven Engineering in Mechanical Engineering* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Reschberger, J. (2022). *Conception of a toolbox for the scalable deployment of executable digital twins* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Saygin, M. C. (2019). *Further Development of a Concept for a Digital Twin in Technical Product Development* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Schöberl, M. (2019). *A Guideline for the Implementation of Modelbased Systems Engineering* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Schwarzburg, J. (2021). *Use Case Catalogue for Digital Twins* [Term Paper]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Stöhr, B. (2018). *Konzeption und Einführung eines Digital-Twin-Ansatzes in der industriellen Praxis* [Master's Thesis]. Friedrich-Alexander-Universität Erlangen-Nürnberg, Nuremberg, Germany.

Uhri, E. (2021). *An Experimental Study on the Effect of Synchronization in Distributed Product Development* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

Wiesinger Michael. (2021). *KPI-based Performance Monitoring for Development Projects* [Master's Thesis]. Technical University of Munich, TUM School of Engineering and Design, Munich, Germany.

APPENDIX

A1 Additional Material on the Literature Review

Table A 1: Incomplete List of Industrial Application Areas of Digital Twins Identified in Academic Studies and Literature Reviews.

	Manufacturing	Product Development	Automotive	Aerospace & Aviation	Healthcare	Power Plants & Energy	Retail & Supply Chains	Agriculture	Smart Cities & Urban Planning	Buildings & Construction	Education & Society
Alnowaiser and Ahmed (2023)	x	x	x								
Attaran and Celik (2023)	x	x	x	x	x		x	x			x
Barricelli et al. (2019)	x			x	x						
Crespi et al. (2023)	x				x	x				x	x
D'Amico et al. (2023)	x	x	x	x		x				x	
Fang et al. (2022)	x	x		x					x		
Fuller et al. (2020)	x				x				x		
M. Liu et al. (2021)	x	x					x				
Lu et al. (2020)	x	x			x						
Rasheed et al. (2020)	x				x	x			x		x
Vogel-Heuser et al. (2023)	x	x					x			x	

A2 Additional Material of the Online Survey on Challenges in the Implementation of Digital Twins

A2.1 Questionnaire of the Online Survey

In this section, the question design and wording are outlined in detail. Therefore, the questions (Q) are numbered. The type of question and the given answers, if existing, are written cursive behind the question. In addition to that, the aim of the questions as well as evaluation methods for the specific questions are described. The survey was introduced with the following statement:

> *"Dear participant,*
>
> *Welcome and thank you for your interest in this study. Digital Twins represent one of the most exciting and promising fields in technology research. For two decades now, the concept of a Digital Twin is known. However, in industry, there is still now comprehensive implementation known to date. Thus, in this survey, we are interested in the IMPEDIMENTS IN IMPLEMENTING DIGITAL TWINS. So, factors hindering implementation and scaling of Digital Twins.*
>
> *The survey takes about 15 minutes to complete. Data will be collected anonymously and used for scientific research purposes only. Also, data collection is in line with Art. 13 EU-DSGVO.*
>
> *The survey begins with a definition of Digital Twins and then asks you to rate experiences with and aspects of Digital Twins. Please read the questions thoroughly and answer them intuitively.*
>
> *Thanks again for your participation. Please enjoy the survey!*
>
> *Yours sincerely,*
>
> *Jakob Trauer & Michael Mutschler"*

Followed by an explanation of the definition of Digital Twins within this project.

> *"Despite a large interest in Digital Twins by both research and businesses, there is still no consistent, overarching definition of Digital Twins. For the purpose of this survey, we use the following definition:*
>
> *"A Digital Twin is a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange."*
>
> *This definition highlights the three crucial aspects of Digital Twins:*
>
> *1. The Digital Twin is a virtual dynamic representation of a physical artifact or system,*
>
> *2. Data is automatically and bidirectionally exchanged between the Digital Twin and the physical system,*
>
> *3. The Twin includes data of all phases of the entire product lifecycle and is connected*

to all of them.

Please refer to this definition as a common basis for the questions on the following pages.

If your or your company's definition has small deviations/variations to this definition, please answer the questions as if the definition is congruent to ours."

After these two editorial parts, the survey begins.

Q1: Does your job involve working with Digital Twins? (In the past or now)

Filter question, single choice

- *Yes → continue with Q2*
- *No → Q20*

Q2: Which of these synonyms are used in your company in the context of Digital Twins? (multiple selection possible)

Multiple choice

- *Digital Shadow*
- *Device Shadow*
- *Digital Replica*
- *Device Replica*
- *Device Twin*
- *Digital Thread*
- *Other*

Q3: Your job involves working with Digital Twins. Please describe the latest use case in a few sentences.

Open question

Q4: How successful was that use case in your opinion?

Closed question: Scale 0-10

Q5: Which departments of your company were involved in the Digital Twin project? (multiple selection possible)

Multiple choice

- *Production*
- *Marketing*
- *Research and Development*
- *Purchasing*
- *Human Resource Management*
- *Accounting and Finance*
- *Sales*
- *Quality Management*

Q6: Others?

Open question

Q7: What was the companies' budget for digitalization in general? (per year)

Open question

Q8: What was the companies' budget for the latest Digital Twin project?

Open question

Q9: Which department was responsible for the implementation of the Digital Twin?

Open question

Q10: When did you or your company start planning the Digital Twin project?

Open question

Q11: How long did it take from planning to implementation?

Open question

Q12: Did difficulties occur during the Digital Twin project?

Filter question, single choice

Q13: Which Department had the greatest difficulties with the implementation of the Digital Twin?

Open question

Q14: Please describe these difficulties in a few sentences.

Open question

Q15: Please rate these categories according to their potential of causing difficulties in implementing Digital Twins.

Likert-type scale (-2, -1,0,1,2)

- *Technical: e.g. difficulties with real-time capability*
- *Organizational: e.g. responsibilities, competencies*
- *Procedural: e.g. no suitable procedures to support the implementation of Digital Twin*
- *Management: e.g no support from management due to missing business models*
- *Cultural: e.g. skepticism about new technologies*
- *Legal: e.g. intellectual properties*
- *Conceptional: e.g. missing methods to support the conception of Digital Twins*

Q16: Could some difficulties be solved?

Filter question, single choice

Q17: Which difficulties could be solved? Please explain briefly.

Open question

Q18: Did the Digital Twin project end because of unsolved difficulties?

Single choice

Q20: Please rate the following aspects by their potential/likelihood to cause problems.

Likert-type scale (-2, -1,0,1,2)

In this question, in literature mentioned impediments, difficulties and barriers to Digital Twins are listed. The list of impediments presented can be seen in Figure A 1.

Q21: In your opinion, are there any other impediments to the implementation of Digital Twins?

Open question

Q22: In your opinion, what should be future directions in research on Digital Twins?
Open question

Q23: Do you know about Digital Twin projects in your company in the future?

Closed question, single choice

- *Yes*
- *No*

Q24: Does your company have a digitalization strategy?

Closed question, single choice

- *Yes → Q25*
- *No → Q26*

Q25: Which of these keywords are part of this strategy?

Closed question, multiple choice

- *Internet of Things*
- *Industry 4.0*
- *Machine Learning*
- *Virtual Reality*
- *Augmented Reality*
- *Artificial Intelligence*

Q26: Did your company create positions to push the digitalization process?

Closed question, single choice

- *Yes*
- *No*

Q27: What is your age in years?

Open question

Q28: What is your current job title?

Open question

Q29: What is your academic background?

Closed question, single choice

- *Mechanical Engineering*
- *Industrial Engineering*
- *Electrical & Computer Engineering*
- *Civil, Geo and Environmental engineering*
- *Informatics*
- *Mathematics and Natural Science*
- *Law, Business & Economics*
- *Social Science & Humanities*
- *Other*

Q30: How much work experience do you have?

Closed question, single choice

- *0-2 years*
- *3-5 years*
- *5-10 years*
- *10-20 years*
- *More than 20 years*

Q31: In which industry does your company operate?

Closed question, single choice

- *Energy*
- *Materials*
- *Capital Goods*
- *Commercial & Professional Services*
- *Transportation*
- *Automobiles & Components*
- *Consumer, Durables & Apparel*
- *Communication Services*
- *Consumer Services*
- *Food, Beverage & Tobacco*
- *Household & Personal Products*
- *Health Care Equipment & Services*
- *Pharmaceuticals, Biotechnology & Life Science*
- *Banks*
- *Insurance*
- *Software & Services*
- *Technology Hardware & Equipment*
- *Semiconductor & Semiconductor Equipment*

- *Telecommunication Services*
- *Media & Entertainment*
- *Utilities*
- *Real Estate*
- *Other*

Q32: How many employees does the company you work for have?

Closed question, single choice

- *Less than 50*
- *50-250*
- *250-500*
- *500-2000*
- *More than 2000*

Q33: What is the organizational structure of your company?

Closed question, single choice

- *Hierarchical*
- *Matrix*
- *Functional*
- *Product*
- *Customer*
- *Geographic*
- *Network*
- *Other*

Q34: Which general methodology does your company follow?

Closed question

- *Waterfall*
- *Agile*
- *Lean*
- *Iterative*
- *Prototyping*
- *DevOps*
- *Spiral*
- *V-Model*
- *Other*

Q35: At what level does your employer operate?

Closed question

- *National*
- *International*

Q36: Any other comments you would like to make about the survey?

Open questions

A2.2 Use Cases Collected in the Online Survey

Table A 2: Use Cases, the Survey Participants are Working on.

ID	Use Case
1	*We are researching into the use of the Digital Twin in early-stage engineering design. While we are influenced by the Digital Twin, we've found that conceptually, elements of it are not suitable in early-stage design and as such we are borrowing concepts from it. The concept of twinning physical and virtual for example. Whereas by-directional and real-time synchronization are currently less applicable/achievable.* *(answer to 2 is "other" because the form needs an answer but we don't use any synonyms for the Digital Twin)* *(answer to 4 is based on the application of the Digital Twin to our use-case rather than the concepts we are borrowing from it)*
2	*We call it "to model". Using a tool for optimizing spare parts, maintenance, systems and their operations. Given the data we have, we guess a lot of data (equal it out) and in the end the customer gets for the first time an overview about his organization, meaning maintenance, operation and the fleet regarding performance and costs. With that tweaking some parameters it is easy to compare it with other parameters to find the optimal solution.*
3	*We wanted to have a digital shadow of a production line, to ease tracking of bottlenecks in the production process.*
4	*We wanted to create a digital twin of a part of the logistic.*
5	*Replicated production cloud environment which includes real-time data for staging/testing purposes*
6	*internet research*
7	*Digital Twin of a weight for the calibration traceability and uncertainty modeling*
8	*digital twin of products and productions*
9	*Wir arbeiten mit einem Anbieter von Digital Twin Technologien zusammen, um Kunden bei der Erstellung digitaler 3D-Repliken für Vermessung, Modellierung und Virtual Reality sowie bei der Validierung des Ist-Zustandes gegenüber dem Soll-Zustand zu unterstützen.*
10	*finite element calculation*

ID	Use Case
11	*Simulation and Modelling of processes*
12	*I develop/update Digital Twin maturity models, research in this area and assess companies in regard to their Digital Twin maturity /capabilities and develop roadmaps to improve their maturity.*
13	*Documentation of our huge portfolio in a digital way and connecting all relevant data objects like BOM's, drawings, templates, text blocks, cost models, etc...*
14	*PLM Projektleiter*
15	*I'm working for the German railway (DB Netz) and I'm responsible for the System design of signal boxes. We are currently working on implementing digital twins of these systems for several purposes. We are still in a starting phase.*
16	*1. Product Digital Twin - model of thermal system behavior and simulation in digital to avoid physical prototypes and tests.* *2. Production Digital Twin - modelling and simulation of production processes for new factory. Here digital product data were used to model the objects of production processes*
17	*Monitoring the (production) life cycle of a workpiece with focus on machining industry:* • *predictive maintenance (abrasion tool, reduction downtime)* • *predictive tool breakage* • *Optimizing work process (tools, angles)* • *Sharing data across corporate boundaries*
18	*Enable digital twin based on development data and homologation data for process optimization*
19	*Virtual product configuration*
20	*Daily work with CAD models. Several simulation models:*
21	*We are currently in the phase of collecting and access all relevant datapoints for our products. This includes data from engineering, manufacturing, procurement, assembly, EoL test, OEM eol test, usage data, service data until the end of the product lifecycle. At the end we try to cover every product that leaves one of our facilities from cradle to grave.*
22	*We develop a digital twin for each product on a green field using existing decentralized data sources, HW and SW - to serve multiple Use Cases from different areas of our company.*
23	*We produce a digital twin of the product portfolio and all associate value*

ID	Use Case
	stream elements (from supplier to customer) from ERP data. The aim is to use this Digital Twin of the enterprise to drive complex decision making, e.g., to optimize the product portfolio. I will answer the following question from the perspective of a typical customer of ours.
24	*We are creating an early model of the future product using METUS, the digital DNA, even before the digital Twin evolves*
25	*Mass product which can be simulated (virtual) and physically reproduced, operated, optimized and maintained both in the company during development and later in real customer operations.*
26	*Exchanging complete data set of all measured operation parameters. Store it in a database, automated analysis of data. Calculating KPIs...)* *Data remains in database in case service actions require a more detailed manual study on the operational behavior of the system.* *(It does not fit the given definition of "digital twin", but at least it covers some of the aspects.)*
27	*To identify gaps inside the twin's parameter landscape (e.g., due to model reduction and simplification for better simulation performance)* *To identify necessary redundancies for parameters (e.g. offline settings like mounting angle of a sensor)*
28	*We are moving from a digital shadow to a digital twin to better simulate upcoming changes*
29	*Defining understanding of digital twins and conceptualization of data models related to them.*

A2.3 Complete List of Challenges in Implementing Digital Twins

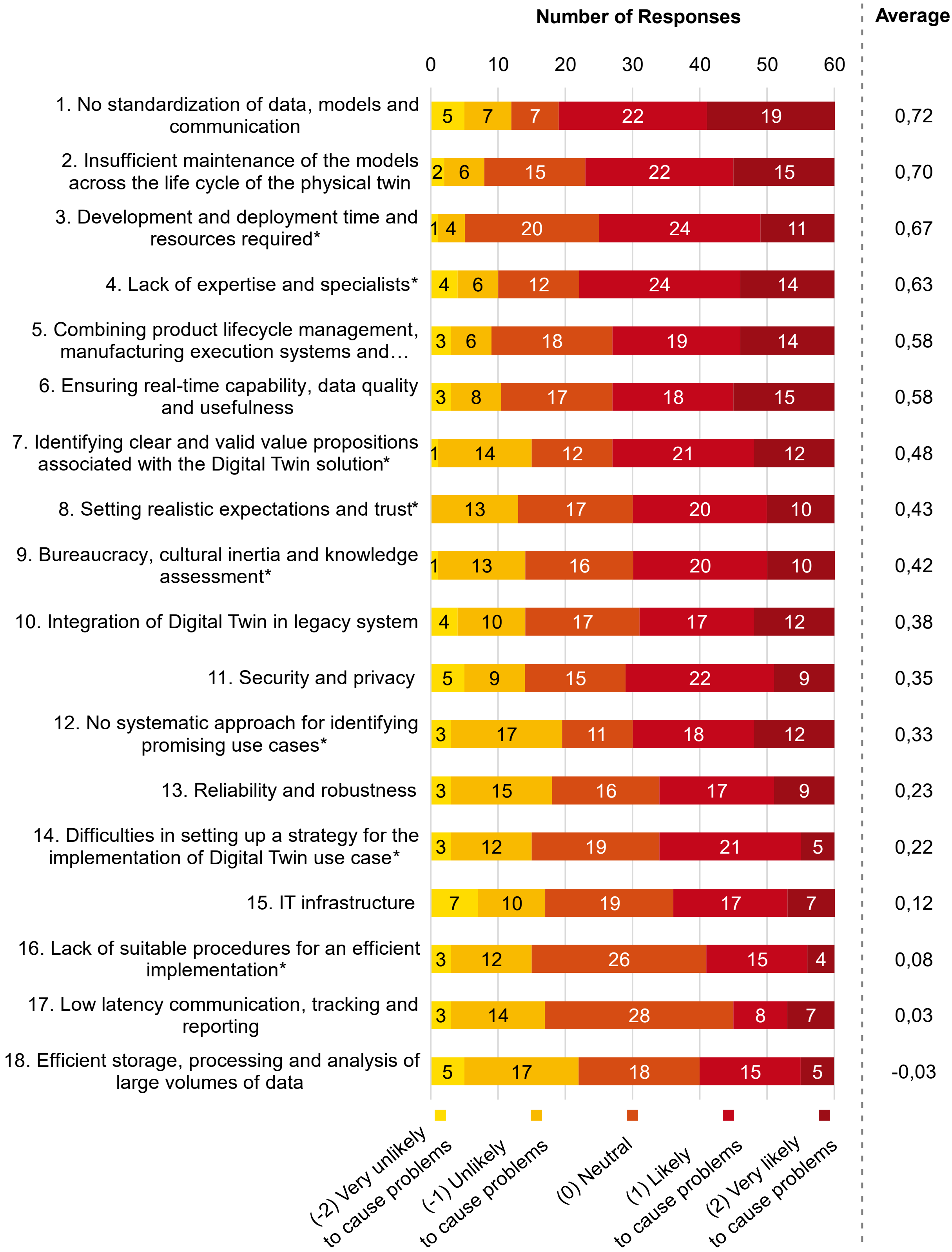


*Figure A 1: Rating of Specific Aspects According to their Average Likelihood to Cause Problems (on a Scale from -2 to 2). Nontechnical Aspects Are Marked with a *.*

Aspects #3-#11, #17, and #18 in Figure A 1 were selected based on the literature review conducted by Perno et al. (2021). Issues #1 and #13 were derived from Tao, Zhang, et al. (2019), while challenges mentioned by Neto et al. (2020) inspired #15 and #16. Aspect #2 was identified as a problem by an industry expert in the interview study conducted by Trauer, Schweigert-Recksiek, et al. (2022). Aspects #7, #12, and #14 were added based on our own experiences, considering the potential influence of non-technical aspects on the success of DT projects. For clarity reasons in Figure A 1, each step was labeled, even though the participants only voted on endpoint labeled scales (cf. section 3.1).

A2.4 Future Research Identified in the Online Survey

Table A 3: Future Research Areas in the Context of Digital Twins Proposed by the Survey Participants (based on Trauer, Mutschler, et al., 2022).

ID	In your opinion, what should be future directions in research on Digital Twins?
1	*Differentiating against predictive maintenance. Or find a proper integration into the topic.*
2	*The impact of human behavior is not considered. Personal preferences and dislikes are hard to implement in any computer or production system, but they influence the output.*
3	*We should follow this idea and should use digital twins as much we can*
4	*Find out how DT will help the producer, operator and thus the customer in public transport systems. Create a need for the customer. Otherwise, the producer and customer will not soon put enough effort into it.*
5	*change management, execution of new software solutions*
6	*qualification of the analytical models, verification of the numerical models and validation on real parts*
7	*Service orientation seems to make for good business models. Depending on the use case and domain, bringing all the stakeholders together by providing models which demonstrate mutual benefits will be important. The technical architecture also needs to be on track, considering networking from subsystem / sensor to system and virtual twin.*
8	*Democratization of the Digital Twin*
9	*B2B, engineering companies with a huge portfolio*
10	*Develop a holistic user model*
11	*Finding a clear guideline: What is the minimum hardware and software you need to implement for a digital twin and what are simple benefits that can be achieved. Most small and mid-size companies in general engineering are product driven. In the meantime they start to make their products "intelligent", but there is no real strategy behind them.*
12	*Identifying clear and valid value propositions associated with the Digital Twin solution*
13	*Focus on when a digital twin can add which value - it’s a nice and promising idea in many*

ID	In your opinion, what should be future directions in research on Digital Twins?
	fields but it will be crucial to have a systematic approach to assess when the implementation of a digital twin really pays out and when it does not.
14	*Showing methods to quantify the benefit of Digital Twins instead of using traditional methodologies/procedures in R&D and production engineering.*
15	*How the data can be used to create added value for maintenance and development, while ensuring that the costs and benefits are in proportion.*
16	*Definition of the technical content of a digital twin for different specific products or product families.*
17	*Providing use cases and best practices to help setting up a DT strategy*
18	*What I am missing today is the big picture with the digital twins. many companies work on similar twin programs but ideally this could end up in an aggregation OEM - Tier 1 supplier - Tier 2 supplier .... with a potential use of data between all the different players.*
19	*combination of digital twins of different companies in one network*
20	*Digital twin research has to include current research on data analytics and decision theory.*
21	*I think the possible uses and advantages of digital twins in business use cases. Since - especially in more "classic" engineering companies - people are quite sceptic against such digitalization and clear arguments and advantages are needed to convince them, that this is the way.*
22	*Early phase modelling of Digital Twins - when information is not yet mature*
23	*First of all, the prerequisites in the company for a digital twin must be created; the respective applications depend very much on the business model.*
24	*1. Define standards and explain use-cases based on Industry proven experts: https://idtwin.org/* *2. Fund research according to the newly set standards for better re-use and take "Best in Class" Research to "Best Practice" demonstrators. Focus on closing in on company based political hurdles by supporting IP protection through FMU implementation.*
25	*Semantic data modelling and management*

A3 Additional Material of the Case Study on Climate solutions

A3.1 Supporting One-Pagers of the Procedure Model as Applied in the Case Study

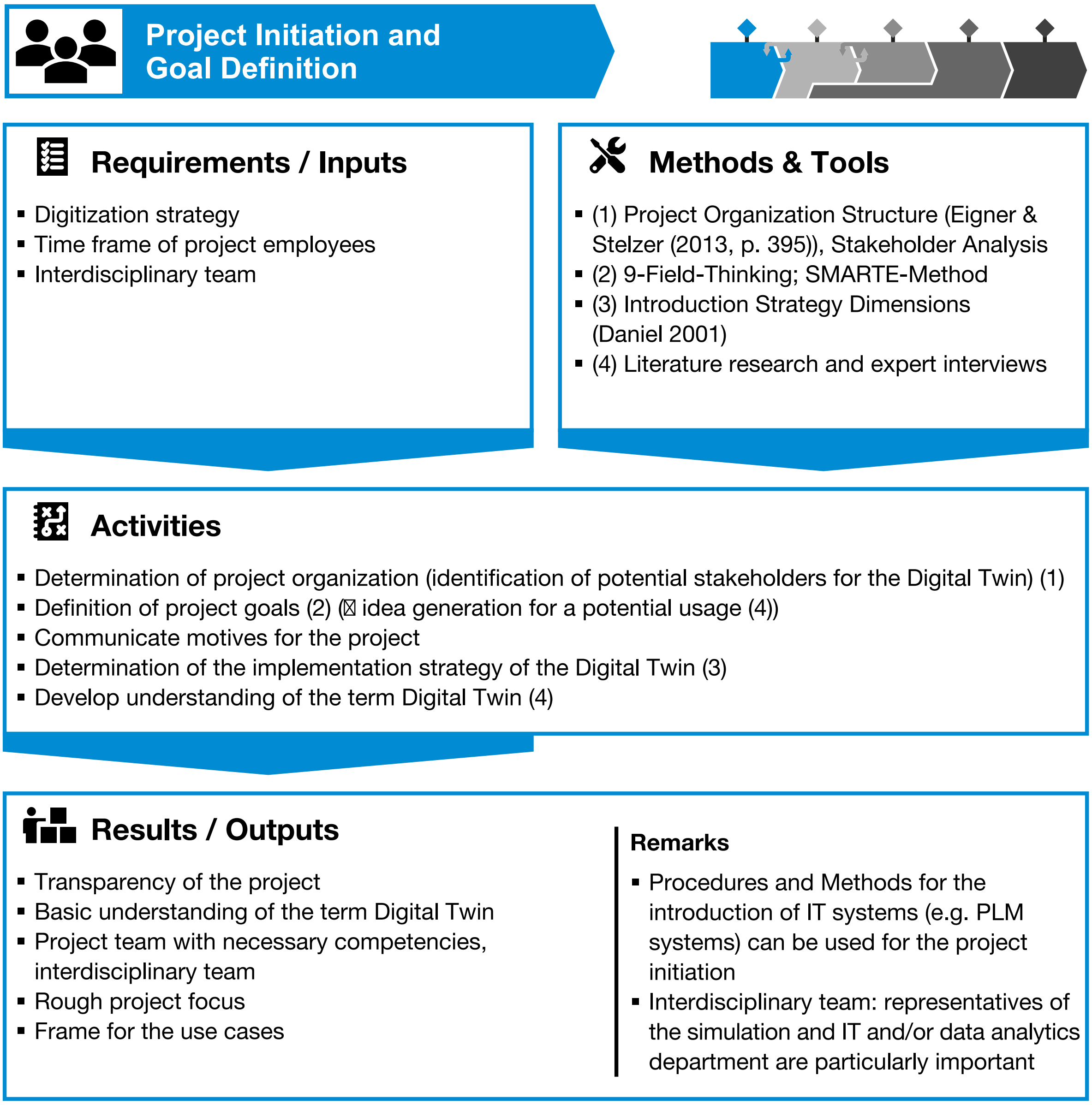
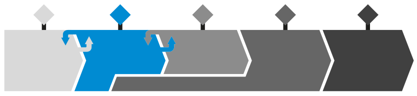


Figure A 2: Overview of the first step Project Initiation and Goal Definition (Schweigert-Recksiek et al., 2020).

Situation Analysis: Use Cases for the Acquisition of Expectations



Requirements / Inputs

- Basic understanding of the term Digital Twin
- Time frame for project employees and Digital Twin stakeholders are identified
- Open-mindedness of project employees regarding the situation analysis
- Rough project focus

Methods & Tools

- (1-a) Expert interview (1-b): Benefit catalogue
- (2) Influence Matrix (MDM and DMM)
- (3) Question catalogue current structure and checklist current process and swimlane diagram
- (4) SWOT analysis; 9-Field-Thinking
- (5) Creativity methods (Lindemann (2016, S. 744)) and literature research, supplier portfolio
- (6) CPS modeling (Westermann (2018))
- (7) Use Case Template (Title, Problem, Goal …)

Activities

- Take up and reflect on problems and expectations (1-a) and cluster problem areas (2)
- Elaborate the term Digital Twin
  - Review and process goal / vision
  - Define characteristics of the Digital Twin → considering expectations and problems
- Elaborate and develop rough / desired use cases (1), (7)
  - Pre-phase – gather explorative ideas / use cases and check compatibility (1), (5)
  - Connect problems and stakeholders with use cases (1), (2)
  - Itemization – elaborate use cases (7)
  - First cost-benefit estimations (1-a, 1-b)
- Analyze current situation of the company
  - Analyze project group(s) (6) (Focus: product architecture with sensors / use phase data, interconnections, interfaces etc.)
  - Analyze the simulation landscape
  - Record and model **current structure**: (3) IT systems / infrastructure, DMS, data / information flows, models, tools, artefacts
  - Record and analyze **current**: Process activities and procedures, areas and responsibilities, classification in PEP (3)
  - Determine current and target degree of maturity
- Benchmark of possible implementation partners
- Perform vulnerability / potential analysis (4)

Results / Outputs

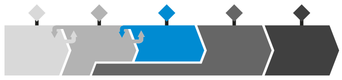
- Strong understanding of terms and problems
- Assessment of / transparency about the digital twin degree of maturity and current status of the company
- Precise target (→ delimited from unjustified expectations)
- Collection of Digital Twin Use Cases in a standardized format

Remarks

- Use Case Template: Current structure = tab sheet 2, current process = tab sheet 3

Figure A 3: Overview of the second step Situation Analysis (Schweigert-Recksiek et al., 2020).

Target concept: Use Cases for the Conception of the Digital Twin



Requirements / Inputs

- Understanding the current situation (Use Cases with current structure, current process)
- Strong understanding of terms (Digital Twin Definition, Goal and Features)
- Sufficient time available to project staff and stakeholders
- Collection of potential DT-Use Cases standardized format (DT-Template)

Methods & Tools

- (1-a) Portfolio Analysis (1-b) Influence Matrix (MDM, DMM); (1-c) Use Case Template
- (2): Expert interviews; Check-list target process; Process chart of coordinated swimlanes
- (3) Benefit catalogue and cost / benefit dimensions (use cases)
- (4) Process from current to target conception
- (5) Iiterative approach between target process and task formulation
- (6) Assignment of roles in target processes
- (7) RACI method
- (8) Methods for data evaluation (cost / benefit)
- (9) Portfolio analysis of data points (cost / benefit)

Activities

- Reduce complexity with a multi-layer model
  - Cluster and pre-select Use Cases (1-c)
  - Define the project focus
- Define target process and target organization (2), (4)
  - Part I. **Target-process** within the use cases (2), (4)
  - Part II. Coupling in the PEP outside the use case
  - Use the Digital Twin where it creates value, without local, process- or person-oriented limitation (without DT interface box) (4)
  - Distinguish digitized and human activities by differently colored marking (4)
  - Use the Digital Twin user interface icon sensibly when transferring responsibility between man and computer
- Work out the details of Use Cases and consolidate them
  - Describe a **virtual model** (Tools, models, parameters, development and use phase data)
  - Evaluate Use Cases in detail (3)
  - Prioritize Use Cases and Define Sequence (1-a), (3)
- Point up the link between selected use cases (tools, virtual models, process steps etc.) (1-b)
- Data evaluation (8), (9)
  - Determine data points i.e. necessity for specific data within specific use cases
  - Perform data evaluations (8)
  - Analyze evaluation results (9)
  - Deduce data management strategies
- Assignment of roles or responsibilities for target status (7), (6)
  - Assignment of roles at decision nodes according to internal role descriptions (6)
  - Assignment of responsibilities to the assigned roles (7)
- Formulate tasks (5)
  - … with regard to the requirements for the implementation of the target concept
  - … in accordance to the target process steps
  - Determine starting and end point
  - Sensible use of the clauses "to be able" (Digital Twin is put forward) and "... offering opportunities" (focus on the human being)
- Derive specifications "90%"
  - Derive tasks or requirements (use "tabs 1 to 6" with Use Case content)
  - Specify requirements and check completeness

Results / Outputs

- Evaluated and selected use cases (with target process, tasks, etc.) for implementation
- Relationships and dependencies between the use cases (first Digital Twin concept)
- Specific project focus: understanding the necessary adjustments to the framework conditions
- Understanding the feasibility of the target concept
- (90%) Specifications including tasks

Remarks

- Digital Twin interface = tab sheet 4, target process = tab sheet 5, virtual model = tab sheet 6 in the use case template
- Multi-layer model: it is restricted to the environment to be controlled e.g. sovereignty over the use phase data (layer I) and then extended step by step (layer II. ... layer n.)

Figure A 4: Overview of the third step Target Conception (Schweigert-Recksiek et al., 2020).

Vendor Analysis: Use Cases for Requirement Definition

Requirements / Inputs

- Target concept and understanding of its feasibility
- Understanding the current situation and specific project focus
- Tasks derived from target process (90 % specification sheet)
- Evaluated and selected use cases and clear depiction of their relationships

Methods & Tools

- (1) Epic
- (2) Requirements template (specific, measurable, focused, domain-specific)
- (3) Contextual Inquiry, Personas and Scenario-JTBD
- (4) User Stories and INVEST

Activities

- Carry out detailed market analysis and evaluate product profiles
- Perform cost and benefit analysis and **select vendors**
- Analyze the user perspective on the Digital Twin (identify prototypical users) (3)
- Define requirements format and structure (1)
  - Coordinate requirement format with implementation partners
  - Determine requirement hierarchy
  - Transition from content of use cases ←→ requirements document
- **Derive specifications** and **acceptance** (use case) (2), (3), (4)
  - Check completeness of tasks and requirements
  - (100%) Provide specification sheet
  - Feasibility study of the DT target concept: to compare implicit tasks or requirements of the use cases with the products of potential vendors
  - Adapt target process or tasks according to the requirement specification
  - Derive implementation roadmap
  - Define test cases and acceptance criteria for the requirement specification

Results / Outputs

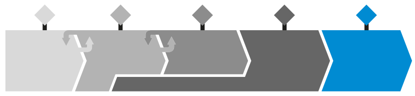
- Transparency of costs and benefits
- Selected vendors
- Concerted form of cooperation
- Scope statement including adapted target processes, tasks and acceptance criteria
- Implementation roadmap

Remarks

- Scenario-JTBD Jobs-to-be-Done (Tagabergenova & Köbler 2018, (S. 334))
- Derive requirements: use the current structure in “tab 1“ that describes an IT perspective
- INVEST: Independent, Negotiable, Valuable, Estimatable, Small, Testable

Figure A 5: Overview of the forth step Vendor Analysis (based on Schweigert-Recksiek et al., 2020).

Implementation: Use Case as Acceptance Criterion / Test Case



Requirements / Inputs

- Target concept
- Selected implementation partner
- Harmonized co-operation
- Requirement specification including adapted target process, tasks and acceptance criteria
- Sufficient time available to project staff
- Implementation roadmap

Methods & Tools

- (1) Communication Events and Change Management (according to Leiting (2012, S. 22))
- (2) Current Structure and Current Process, and Target Concept and Tasks
- (3) ALM Tool

Activities

- Communicate changes in the company (1), (2)
- Pilot and implement Digital-Twin
- Implement target concept
- Adapt current processes and organization to target conception (2)
- Train and supervise user
- Realize implementation roadmap
- Monitor target achievement and do Lessons Learned (3)

Results / Outputs

- Adapted processes
- Implemented Digital-Twin (Use-Case)
- Understanding the next steps

Remarks

- Use experience of change management
- Demonstrate the link between the Digital Twin and the digitization strategy in the company (if applicable)

Figure A 6: Overview of the fifth step Implementation (Schweigert-Recksiek et al., 2020).

A3.2 Completed Use Case Template for Use Case A1

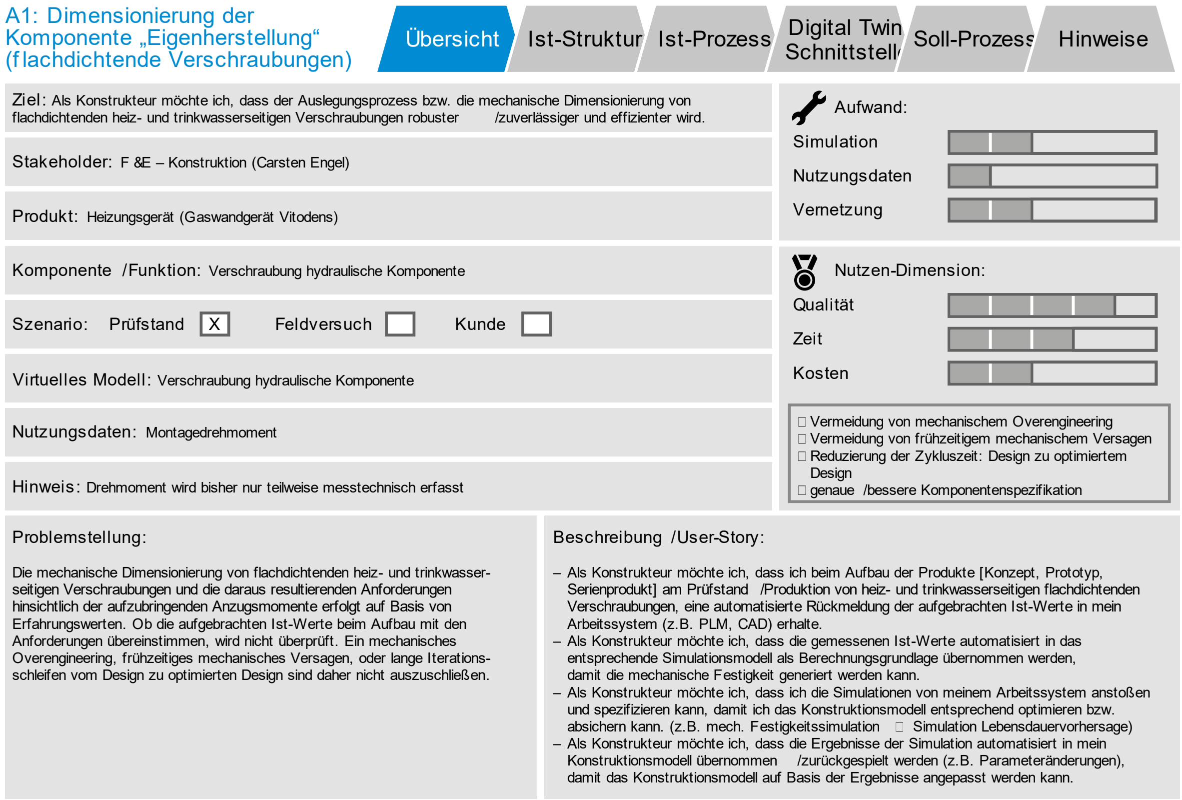


Figure A 7: Overview of Use Case A1 “Flat-Sealing Water Fittings” (Schweigert-Recksiek et al., 2022). Reduced Template for the Application of an Engineering Twin.

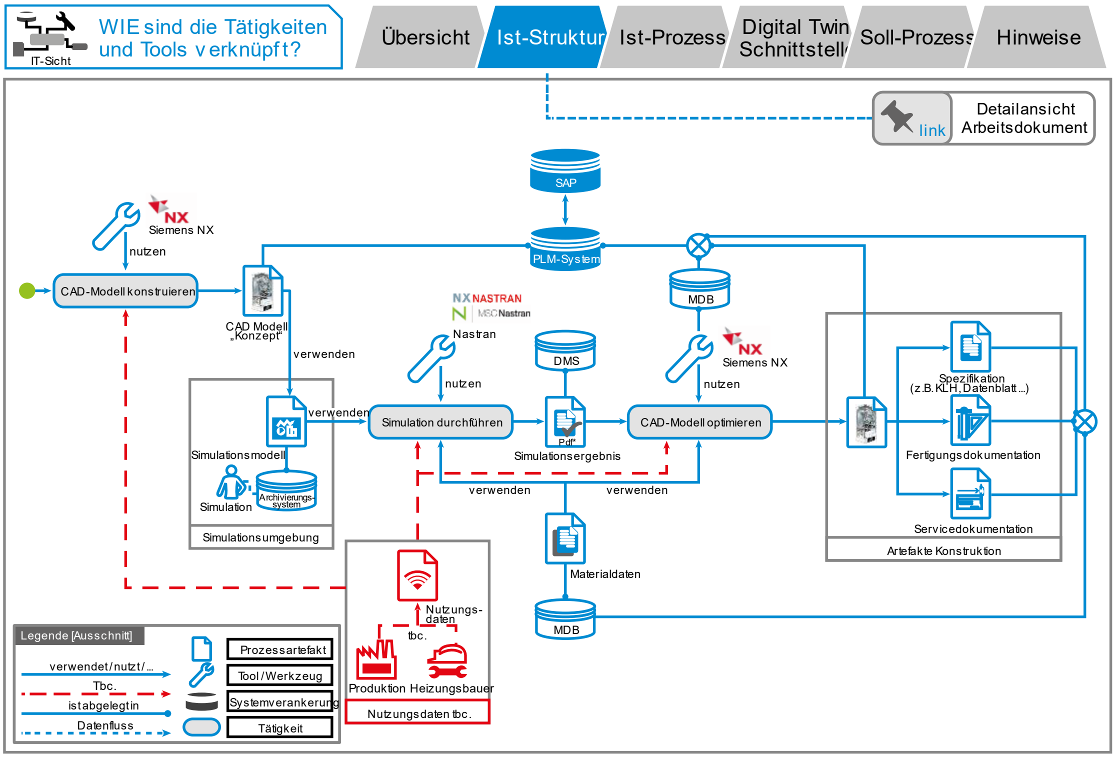


Figure A 8: As-Is Structure of Use Case A1 "Flat-Sealing Water Fittings" (Schweigert-Recksiek et al., 2022). Reduced Template for the Application of an Engineering Twin.

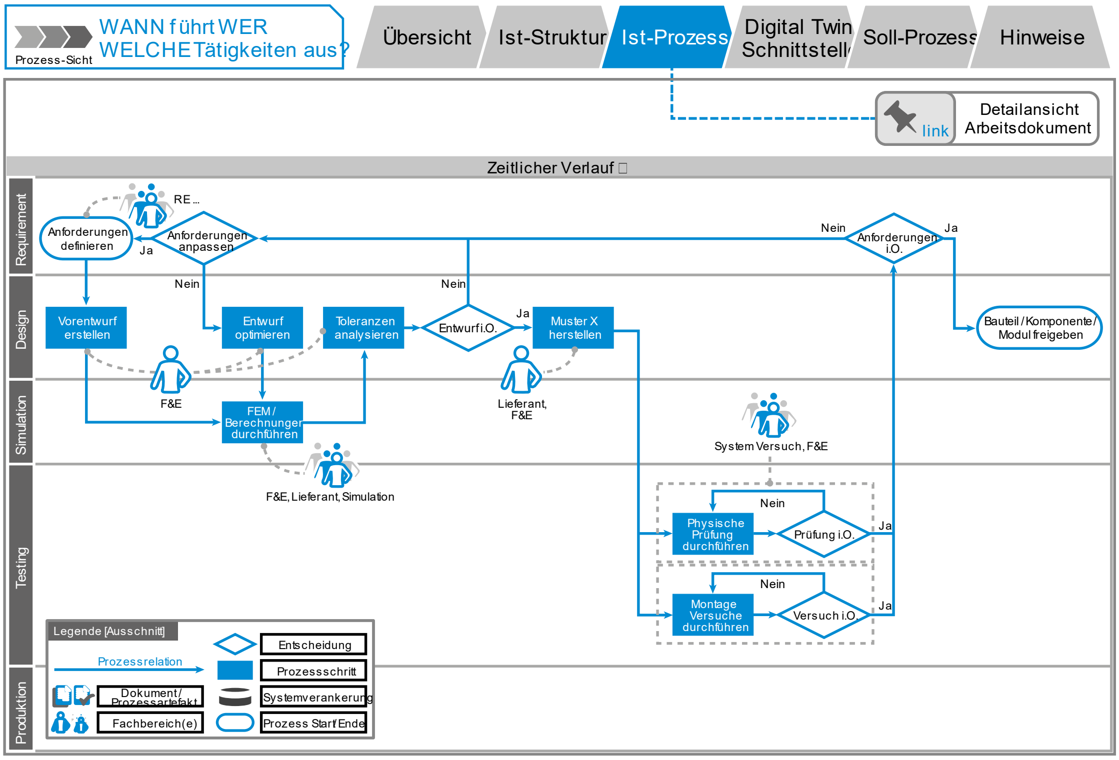


Figure A 9: As-Is Process of Use Case A1 "Flat-Sealing Water Fittings" (Schweigert-Recksiek et al., 2022). Reduced Template for the Application of an Engineering Twin.

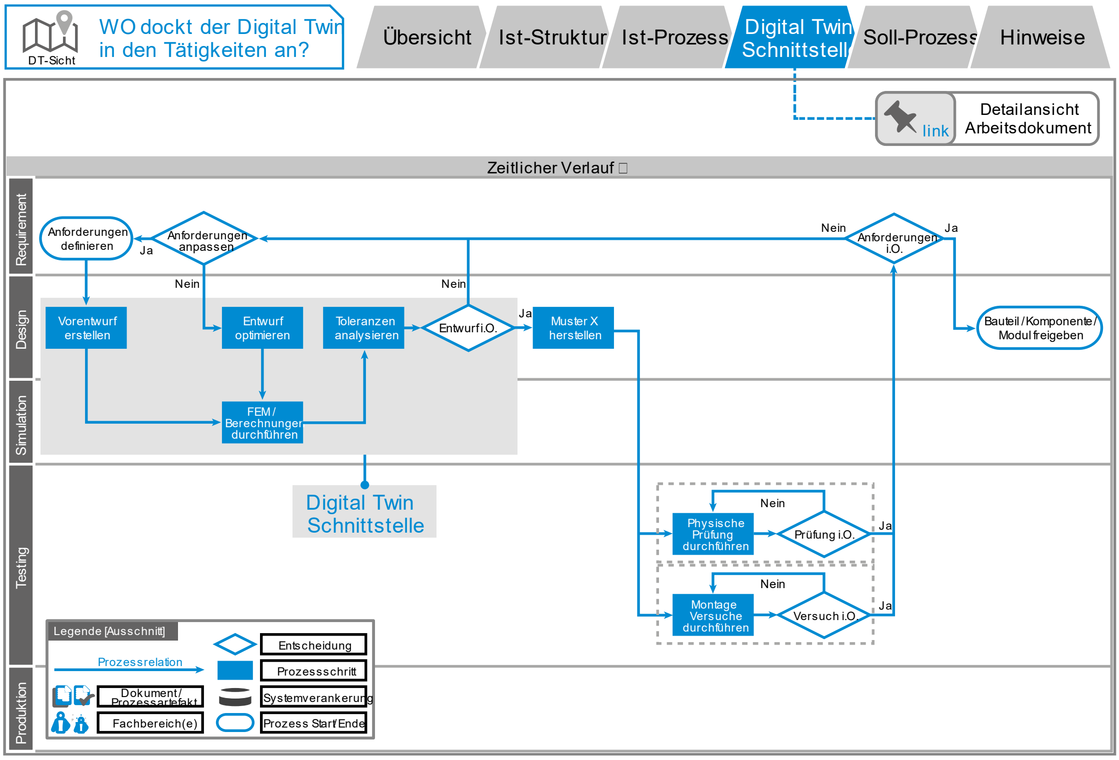


Figure A 10: Digital Twin Interface of Use Case A1 "Flat-Sealing Water Fittings" (Schweigert-Recksiek et al., 2022). Reduced Template for the Application of an Engineering Twin.

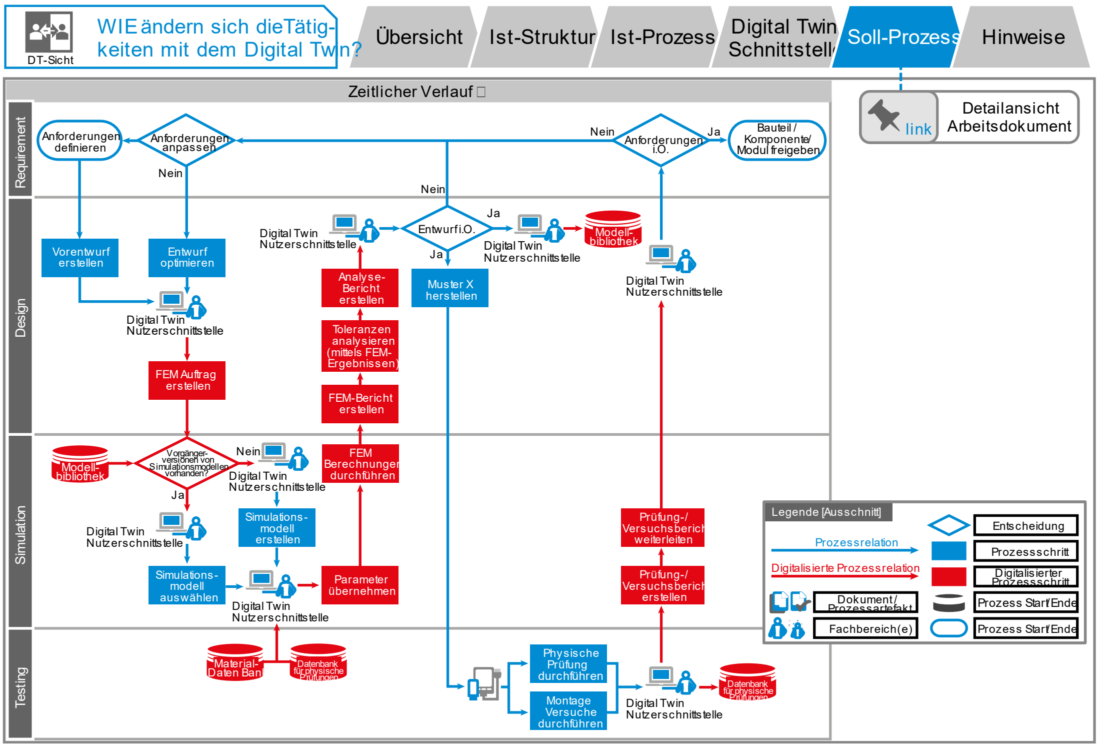


Figure A 11: Target Process of Use Case A1 "Flat-Sealing Water Fittings" (Schweigert-Recksiek et al., 2022). Reduced Template for the Application of an Engineering Twin.

A3.3 Evaluation of the Case Study on Engineering Twins for Climate solutions

In the following, the evaluation form used in the case study on DTs for climate solutions is presented. As all participants were German native speakers, the questions were formulated in German to avoid misunderstandings.

Evaluationsbogen

Fokussierung auf die drei Dimensionen - Anwendbarkeit, Tauglichkeit und Nützlichkeit

Falls Sie mit „nicht zustimmen" geantwortet haben, geben Sie bitte an, was ihre Gründe sind und wie eine Verbesserung aussehen könnte.

Interviewpartner	
Name, Vorname	
Position	
Abteilung	
Bereich	Forschung und Entwicklung

Aufbau der Evaluierung

- A. Offene Fragen Digital Twin
- B-I. Bewertung: Vorgehensmodell – theoretischer Kontext
- B-II. Bewertung: Vorgehensmodell – praktische Anwendung
- C. Bewertung: Methoden & Ergebnisse → Nur Kern-Stakeholder
- D. Gesamtbewertung
- E. Optional - Auswirkungen auf die Abläufe in der Produktentwicklung

A. Offene Fragen zum Digital Twin

Welche Chancen/Potential sehen Sie im vorgestellten Konzept eines Digital Twin?

____

____

____

____

Welche Herausforderungen sehen Sie bei der Einführung dieses Konzeptes eines Digital Twin?

____

B-I. Bewertung des Vorgehensmodells im theoretischen Kontext

Vorgehensmodell – theoretischer Kontext					
B-I. 1	Eine strukturierte Herangehensweise zur Konzeption und Einführung eines Digital Twin ist notwendig.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-I. 2	Das Vorgehensmodell enthält die notwendigen bzw. wesentlichen Schritte, von der Initiierung & Zieldefinition, bis zur Implementierung.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-I. 3	Die Reihenfolge der Schritte des Vorgehensmodells ist sinnvoll.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-I. 4	Die Schritte enthalten die notwendigen Methoden und Aktivitäten, um die Konzeption und Einführung eines Digital Twin ausreichend zu unterstützen.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-I. 5	Es ist sinnvoll Aktivitäten der Anbieteranalyse wie bspw. „*feasibility study*“ bereits in den Phasen der Situationsanalyse und Soll-Konzeption durchzuführen, um die „Umsetzbarkeit“ der später identifizierten Anforderungen zu gewährleisten.				
☐	☐	☐	☐	☐	☐

Stimme überhaupt nicht zu	Stimme nicht zu	Stimme eher nicht zu	Stimme eher zu	Stimme zu	Stimme völlig zu
B-I. 6	Das Format und der Inhalte der Use Cases sind ausreichend strukturiert.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu

B-II. Bewertung des Vorgehensmodells in der praktischen Anwendung

Vorgehensmodell – praktische Anwendung					
B-II. 1	Die Limitierung des Anwendungsbereichs war für den Einführungsprozess sinnvoll. *- Engineering Twin, Schalenmodell, Fein/Grob/Fein -*				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-II. 2	Die Formulierung von Use Cases für den Digital Twin, ist ein hilfreicher Ansatz zur Ableitung von Anforderungen.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-II. 3	Die identifizierten Use Cases sind sinnvoll für die Umsetzung eines Digital Twin Konzeptes.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-II. 4	Die Ausgewählten Use Cases stehen in einem ausreichenden und sinnvollen Aufwand Nutzen-Verhältnis.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu

B-II. 5	Die Umsetzung der ausgewählten Use Cases ist als realistisch einzuschätzen.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-II. 6	Die Konsolidierung und Identifikation von Schnittstellen der Use Cases unterstützt die Konzeption eines Digital Twin.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
B-II. 7	Das Vorgehensmodell ermöglicht eine strukturierte Herangehensweise zur Einführung eines Digital Twin.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu

C. Bewertung der Methoden und Ergebnisse

Methoden und Ergebnisse					
C.1	Die strukturelle Modellierung der IST-Struktur/IT-Sicht (Use Case Reiter 2) ist hilfreich, um Brüche zwischen Tools, Datenquellen und Tätigkeiten aufzudecken.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
C. 2	Die Darstellungsform des IST-Prozesses und der Digital Twin Schnittstelle (Use Case Reiter 3 & 4) hilft, den SOLL-Prozess und die damit verbundene Änderung der Prozessschritte durch den Digital Twin strukturiert abzuleiten.				
☐ Stimme überhaupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
C. 3	Der modellierte SOLL-Prozess (Use Case Reiter 5) macht die Änderung der Prozessschritte durch den Digital Twin transparent.				

☐ Stimme über-haupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
C. 4	Die gesamte Darstellungsform des Use Cases mit IST-Struktur, IST-Prozess, Digital-Twin Schnittstelle und SOLL-Struktur sowie virtuelles Modell (Use Case Reiter 2 bis 6) ist hilfreich, um Anforderungen für das Digital Twin Konzept abzuleiten.				
☐ Stimme über-haupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
C. 5	Die herausgearbeiteten Use Cases verdeutlichen die spezifische Ausprägung des Digital Twin.				
☐ Stimme über-haupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu
C.6	Die Beschreibung des virtuellen Modells eines Digital Twin (Use Case Reiter 6) verdeutlicht/konkretisiert das abstrakte Bild/Verständnis des Digital Twin Konzeptes.				
☐ Stimme über-haupt nicht zu	☐ Stimme nicht zu	☐ Stimme eher nicht zu	☐ Stimme eher zu	☐ Stimme zu	☐ Stimme völlig zu

D. Gesamtbewertung

Gesamtbewertung des Vorgehens und der Methoden					
D	Bitte geben Sie eine Gesamtbewertung ab.				
☐ Ungenügend	☐ Mangelhaft	☐ Ausreichend	☐ Befriedigend	☐ Gut	☐ Sehr Gut

Bitte hinterlassen Sie weitere Kommentare und Anregungen. Welche weiteren Empfehlungen haben Sie? Gibt es Punkte, die aus Ihrer Sicht wichtig sind, welche nicht betrachtet wurden?

____

____

Results of the Evaluation

Table A 4: Detailed Results of the Evaluation of the Case Study on Engineering Twins for Climate Solutions

	strongly disagree 1	disagree 2	slightly disagree 3	slightly agree 4	agree 5	strongly agree 6	Average
B.I-1	0	0	0	0	2	4	5,67
B.I-2	1	0	0	0	4	1	4,50
B.I-3	0	0	0	1	2	3	5,33
B.I-4	0	0	2	0	2	2	4,67
B.I-5	0	0	0	0	6	0	5,00
B.I-6	0	0	0	1	5	0	4,83
B.II-1	0	0	0	0	1	5	5,83
B.II-2	0	0	0	1	1	4	5,50
B.II-3	0	0	0	0	5	1	5,17
B.II-4	0	0	0	3	3	0	4,50
B.II-5	0	0	1	0	4	1	4,83
B.II-6	0	0	0	0	4	2	5,33
B.II-7	0	0	0	0	4	2	5,33
C-1	0	0	0	0	3	3	5,50
C-2	0	0	0	0	4	2	5,33
C-3	0	0	1	0	4	1	4,83
C-4	0	0	1	0	2	3	5,17
C-5	2	0	0	0	1	3	4,17
C-6	0	2	0	0	1	3	4,50
D	0	0	0	0	2	4	5,67

A4 Applied Methods of the Case Study on Production Twins for Aluminum Extrusion Processes

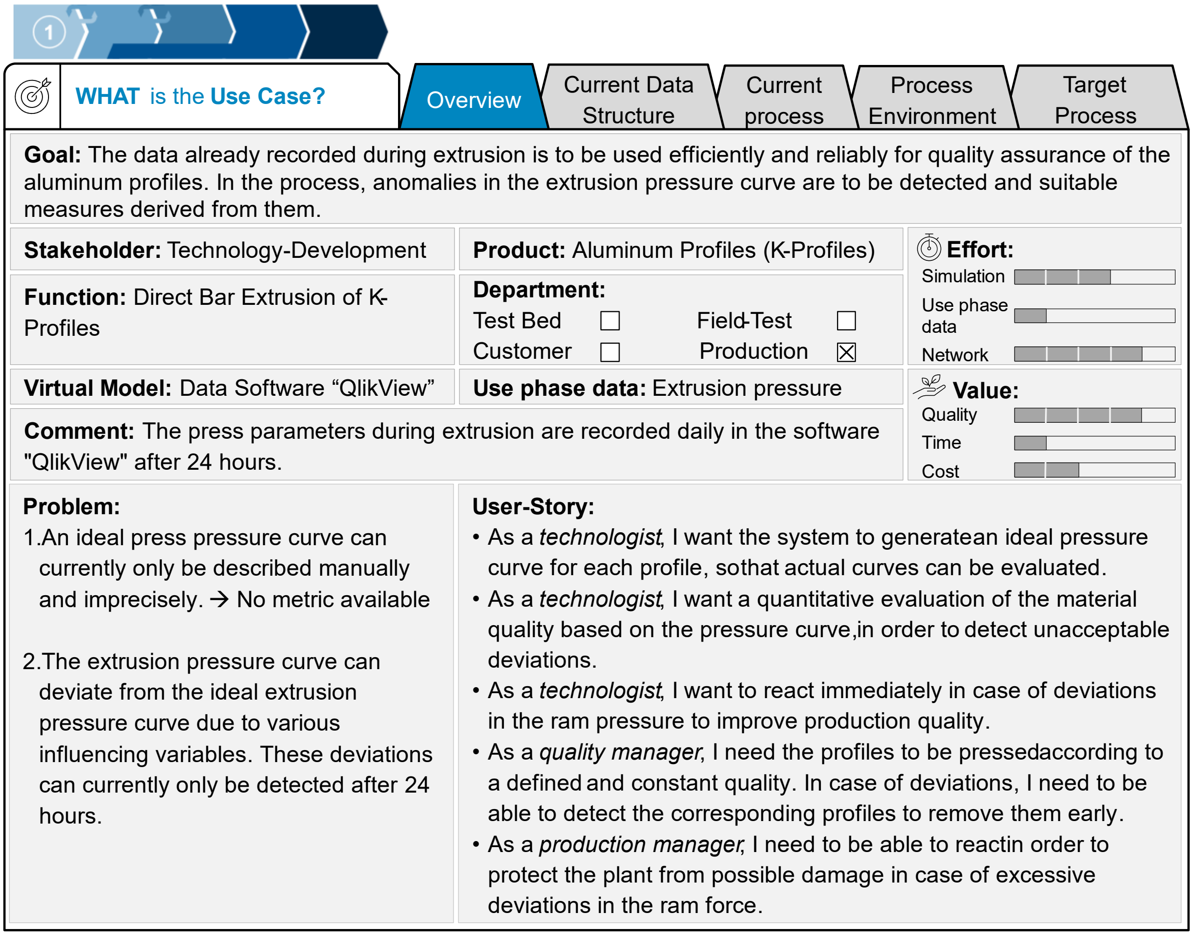


Figure A 12: Overview of the use case "Detection of Defective Products Based on Ram Pressure Curves" (Trauer, Pfingstl, et al., 2021).

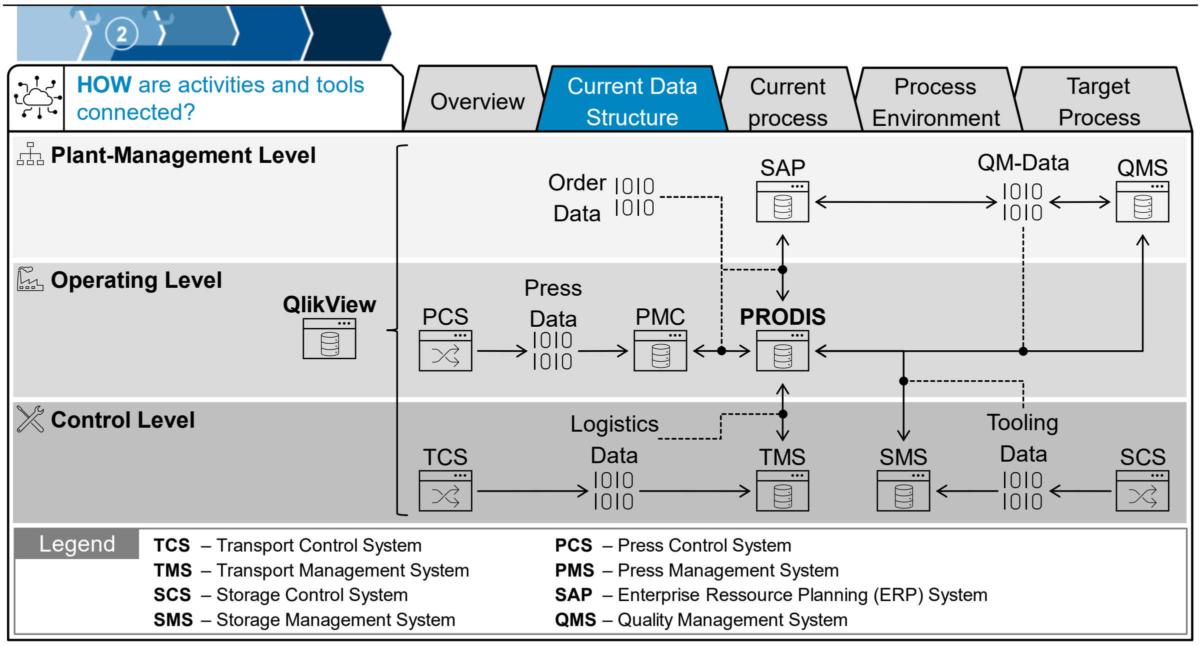


Figure A 13: Current data structure of the use case. (Trauer, Pfingstl, et al., 2021).

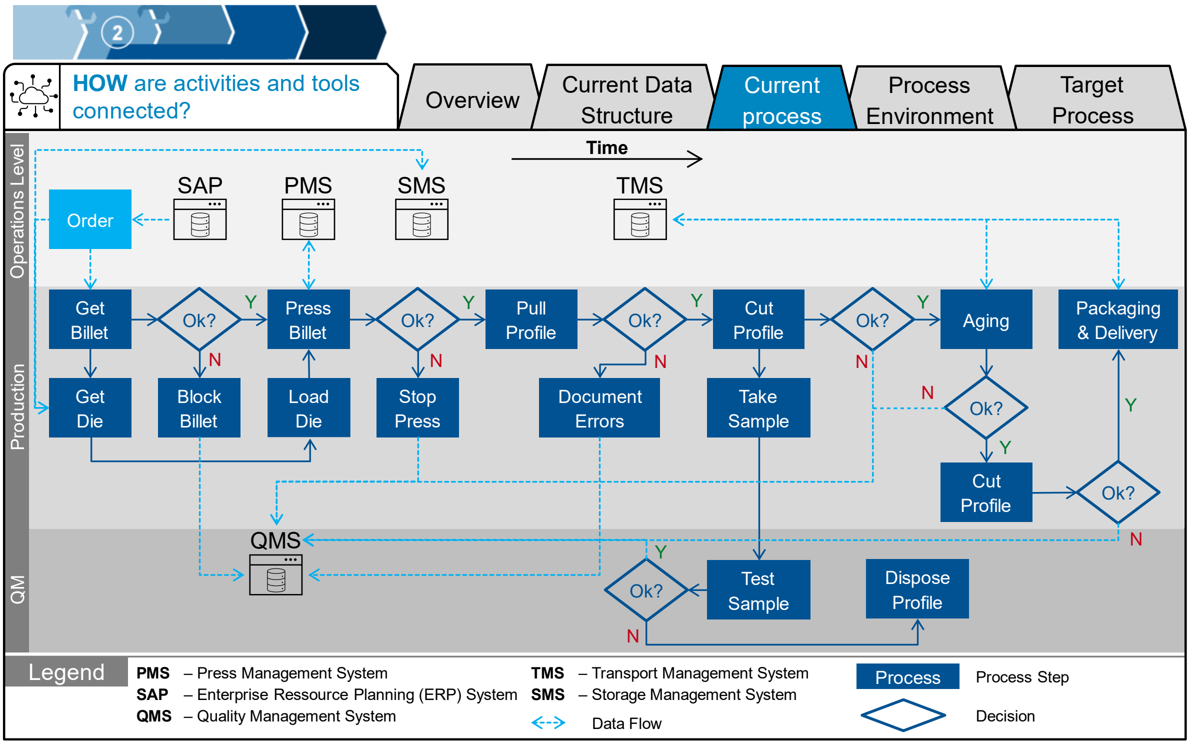


Figure A 14: Current process of the use case. (Trauer, Pfingstl, et al., 2021).

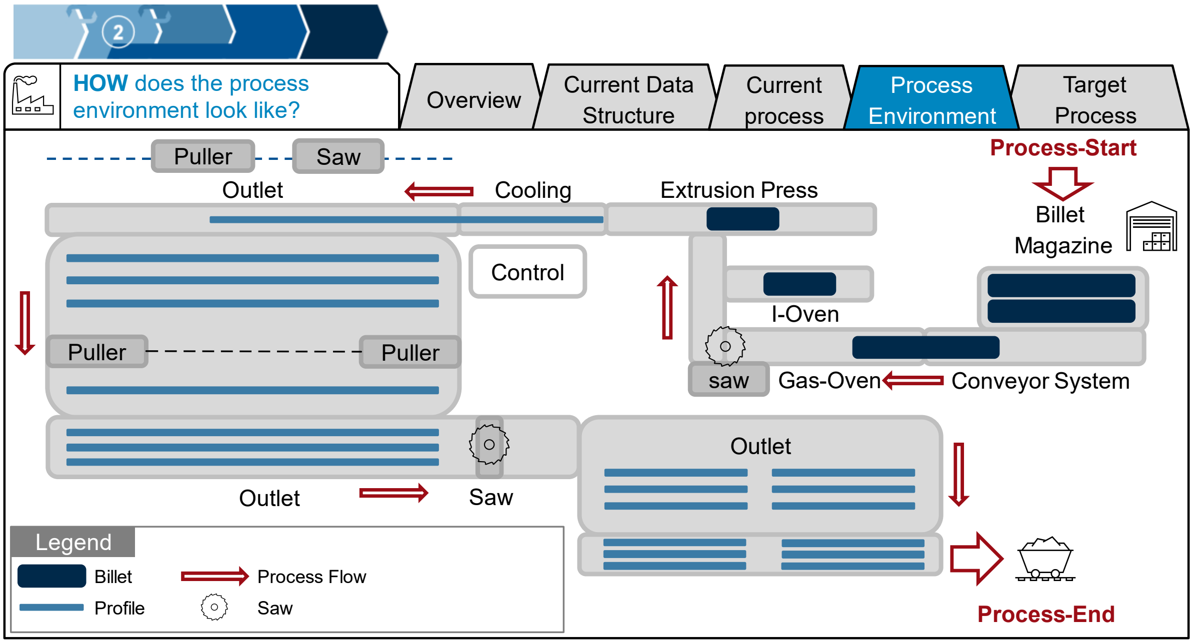


Figure A 15: Process environment of the use case. (Trauer, Pfingstl, et al., 2021).

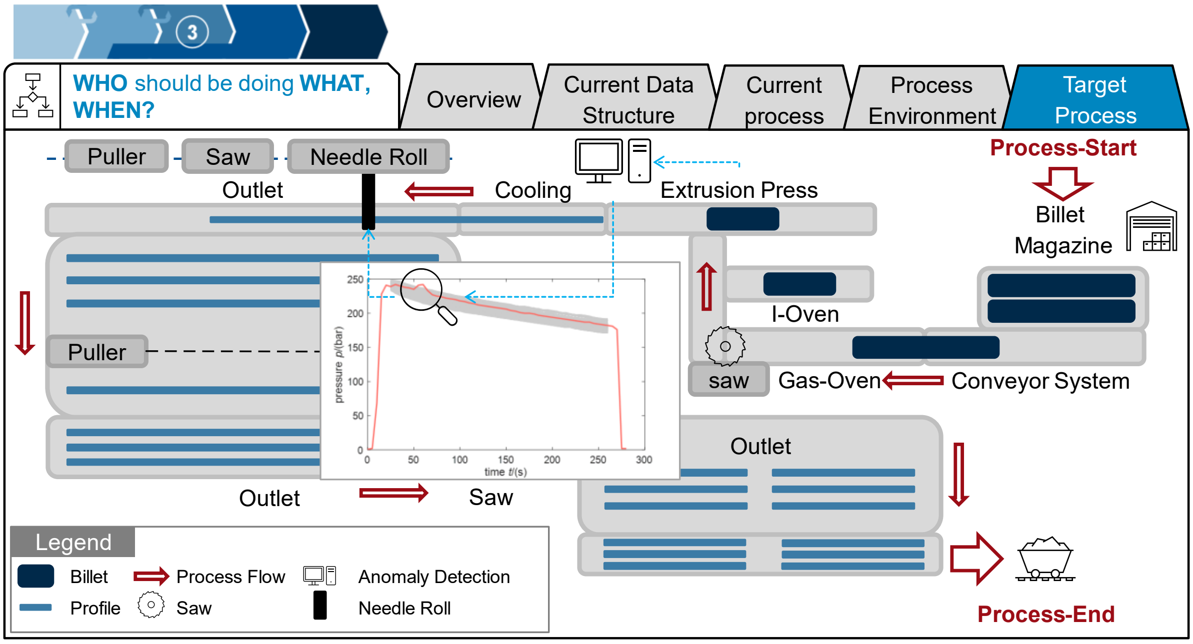


Figure A 16: Target process of the use case. (Trauer, Pfingstl, et al., 2021).

A5 Additional Material on the Academic Case Study on the Development of a Digital Twin Demonstrator

A5.1 List of All Identified Digital Twin Use Cases for the Demonstrator

Table A 5: List of Digital Twin Use Cases Collected for the Demonstrator.

Title	Explanation	Source	Index
Determination of the order processing	The bottling plant works off a current order book made up of orders from customers (e.g., buyers of bottles for commercial sale; winemakers who want to use bottles for their own production) When converting from one filling medium to another, certain conversion times are required. The DT is used to display the current order situation and to store data on the changeover processes. Based on this input data/information, the DT simulates various order processing scenarios to identify the most optimal processing of the orders, taking into account the changeover processes If a better flow is identified, the DT automatically adjusts the order situation and informs the affected customers and the beverage producer	Analogy building Specialist literature	UC1
Consideration of changes in order processing	The bottling plant has an up-to-date order book with an already optimized processing of orders. External changes now occur, e.g., market changes (short-term discontinuation of orders) or raw material changes (rising energy costs) The production mapped via the DT is adapted to the external changes in order to optimally use the system under the given	Analogy building Specialist literature	UC2

Title	Explanation	Source	Index
	conditions. To do this, the DT simulates different scenarios of utilization under the given inputs and target variables and selects the most optimal strategy. For example, downtimes are to be avoided through a lower utilization for a given time (start-up/shut-down processes can be cumbersome and make the plant unprofitable). From the analysis of production over several years, periods of higher and lower utilization can also be identified via the DT -> this knowledge can be used, for example, for better scheduling of maintenance work.		
Investigation of current process parameters	- To investigate whether the current filling can be improved with the process parameters regarding pressure and temperature - DT takes current and historical production data and extrapolates scenarios based on physical and data-driven models. - Here the temperature and pressure are varied - The simulated scenarios can be used to evaluate whether a change is worthwhile - The final decision influences the current mode of production	Own idea	UC3
Investigation of raw material procurement	- Data on the quality and cost of the filling medium are available from various manufacturers. - At the moment a specific supply chain is used - On the basis of current production and supplier data, scenarios are to be extrapolated that simulate changes in the supply chain. - If a more ideal scenario arises than the current production, the supply chain can be changed here	Own idea	UC4

Title	Explanation	Source	Index
Optimization of resource storage	- Data exists on the use of required resources and current storage capacities - With the help of the DT, the influence of the lack of various resources on certain scenarios is to be simulated. - Sensitivity analysis can be used to determine which resources are critical and may need to be stored with a larger buffer than others that are only used sporadically and can be replenished quickly. - With the help of the simulated scenarios, resource stocks can be adjusted preventively	Own idea	UC5
Reduction of under/over-engineering through requirements management	-As a rule, components are designed for many times the actual load. -Some components wear out faster than others or fail earlier (system bottleneck). -With the help of usage data, it is possible to determine how the components are actually stressed. -The operating data of the components can be used to determine which components are "underengineered" or "overengineered". -In case of multiple failures of a particular component, different manufacturers/suppliers can be considered for future ordering. -This ensures that product development has knowledge about the future selection of components for the system in terms of functionality. The knowledge generated can also be used for the maintenance of the plant.	Own idea	UC6
Improving the tank filling strategy	- At the moment, the upper tank is always filled from above - An alternative is to fill the tank from below, which is quieter than from above, but more energy-intensive when the level is	Own idea	UC7

Title	Explanation	Source	Index
	high. - Depending on the current fill level and the medium to be filled, an optimum control strategy is to be developed to guarantee as little foaming as possible with low energy consumption. - This is done using a physical mapping of the structure and historical data from previous filling processes. - The filling process is automatically controlled with the aid of the developed control system.		
Ensuring the final quality of the product	- The acid content, which is measured by the pH value, is decisive for the end product quality of apple juice. - Different apple varieties make for different acidic end products - In the end, the same acidity level should always be aimed for in the plant in order to guarantee a consistent taste experience - For this purpose, the pH value of the apple juice supplied is measured and, if necessary, adjusted with water - The DT maps the ph value of the current product at the input and output of the system and thus regulates the water supply to guarantee a constant ph value at the end - In addition, the DT can use the communicated apple variety as an additional data element	Analogy building Specialist literature	UC8
Optimized utilization of the storage space	- The filling media should be stored in a specific temperature field - The DT maps the current state of the storage parameters (storage time, temperature) and simultaneously obtains data on the ambient temperature from the weather - Depending on the weather conditions, this can be used to support storage (e.g., media	Own idea	UC9

Title	Explanation	Source	Index
	for longer standing times can be stored with an open window in cold outside temperatures; media to be used can be brought to filling temperature via warm outside weather). - The DT thereby controls access to the outdoor environment on a daily basis with regard to the use and storage of the media		
Tracking of filling media	- Parameters such as pH content, temperature or pressure are measured at certain stations, e.g., in the two tanks. - These are linked to time and associated with the filled batches - In the event of deviating values in the parameters, for example, flats are automatically sorted out or sent to additional quality assurance. - The data can be made available to the company, but also to the end customer - Tracking can be used to trace problems that arise later when the product is consumed back to the source and thus errors can be found earlier or proactively prevented.	Own idea	UC10
Improving the energy efficiency of the construction	Identify constructive energy-saving potential based on operating data, which can be addressed in product development.	Own idea	UC11
Automated reordering of raw materials	- The DT is used to map the entire processing procedure, especially the required inflows of raw materials for the current production capacity utilization. - The DT assists with the automatic reordering of raw materials to maintain production so that it can be continuous - Delivery times, storage capacities, durability of materials, suppliers and costs are all taken into account.	Own idea	UC12

Title	Explanation	Source	Index
	- Repeat orders can be made automatically or with the consent of the responsible personnel		
Securing the insurance cover of the plant	- The insights generated by DT regarding the reliability/functionality of the plant and the conformity of the filled liquids enable plant manufacturers/insurers to provide better guarantees to the end user. - Value-added insurer: better pricing - Added value users: Guarantees	Own idea from experience	UC13
Automated creation of an initial plant model	- The plant is mapped with its processes and operations via the DT - The customer can test whether the system meets his requirements and can run through scenarios (enter start parameters) -> DT suggests system layout - Based on usage data from other installations - Added value: Equipment salesman can show the customer the value free of charge	Own idea from experience	UC14
Increasing transparency in product development	- Customer can see what is happening in the product development of the plant and can suggest changes in real time - Based on data from product development	Own idea Brainstorming	UC15
Securing of maintenance work/ assembly of the plant	- For a regular appointment, the system is serviced either completely or in parts. - The maintenance process is mapped by the DT, i.e., the progress of the maintenance workers is automatically transmitted to the DT by sensors - In case of unforeseen problems, the DT communicates them to the maintenance workers - After completion of the maintenance work, the DT carries out a final check and gives feedback on unintentional errors (e.g., valve forgotten to open), if necessary.	Analogy building Specialist literature	UC16

Title	Explanation	Source	Index
	- Add-on: During the repair, the DT provides support with questions, e.g., by means of augmented reality, and serves as a customizable knowledge base. - Difference to PM: Rule date adhered to only differently timed due to experience in recent years		
Improving the cleaning of the plant	- Disinfection of bottling plants take place through (in high quantities) toxic substances - Certain bottled liquids contain additives that can be dangerous in high quantities - The combination of different filled substances as well as disinfectants can have undesirable consequences - The intake of the above-mentioned substances is mapped via the DT - The staff will be informed in case of border violations - The time of contamination can be well delimited -> less loss add-on: possible to improve disinfection process and dosage of additives. - How much water is actually needed to rinse? - It is unclear how big this problem really is → current solution, empty bottle inspector before filling	Analogy building Specialist literature	UC17
Data logging of the flow behavior	DT as a logger that runs through the system and records the flow behavior. → System design improvement, validation of simulation	Analogy building Specialist literature	UC18
Predictive Maintenance	- The system is permanently mapped via the DT, especially safety-relevant components with their current service life - The optimum time and size of	Analogy building Specialist literature	UC19

Title	Explanation	Source	Index
	maintenance is calculated based on the predicted service life, number and cost of repairs, current order situation and capacity utilization of the system. - The results are transmitted to the responsible personnel, or the maintenance personnel are automatically informed about the next appointment and upcoming work, so that, for example, spare parts can be reordered in good time.		
Training module for staff training	- The plant is mapped with its processes and operations via the DT - The production process can be made clear to new personnel via the visual illustration, thus helping them to understand what is happening in the plant - Theoretical scenarios can also be simulated and staff trained on them for critical incidents in virtual space	Own idea from experience	UC20
Prevention of component damage	When a pipe becomes clogged, the pump's output is automatically reduced to allow continued operation but not to damage the pump.	Idea plant partner	UC21
Determination of quantities that are difficult to measure	- The volume content in the upper container is sometimes difficult to detect due to turbulence during the filling process - The volume in the upper tank can also be measured indirectly in another way via the power and flow rate of the pump - By means of this method, the value from the direct sensor measurement can be compared in DT and thus the filling process can be designed even more precisely.	Analogy building Specialist literature	UC22

A5.2 Design Structure Matrix Showing the Interdependencies of Use Cases

Benefit			4,3	4,0	3,7	3,7	3,3	3,0	4,3	3,3	4,7	4,3	5,0	4,0	3,0	3,7	3,0	2,3	3,0	4,0	2,3	2,3	4,0	3,3
	Effort		2,7	3,7	3,0	3,7	3,7	4,3	4,0	3,3	3,7	3,3	4,0	2,7	2,0	2,3	2,0	1,3	3,3	2,7	3,0	4,7	4,3	5,0
		Use Cases	UC 10	UC 11	UC 3	UC 15	UC 14	UC 18	UC 6	UC 7	UC 19	UC 21	UC 22	UC 20	UC 1	UC 2	UC 4	UC 5	UC 12	UC 13	UC 16	UC 17	UC 8	UC 9
4,3	2,7	UC 10		3	3	4	3	2	4	2	3	3	4	3	5	2	1	2	2	6	3	2	3	2
4,0	3,7	UC 11	3		6	6	5	6	7	7	7	4	4	5	3	2	1	3	2	4	4	3	4	2
3,7	3,0	UC 3	3	6		5	6	4	8	8	6	8	5	7	5	3	2	3	3	3	3	4	5	6
3,7	3,7	UC 15	4	6	5		6	5	7	4	6	3	3	4	3	3	2	2	2	5	4	2	3	3
3,3	3,7	UC 14	3	5	6	6		[illegible]	7	6	6	2	3	6	5	4	3	3	2	3	4	2	3	4
3,0	4,3	UC 18	2	6	4	5	[illegible]		6	5	6	2	3	4	3	1	1	1	1	4	3	2	3	1
4,3	4,0	UC 6	4	7	8	7	7	6		6	11	6	6	6	3	1	0	1	1	6	7	4	2	3
3,3	3,3	UC 7	2	7	8	4	6	5	6		7	7	5	7	4	3	3	3	3	4	4	5	5	4
4,7	3,7	UC 19	3	7	6	6	6	6	11	7		5	6	7	5	3	2	3	3	6	7	6	3	2
4,3	3,3	UC 21	3	4	8	3	2	2	6	7	[illegible]		5	5	2	1	0	1	2	3	4	4	4	4
5,0	4,0	UC 22	4	4	5	3	3	3	6	5	6	5		6	3	1	0	1	1	4	4	3	4	1
4,0	2,7	UC 20	3	5	7	4	6	4	6	7	7	5	6		4	2	1	2	1	4	5	3	3	2
3,0	2,0	UC 1	5	3	5	3	5	3	3	4	5	2	3	4		6	4	5	4	5	2	5	3	5
3,7	2,3	UC 2	2	2	3	3	4	1	1	3	3	1	1	2	6		6	6	5	2	1	4	2	6
3,0	2,0	UC 4	1	1	2	2	3	1	0	3	2	0	0	1	4	6	[illegible]	5	5	1	0	2	3	4
2,3	1,3	UC 5	2	3	3	2	3	1	1	3	3	1	1	2	5	6	5		5	2	1	3	2	4
3,0	3,3	UC 12	2	2	3	2	2	1	1	3	3	2	1	1	4	5	5	5		2	1	4	4	4
4,0	2,7	UC 13	6	4	3	5	3	4	6	4	6	3	4	4	5	2	1	2	2		4	3	2	2
2,3	3,0	UC 16	3	4	3	4	4	3	7	4	7	4	4	5	2	1	0	1	1	4		4	2	1
2,3	4,7	UC 17	2	3	4	2	2	2	4	5	6	4	3	3	5	4	2	3	4	3	4		3	4
4,0	4,3	UC 8	3	4	5	3	3	3	2	5	3	4	4	3	3	2	3	2	4	2	2	3		3
3,3	5,0	UC 9	2	2	6	3	4	1	3	4	2	4	1	2	5	6	4	4	4	2	1	4	3	

Cluster1 Cluster2 Cluster3

Figure A 17: Design Structure Matrix Showing the Interdependencies of the Use Cases (Inner Part). The Numbers Represent the Number of Common Assigned Categories. On the Outer Part, The Estimated Average Values for Benefit and Effort of the Use Cases Are Depicted (on a scale from 1 to 5).

A5.3 Benefit Effort Portfolio of the Identified Use Cases

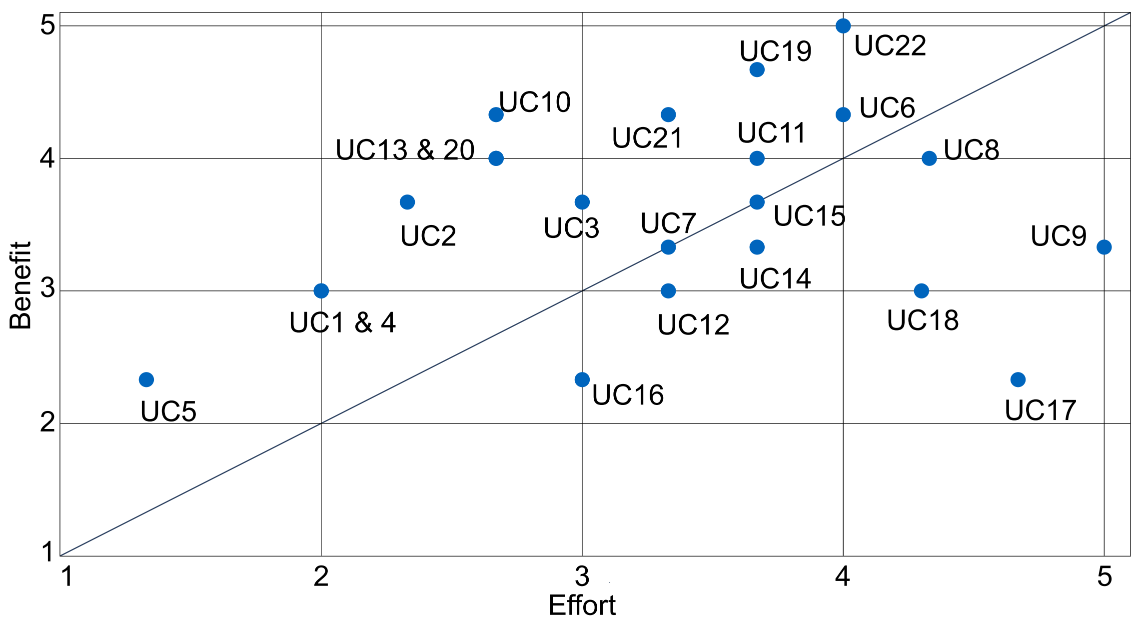


Figure A 18: Benefit-Effort Portfolio of the Identified Use Cases. The Values show the Average of the Qualitative Estimations made by the Project Team.

A5.4 The Use Case “Preventive Operations”

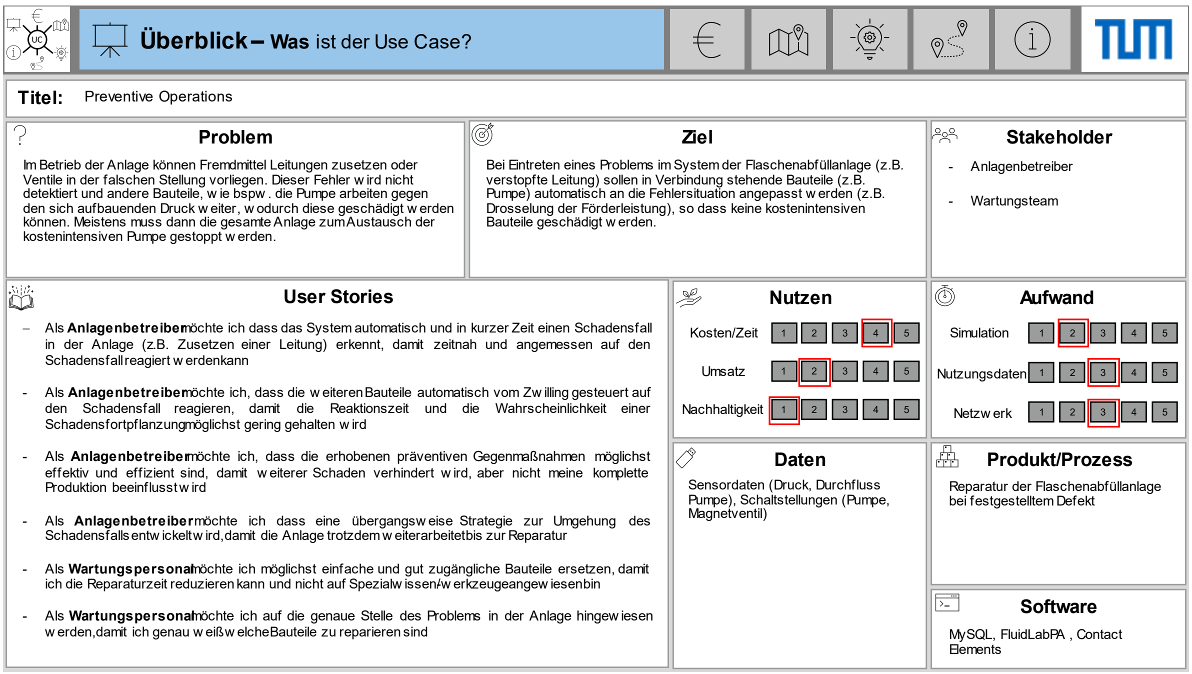


Figure A 19: Overview of the Use Case Preventive Operations.

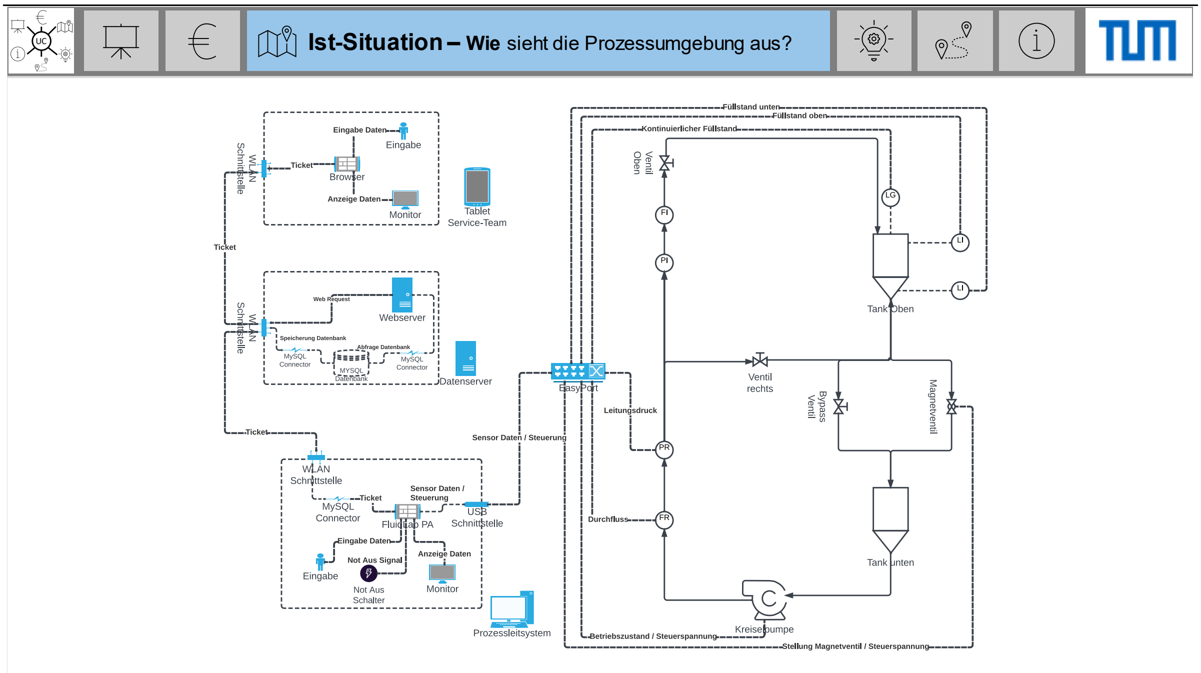


Figure A 20: Current Situation of the Current Process Environment of the Use Case Preventive Operations.

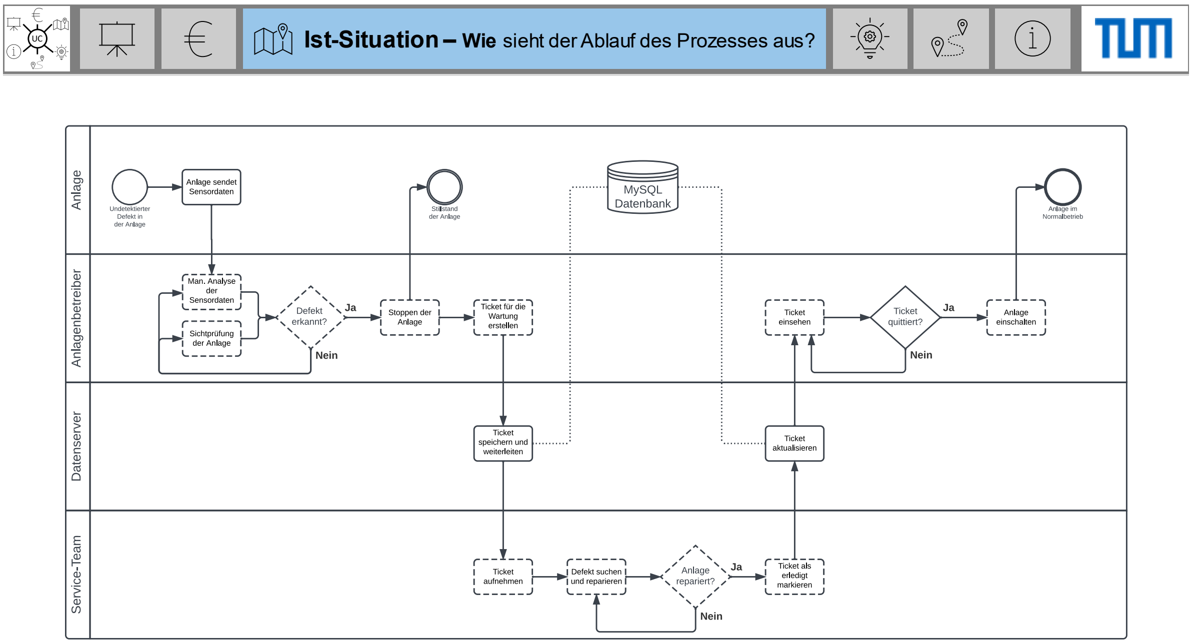


Figure A 21: Current Situation of the Process of the Use Case Preventive Operations.

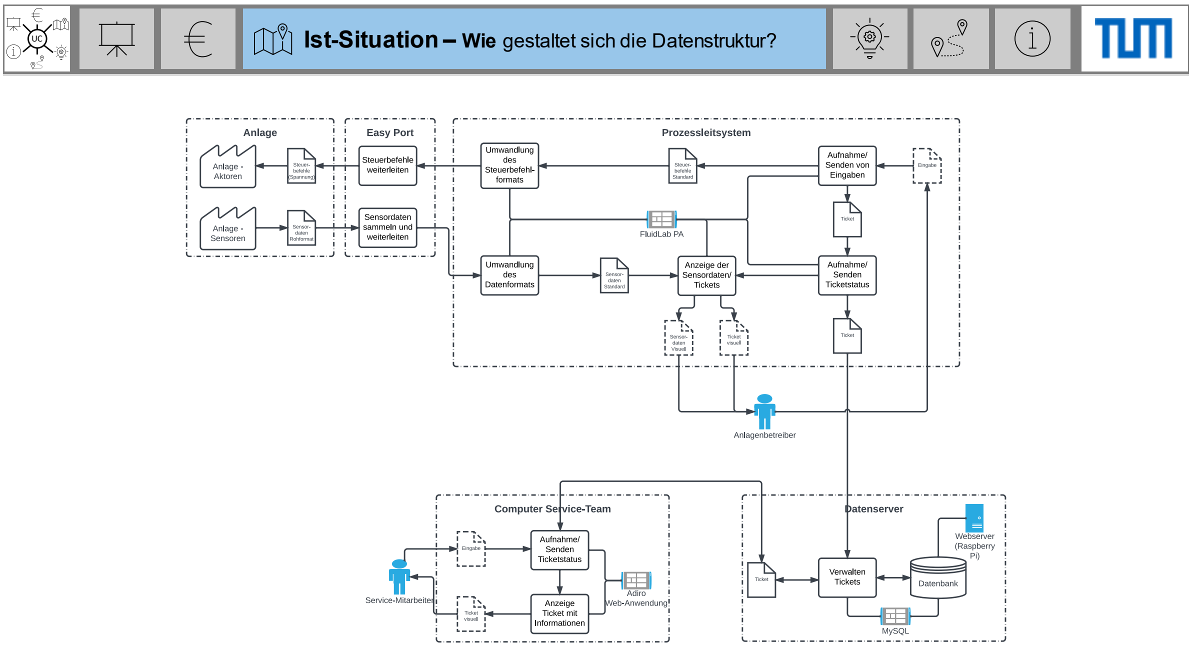


Figure A 22: Current Situation of the Data Structure of the Use Case Preventive Operations.

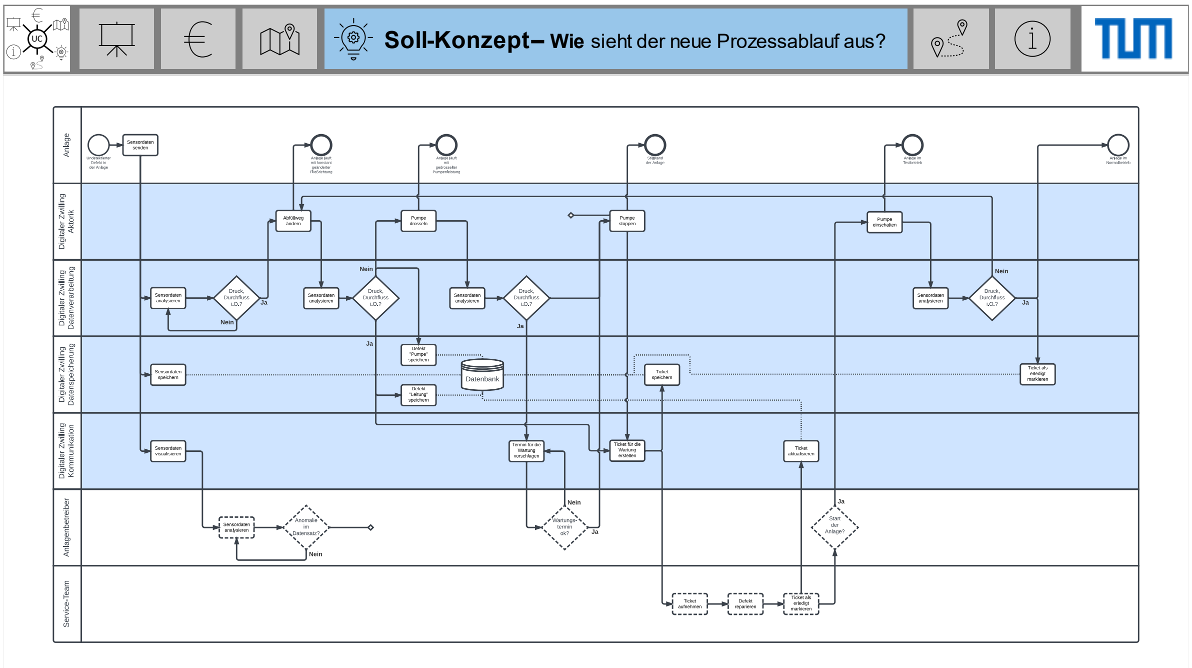


Figure A 23: Target Concept for the Process of the Use Case Preventive Operations.

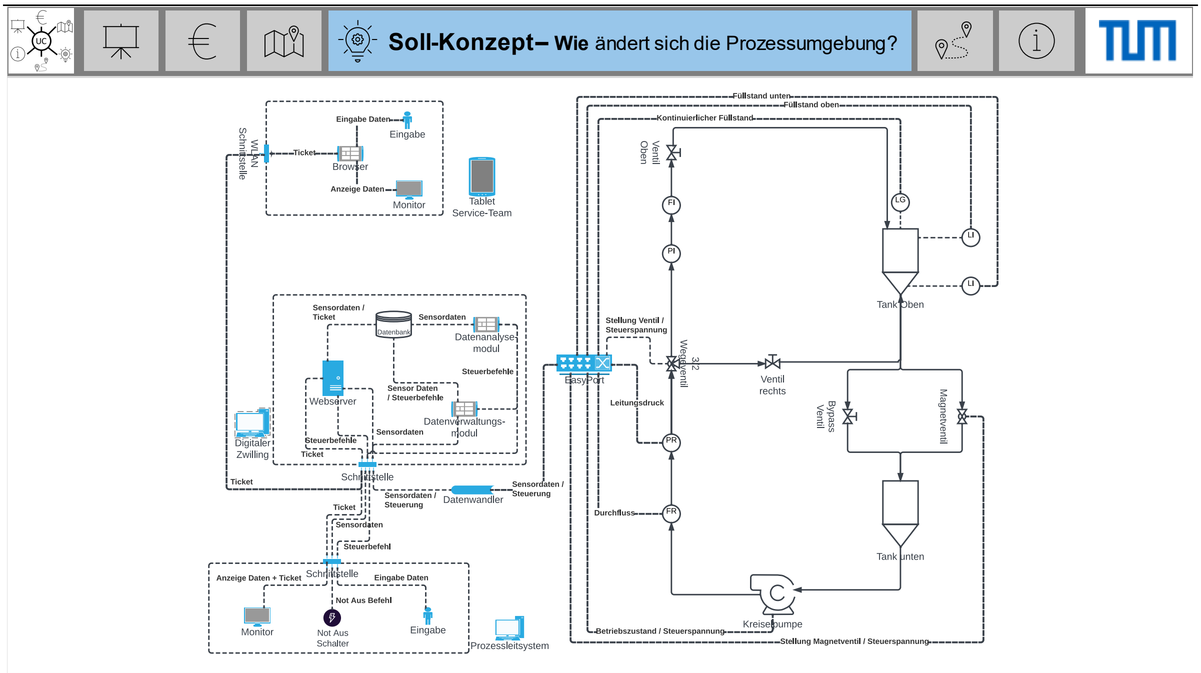


Figure A 24: Target Concept of the Process Environment of the Use Case Preventive Operations

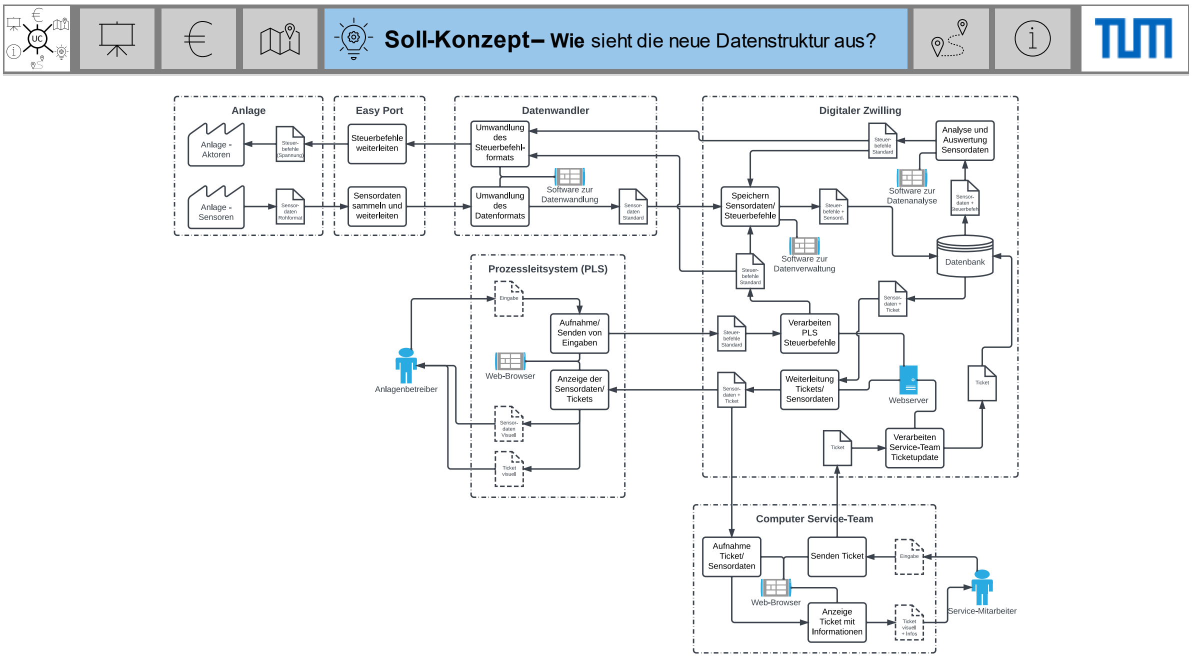


Figure A 25: Target Concept of the Data Structure of the Use Case Preventive Operations.

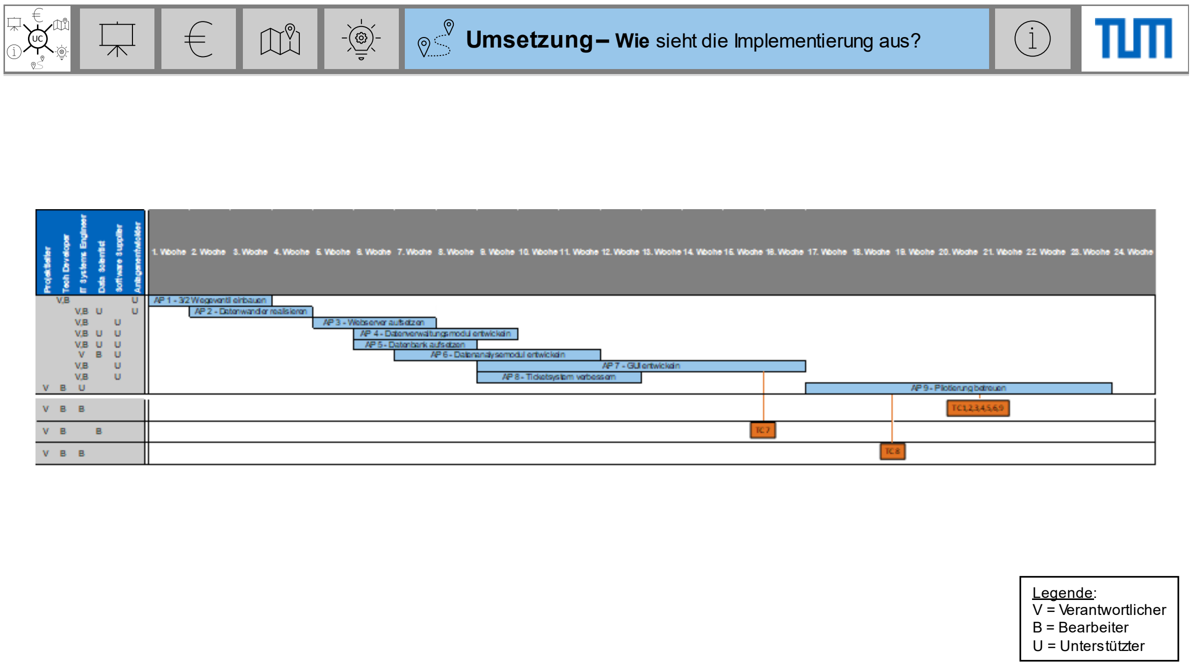


Figure A 26: Implementation Roadmap for the Use Case Preventive Operations.

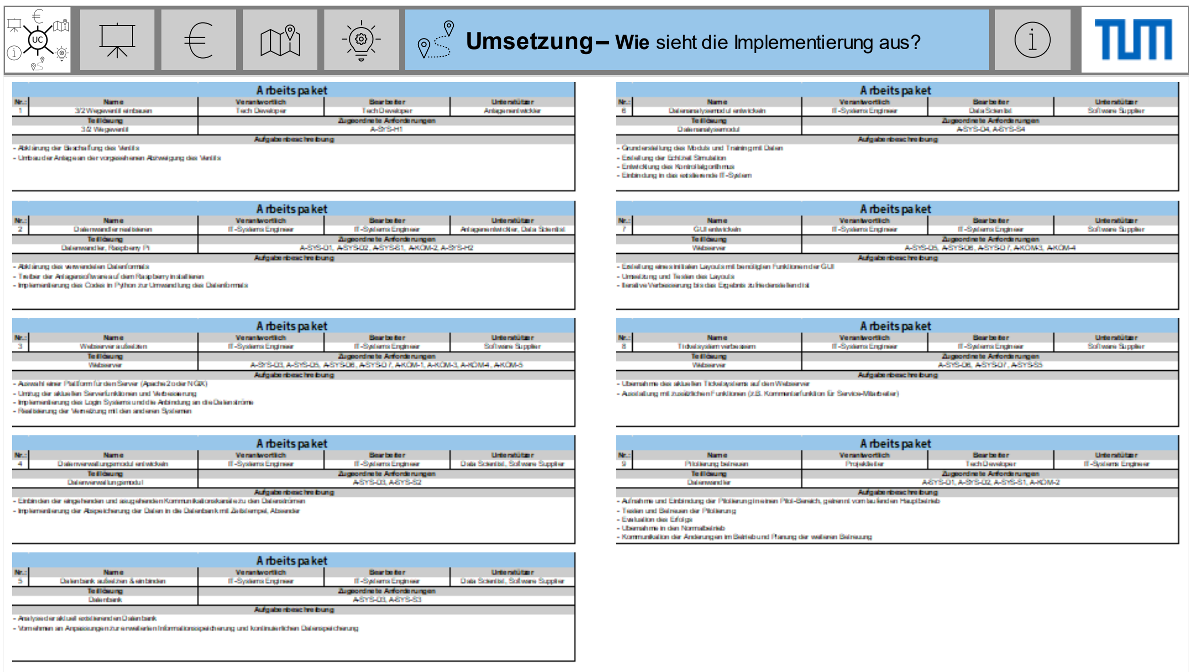


Figure A 27: The Implementation Tasks of the Use Case Preventive Operations.

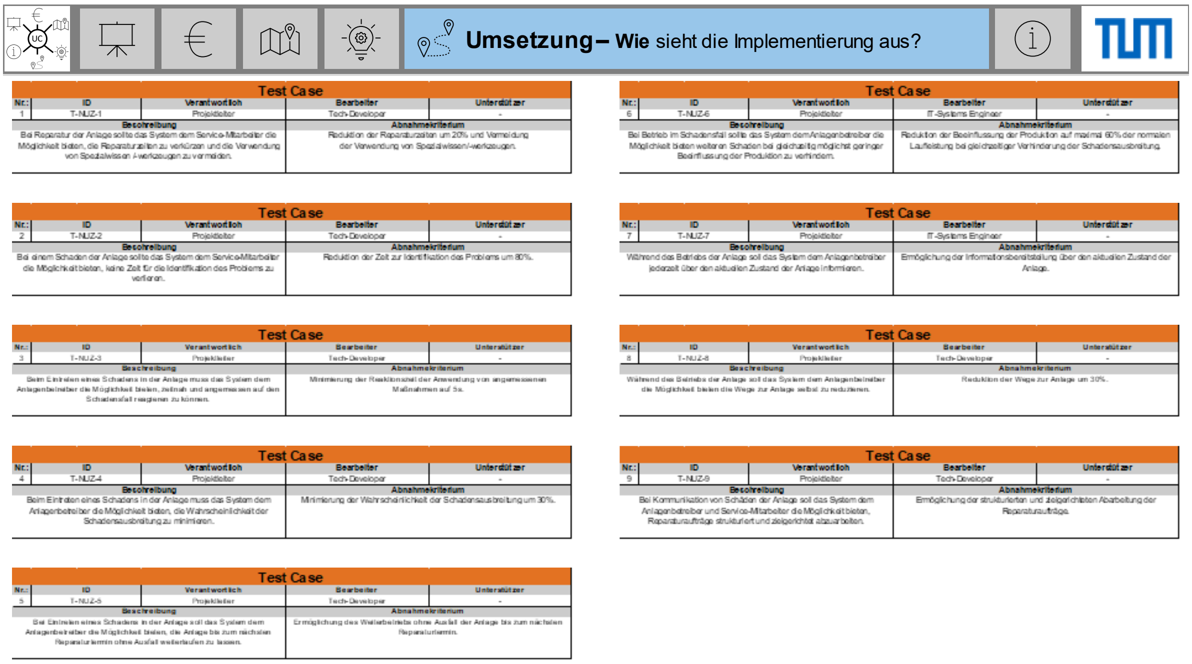


Figure A 28: The Test Cases for the Implementation of the Use Case Preventive Operations.

A5.5 Requirements Template

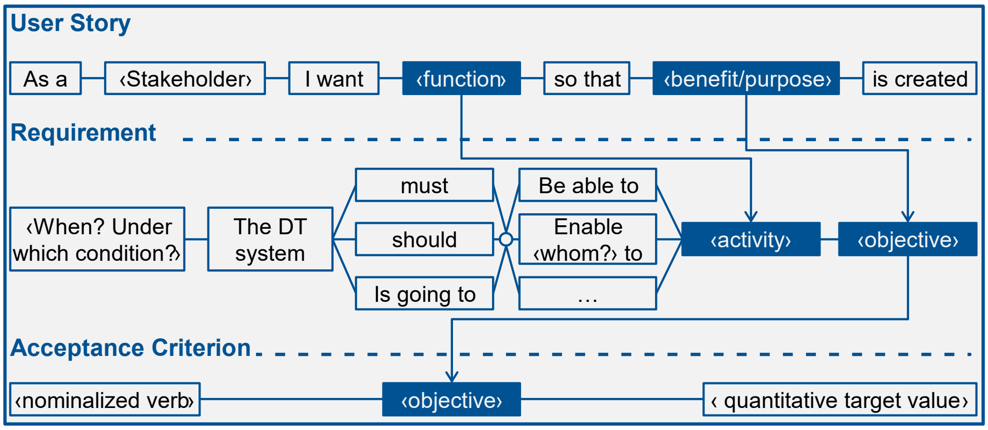


Figure A 29: Systematic Deduction of Requirements and Acceptance Criteria.

A6 Additional Material on the Case Study on Trust in Digital Twins

A6.1 Literature Research Strategy

Table A 6: Literature Research Strategy Regarding Trust in Digital Twins and Digital Solutions (adapted from Trauer, Schweigert-Recksiek, et al., 2022).

	Aspects			
Synonyms	Digital Twin	Trust	Framework	Classification
	Simulation	Distrust	Concept	Quality*
	Digital Transformation	Mistrust	Process	Certification
	Digital*			Validation
	Technology Acceptance / Adoption			Verification
	Transformation			Traceability

A6.2 Interview Guideline

Table A 7: Interview Guideline (adapted from Trauer, Schweigert-Recksiek, et al., 2022).

ID	Question
1	When we first contacted you about trust and DTs, what was the first thing that came to your mind?
2 (opt.)	You indicated that you are actively working on DTs - Please specify.
3 (opt.)	You indicated that you use DTs in your everyday work. For which tasks and in what context?
4	Which use cases do you currently work on in your company?
5	You indicated that you have never/already doubted DTs. Can you explain why?
6	You indicated in the survey that colleagues have (never) distrusted DTs / simulations. Can you explain why?
7	From your point of view, what could generally be solution elements to increase trust in DTs?
8	What is being done in your company to increase trust in simulations / DTs?
9	Which objective do you consider more promising / necessary: building trust or covering risks?
10	Which stakeholders are there in the context of trust & DTs? Who needs to trust whom?
11	What situations/use cases can you think of in which trust-building methods would be needed? What do you think the collaboration between the stakeholders should look like?

A6.3 Interview Transcription

Table A 8: Transcribed and Translated Quotes of the Interview Study Assigned to the Elements of the Digital Twin Trust Framework. All Interviews were Conducted in German. The Quotes were Translated by the Author of the Thesis.

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
		Stakeholders	
Supplier	*„Unserer DT ist eine Technologie, die dahintersteckt, das heißt, wir verkaufen keine DTs an sich. Die Technologie wird durchaus auch kommuniziert, die ist aber nicht die Hauptsache. Die Hauptsache vom Projekt ist wirklich der Antriebsstrang, seine Überwachung und dort entsprechende Use-Case-Mehrwerte zu generieren.“*	*“Our Digital Twin is the technology behind it, which means we don't sell the DTs per se. The technology is also communicated, but that is not the main thing. The main thing about the project is really the powertrain, its monitoring and generating corresponding added value through use cases.”*	Project Lead Digital Manufacturing – Digital Industries Company
User	*„In der digitalen Welt kommt man sehr schnell beim Thema vom geistigen Eigentum und von den Betriebsgeheimnissen an. Und das sind alles Informationen, die man unter keinen Umständen rausgibt. Aus meiner Sicht hat dieses Thema der DT nur eine Chance, wenn es auch nicht geschieht. Man sollte die DT so gestalten, dass das Thema Datensicherheit gar nicht erst zum Problem wird. Das ist meiner Meinung nach ein wesentlicher Aspekt bei der Betrachtung von DT.“*	*„In the digital world, you very quickly come to the issue of intellectual property and company secrets. And this is all information that you never give out under any circumstances. You should design the Digital Twin in such a way that the issue of data security is not even a problem in the first place. It also has to be clear what I gain from it in business terms. That's where you have to look at the tradeoff of effort versus the business benefit."*	Vice President Methods, Analyses & Materials – Aerospace & Defense Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
Partner	*„Beim Vertrauen geht es bei mir immer sofort auch um das Kaufmänische. Also die Frage: Wenn ich Daten hergebe, was passiert mit meinen Daten? Und wie kann ich daraus auch noch weiter Geld verdienen?“*	*“For me, it's always about the commercial aspects. What happens to my data and how can I continue to create value from it even after the sale? If things should work in the long term, the know-how has to stay in-house. But this also stands in the way of a complete, true digital twin, which in the ideal case is openly designed. “*	General Manager – Automation Engineering Company
		User Stories	
Supplier to User	*„Im Bauwesen haften die Softwarehersteller nicht für das, was Sie produzieren. Die Haftung liegt immer beim Ingenieur. Ein Ingenieur, der Simulationssoftware oder DT nicht misstraut, steht bereits mit einem Bein im Gefängnis.“*	*“In civil engineering, software vendors are not liable for what you produce. The liability always lies with the engineer. An engineer who does not distrust simulation software or DT already has one foot in jail.”*	Lead Project Engineer - Construction & Engineering Company
	„Die Ziele den Kunden klarzustellen. Der Prozess von DT an sich, ist den Kunden egal. Sie wollen nur wissen, inwiefern der DT Ihnen ein betriebswirtschaftlicher Mehrwert geben kann. Dem Kunden interessiert hauptsächlich die Ausfallzeit reduzieren, die Kosten reduzieren, usw. Wie man das erreicht, ist Ihnen	*“To make the goals clear to the customers. The customers do not care about the DT process itself. They only want to know how DT can add value to their business. The customer is mainly interested in reducing downtime, reducing costs, etc. How this is achieved is of no concern to them.”*	Head of Function Development & Software Engineering - Energy and Climate Solutions Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„In der Energiewirtschaft ist es so, dass viele Daten auch schon vorhanden ist. Jedoch muss man diese Daten runterbrechen. Wir arbeiten daran, wie man sich Step by Step ein bisschen Richtung vollautomatisierten Super DT langhangeln kann, also das Ganze versuchen greifbar zu machen. [...] In der Energiewirtschaft kommen die Unternehmen noch nicht auf uns zu. Ich glaube das der Mehrwert existiert, aber der Mehrwert muss erstmal dargelegt werden. Die Firmen kommen, um das Thema anzureißen und Entwicklungspfade aufzeigen."	*"In the energy industry, a lot of data is already available. However, this data has to be analyzed. We are working on how we can move step by step towards fully automated Super DTs, thus. trying to make the whole thing tangible. [...] In the energy industry, companies are not approaching us yet. I believe that the added value exists, but the added value has to be presented first. The companies are coming to touch on the subject and show development paths."*	Project Lead Digital Manufacturing – Digital Industries Company
Supplier to Supplier	*„Wenn es langfristig funktionieren soll, sprich dass alle noch ihr Geld verdienen können, muss das Know-How im Haus bleiben. Das steht aber auch im Weg vom kompletten, echten DT, der im idealen Fall offen gestaltet ist."*	*"If it is to work in the long term, i.e., if everyone can still earn their money, the know-how must remain in-house."*	General Manager - Automation Engineering Company
Supplier to Partner	*„Es gab einige positiv eingestellte Kolleg*innen, die sich schon etwas mit dem Thema von DT beschäftigt haben und sich auskennen. Jedoch gab es auch Leute, die nach wie vor nichts damit anfangen können. Das*	*"There were some colleagues with a positive attitude who had already dealt with the topic of Digital Twins and were familiar with it. However, there were also people who still had no idea what to do with*	Project Lead Digital Manufacturing – Digital Industries Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
User to Supplier	*„Es gibt einige Stakeholder, die auf jeden Fall an Digital Twins glauben, ihnen vertrauen und dieses Konzept auch nutzen wollen. Jedoch vertreten auch einige - besonders in eher klassischen Bereichen (z.B. Konstruktionsbereich, Maschinenbaubereich) - die Meinung, dass man Modellen nicht wirklich vertrauen kann. Sie beschweren sich immer über die Genauigkeit der Modelle und denken, dass die ganze Simulationssache nur eine Spielerei sei.“*	*“There are some stakeholders who definitely believe in Digital Twins, trust them and want to use this concept. However, there are also some - especially in more traditional areas (e.g., construction, mechanical engineering) - who think that models can't really be trusted. They always complain about the accuracy of the models and think that the whole simulation thing is just a gimmick”*	Head of Function Development & Software Engineering - Energy and Climate Solutions Company
User to User	*„Schnittstellen: Die Simulation sollte besser offline durchgeführt werden, damit die Daten besser geschützt sind. Also die Simulation am besten nicht in externen Servern durchführen.“*	*“Interfaces: It is better to run the simulation offline so that the data is better protected. So, it is best not to run the simulation in external servers.”*	General Manager - Automation Engineering Company
User to Partner	*„Wenn du mit Lieferanten arbeitest, kann es zu Problemen bei einer Übergabe von Kow-How kommen. Die Schnittstellen sicher zu gestalten ist schon sehr wichtig. Das ist ein Problem, dass man über irgendein Vertragswerk juristischer Art absichern kann - Ja, kann man machen. Aber juristisch wasserdicht heißt noch lange nicht, dass du das auch letzten Endes wirklich machen willst.“*	*“If you work with suppliers, there may be problems with the transfer of know-how. It is very important to make the interfaces secure. This is a problem that can be covered by some kind of legal contract - yes, you can do that. But legally watertight does not mean that you really want to do it in the end.”*	Head of Function Development & Software Engineering - Energy and Climate Solutions Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
Partner to Supplier	*„Beim Vertrauen geht es bei mir immer sofort auch um das Kaufmänische. Also die Frage: Wenn ich Daten hergebe, was passiert mit meinen Daten? Und wie kann ich daraus auch noch weiter Geld verdienen?“*	*“When it comes to trust, I'm always immediately concerned with the business side of things. In other words, the question is: If I provide data, what happens to my data? And how can I continue to earn money with it?”*	General Manager - Automation Engineering Company
	„Vertrauen muss man langsam schaffen. Wir durchlaufen verschiedene "Steps" in der Datenverwertung und man muss auch alle "Steps" gut kennen, damit ein umfassendes Vertrauen entsteht. Für jemand Außenstehenden, der nicht an der Entwicklung beteiligt war, ist es natürlich sehr schwierig daran zu glauben. Jedoch bleibt nichts anderes übrig... Wenn ich ein Auto kaufe, muss ich auch vertrauen, dass es funktioniert. Ich kann einfach nicht jede einzelne Komponente überprüfen. “	*“Trust has to be created slowly. We go through various "steps" in data utilization, and you also have to know all the "steps" well in order for comprehensive trust to develop. For someone from the outside, who was not involved in the development, it is of course very difficult to believe. However, there is nothing else to do... When I buy a car, I have to trust that it works. I simply cannot check every single component. “*	Managing Director - Construction & Engineering Company
Partner to User	*„Wenn es um Vertrauen geht, dann es ist wichtig nicht zu generisch ranzugehen. Ich denke man wird sich schwer tun mit generischen Digital Twins, die für viele Anwendungsfälle gedacht sind. Es gibt lokale Rationalitäten, die den Kontext und die Anwendungs-*	*“When it comes to trust, it's important not to be too generic. I think you will have a hard time with generic digital twins that are meant for many use cases. There are local rationalities that change the context, and the use cases a lot. Organizations have a history that*	Research Associate - University for Digital Studies

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
Partner to Partner	*„Wenn ich Daten von verschiedenen Partnern zusammen mische, inwiefern kann ich mich auf diese Daten verlassen im Sinne von Prozesssicherheit? Zurzeit wird sehr blauäugig vom DT gesprochen und die Leute stecken nicht so weit drin, wie ich es bin.“*	*“If I mix data from different partners together, to what extent can I rely on this data in terms of process reliability? At the moment, people are talking about DT in a very naive way and are not as far into it as I am.”*	General Manager - Automation Engineering Company
		Solution Elements	
Explain your twin!	*„Im Prinzip muss man immer auch den Anwendungsfall betrachten und eine gewisse Skalierbarkeit des DT schaffen. Das ist auch die Herausforderung des Ganzen. Je besser mein DT ist, bzw., je mehr Entwicklungsaufwand ich reinstecke, desto mehr Lösungen wird der DT in einem spezifischen Anwendungsfall bringen. Die Frage ist dann, inwieweit kann ich den DT in andere Anwendungsfälle übertragen.“*	*“In general, you always have to consider the use case and create a certain scalability of the DT. That is also the challenge of the entire thing. The better my DT is, or the more development effort I put into it, the more solutions the DT will provide in a specific use case. The question is then, to what extent can I transfer the DT to other use cases?”*	Project Lead Digital Manufacturing – Digital Industries Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Es ist sehr wichtig einen offenen Raum zu schaffen, in dem die Beteiligten oder davon betroffenen Menschen dieses neue Konzept kennenlernen und ausprobieren können. Alle Stakeholder müssen am Anfang erkannt und "ins Boot" genommen werden. Damit sie auch alle Fragen stellen können, um das System zu verstehen. Auch um Antworten auf die Fragestellung zu geben: Wie verändert sich meine Arbeit konkret mit der Implementierung von Digital Twins? Es ist sehr wichtig, dass die Leute die Digital Twins ausprobieren und selbst bewerten, ob der Digital Twin nützlich ist oder eben nicht.“	*“It is very important to create an open space where the stakeholders or people affected by it can get to know and try out this new concept. All stakeholders have to be recognized and taken "on board" at the beginning. So that they can also ask all the questions to understand the system. Also, to provide answers to the question: How does my work specifically change with the implementation of Digital Twins? It is very important that people try out the Digital Twins and evaluate for themselves whether the Digital Twin is useful or not.”*	Research Associate - University for Digital Studies
	„Die allgemeine Frage lautet: Wann vertraue ich einer Simulation? Simulationen werden auch sehr selten für Genehmigungsfragen verwendet, weil man nicht nur den Modellen, sondern auch den Verfahren, mit denen sie erstellt wurden, vertrauen muss. Das Problem beim digitalen Zwilling ist der Gültigkeitsbereich. Oft fehlt der Kontext der Daten. Es ist unklar, was berücksichtigt und was vernachlässigt wurde. Welche Effekte sollten mit welcher Genauigkeit berücksichtigt werden?“	*“The general question is: When do I trust a simulation? Simulations are also very rarely used for approval issues because you have to trust not only the models, but also the procedures by which they were generated. The problem with the digital twin is the scope of validity. Often the context of the data is missing. It is unclear what has been considered and what has been neglected. Which effects should be considered and to what accuracy? “*	Team Lead - Electrical Equipment Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Fehlende Transparenz und fehlendes Erwartungsmanagement sind wichtige Schwachstellen digitaler Zwillinge. Und auch das Thema "ungelöste Pflege-Wartungskonzept". Wo erfolgt eine Aktualisierung? Die Gültigkeit der Informationsketten muss auch beachtet werden und dementsprechend den digitalen Zwilling aktualisieren.“	*“Lack of transparency and lack of expectation management are important weaknesses of digital twins. And also, the issue of "unresolved care-maintenance concept". Where does an update take place? The validity of the information chains must also be observed and update the digital twin accordingly.”*	Team Lead - Electrical Equipment Company
	„Ich würde auch den Scope festlegen. Das ist mir sehr wichtig. Man muss eine Vision aufzeigen, wo es sich hin entwickeln soll - das auf jeden Fall. Man muss frühzeitig definieren, in welchen Bereich man sein will und wo man dann damit auch hin will.“	*“I would also define the scope. That is very important to me. You have to show a vision of where you want to go - that's for sure. You have to define early on what scope you want to be in and then where you want to go with it.”*	Project Lead Digital Manufacturing – Digital Industries Company
	„Transparenz ist auch ein wichtiger Aspekt für den Aufbau von Vertrauen. Es ist nicht so das es nur ein DT geben wird, sondern es wird mehrere geben für verschiedenen Anwendungsfälle.“	*“Transparency is also an important aspect for building trust. It is not that there will be only one DT, but there will be several for different use cases.”*	Head of Function Development & Software Engineering - Energy and Climate Solutions Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Das Ganze begreifbar für die Leute zu gestalten. Ein großer Fehler ist die DTs zu abstrakt zu gestalten. Wenn es zu abstrakt wird ist das Thema der Begreifbarkeit wieder weg. Was in der Black Box passiert ist nicht das Wichtige. Das Wichtige ist das Input bzw. Fehlerfall zu verstehen und den Ziel klarstellen. Und dann auch zeigen, hier war der DT bzw. die Simulation sehr hilfreich."	*"Making the whole thing comprehensible to people. A big mistake is to make the DTs too abstract. If it becomes too abstract, the theme of comprehensibility is gone again. What happens in the black box is not the important thing. The important thing is to understand the input or error case and clarify the goal. And then also show, here the DT or the simulation was very helpful."*	Head of Processes, Methods & Tools - Energy and Climate Solutions Company
	„Die Organisation mitzunehmen. Mentoring. Die Leute an die Hand zu nehmen. Das Vertrauen immer weiter aufzubauen mit kleinen realen Beispielen."	*"Taking the organization with you. Mentoring. Taking people by the hand. Building the trust more and more with small real examples."*	Head of Processes, Methods & Tools - Energy and Climate Solutions Company
	„Da ist auch vielleicht auf euer Thema Vertrauen hinzuarbeiten ein Punkt, dass man das Ganze greifbar macht. Also, dass man vielleicht mit den generische "Buzz words" aufhört, und stattdessen eher handfeste Use Cases und Business Cases analysiert. Wirklich branchenspezifisch oder produktspezifisch durch Verbände, Communities oder auch durch handfeste Best Practices und Veröffentlichungen zeigt, wie es ausschauen kann."	*"Perhaps one point to work on your topic of trust is to make the whole thing tangible. In other words, maybe we should stop using generic buzz words and instead analyze tangible use cases and business cases. Really industry-specific or product-specific through associations, communities or also through tangible best practices and publications shows how it can look."*	Management Consultant Intelligent Industries – Engineering Consulting Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
Create a common incentive!	*„Im Prinzip muss man immer auch den Anwendungsfall betrachten und eine gewisse Skalierbarkeit des DT schaffen. Das ist auch die Herausforderung vom Ganzen. Je besser mein DT ist, bzw. je mehr Entwicklungsaufwand ich reinstecke, desto mehr Lösungen wird der DT in einem spezifischen Anwendungsfall bringen. Die Frage ist dann, inwieweit kann ich den DT in andere Anwendungsfälle übertragen."*	*"In general, you always have to consider the use case and create a certain scalability of the DT. That is also the challenge of the entire thing. The better my DT is, or the more development effort I put into it, the more solutions the DT will provide in a specific use case. The question is then, to what extent can I transfer the DT to other use cases?"*	Project Lead Digital Manufacturing – Digital Industries Company
	„Ich mach mir immer zunächst klar was für ein Verwendungszweck dahinter steckt, wenn es um Digital Twins geht. Was will den der Kunde? Man ist nicht fertig, wenn die Simulation abgeschlossen ist. Man muss zum System hingehen und kontrollieren, dass die Daten stimmen. Am Ende ist es wichtig dass man eine Community hat, die für die selbe Ziele stehen. Das verbessert das Vertrauen."	*"When it comes to digital twins, I always start by clarifying what the intended use is. What does the customer want? You are not done when the simulation is finished. You have to check the system and make sure the data is correct. In the end, it is important to have a community that shares the same intentions. This improves trust."*	General Manager - Automation Engineering Company
Make one step at a time!	*„Inkrementelle Entwicklung. Fähigkeiten demonstrieren, erst kompakte kleine Projekte am Anfang durchführen, wo man sehr abgesteckte Themen betrachtet und sehr schnell Vorteile und Mehrwert zeigen kann."*	*"Incremental development. Demonstrate capabilities, first do compact small projects at the beginning where you can look at very defined topics and show benefits and added value very quickly."*	Vice President Methods, Analyses & Materials – Aerospace & Defense Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Kleine Beispiele oder Nutzen aufzeigen würde auch helfen. Es muss nicht immer die High-End Lösung sein, aber dass man konkrete Referenzen aufbaut und anhand dieser dann den Mehrwert digitaler Zwillinge glaubhaft zeigt - darum geht es. Mehr vom Problem aus denken, als von der Technologie oder dem Produkt."	*"Showing small examples or benefits would also help. It doesn't always have to be the high-end solution, but the idea is to build up concrete references and then use them to credibly demonstrate the added value of digital twins. Think more from the problem than from the technology or the product."*	Project Lead Digital Manufacturing – Digital Industries Company
	„Es hat sich halt auch gezeigt, dass kleine Schritte auch dafür hilfreich sind, dieses Vertrauen einerseits zu schaffen und anderseits auch zu zeigen, was denn geht und in welche Richtung sich das entwicklen kann. Vor allem auch schnell kleine Ergebnisse oder kleine Erfolge darstellbar sind."	*"It has also been shown that small steps are also helpful in creating this trust on the one hand, and on the other hand also to show what is possible and in which direction it can develop. Above all, small results or small successes can be achieved quickly."*	Head of Function Development & Software Engineering - Energy and Climate Solutions Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Ich vertraue den DT schon. Aber ich misstraue, dass die Etablierung von DTs kurzfristig passieren wird. Ich misstraue die erwartete Schnelligkeit. Deshalb glaube ich, dass man jetzt kleine Schritte gehen muss. Am besten entwickelt man erstmal ein Engineering Twin für Mechanik, noch einen für die Software, usw. Wenn diese sauber ausgestaltet sind, dann geht man wirklich mit so einem Master Twin überall rein und kann nachweisen, dass es passt. Dann kriegt man durchaus auch irgendwann den Match hin. Aber das ist genau das Problem, oder? Ich glaube nicht, dass es so einfach und so schnell zu realisieren ist.“	*“I already trust the digital twin. But I distrust the fact that the establishment of DTs will happen in the short term. I distrust the expected speed. That's why I think you have to take small steps now. The best way is to first develop an engineering twin for mechanics, another one for electronics, etc. When these are cleanly designed, then you really move on to a master twin.”*	Head of Processes, Methods & Tools - Energy and Climate Solutions Company
Protect the IP!	*„In der digitalen Welt kommt man sehr schnell beim Thema vom geistigen Eigentum und von den Betriebsgeheimnissen an. Und das sind alles Informationen, die man unter keinen Umständen rausgibt. Aus meiner Sicht hat dieses Thema der DT nur eine Chance, wenn es auch nicht geschieht. Man sollte die DT so gestalten, dass das Thema Datensicherheit gar nicht erst zum Problem wird. Das ist meiner Meinung nach ein wesentlicher Aspekt bei der Betrachtung von DT.“*	*“In the digital world, you very quickly come to the issue of intellectual property and company secrets. And this is all information that you never give out under any circumstances. You should design the Digital Twin in such a way that the issue of data security is not even a problem in the first place. It also has to be clear what I gain from it in business terms. That's where you have to look at the trade off of effort versus the business benefit.”*	Vice President Methods, Analyses & Materials – Aerospace & Defense Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Ganz klar, nicht in die Haftungsrichtung. Das ist ein stumpfes Schwert. Das Konzept muss so sein, dass man von vorne rein ein sehr hohes Niveau an Sicherheit herstellt, sicherstellt und auch laufend aufrechterhält. Alles andere ist nur ein Pflaster auf eine große Wunde. In dieser Richtung gehen wir auch immer in die Gespräche.“	*“It is quite clear that merely clarifying liability issues is not the right direction; it is a blunt sword. The concept must be such that a very high level of safety is established, ensured and also continuously maintained from the start. Anything else is just a plaster on a wound that is too big and cannot repair the damage.”*	Vice President Methods, Analyses & Materials – Aerospace & Defense Company
	„Wenn es langfristig funktionieren soll, sprich dass alle noch ihr Geld verdienen können, muss das Know-How im Haus bleiben. Das steht aber auch im Weg vom kompletten, echten DT, der im idealer Fall offen gestaltet ist.“	*“If it is to work in the long term, i.e. if everyone can still earn their money, the know-how must remain in-house.”*	General Manager - Automation Engineering Company
Prove your quality!	*„Das schafft man nur mit Erfahrung. Ich vertraue etwas, wenn ich Erfahrung damit gewonnen habe. Und das ist hier der menschliche Aspekt, den man berücksichtigen muss. Und dann muss ich zum TÜV oder irgendjemanden gehen und der muss es auch vertrauen. Es wurde in den letzten 20-30 Jahren viel mit Prototypen im Bereich von Simulationen gearbeitet, was die Erfahrung erhöht hat. Inzwischen werden Simulationen schon vertraut, aber wenn jetzt ein anderes System kommt (z.B. DTs) muss das ganze noch einmal von neu anfangen.“*	*“You can only do that with experience. I trust something when I have gained experience with it. And that's the human aspect here that you have to take into account. And then I have to go to the TÜV or somebody and they have to trust it as well. There has been a lot of work with prototypes in the field of simulations in the last 20-30 years, which has increased the experience. In the meantime, simulations are already trusted, but if another system comes now (e.g. DTs) the whole thing has to start all over again.”*	Team Lead - Electrical Equipment Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
	„Jetzt wird es sich herauskristallisieren was für Industrien es gibt, was für spezifische Bereiche es gibt und wo genau der DT konkret einen Mehrwert stiftet. Damit wird es für mich auch ein Stück weiter in dem Vertrauen von DTs gehen. Denn Vertrauen kann nur entstehen, wenn man Erfahrungswerte hat.“	*„Now it will become clear what industries there are, what specific areas there are, and where exactly the Digital Twin adds value. For me, this will also take the trust of Digital Twins a bit further. Because trust can only develop if you have experiences.“*	Project Lead Digital Manufacturing – Digital Industries Company
	„Da ist im Kontext Vertrauen auch ein Punkt, dass man das Ganze greifbar macht. Also, dass man vielleicht mit den zu generischen "Buzz words" aufhört, und stattdessen eher handfeste Use Cases und Business Cases analysiert. Wirklich branchenspezifisch oder produktspezifisch durch Verbände, Communities oder auch durch handfeste Best Practices und Veröffentlichungen zeigt, wie es ausschauen kann.“	*“In the context of trust, it is also important to make the whole thing more tangible. In other words, we should perhaps stop using buzz words that are too generic and instead analyze concrete use cases and business cases. Really demonstrating industry-specific and product-specific by associations, communities or also by tangible best practices and publications how it could work.”*	Management Consultant Intelligent Industries – Engineering Consulting Company
Ensure a uniform environment!	*„Wir haben ja inzwischen verschiedenste Stakeholder, die auf einen zentralen Datensatz zugreifen möchten. Da braucht man ein Konsens, sprich man braucht Standards bei den Schnittstellen und auch ein Agreement der definiert wer und wie zugreifen kann. Die Erfahrungswerte einer Community oder ein Netzwerk kann einfach extrem Mehrwert stiften.“*	*“We now have a wide variety of stakeholders who want to access a central data set. You need a consensus, i.e. you need standards for the interfaces and also an agreement that defines who can access when and how. The experience of a community or a network can simply add a lot of value here.”*	Management Consultant Intelligent Industries – Engineering Consulting Company

Element of the DT Trust Framework	German (transcribed)	English (translated)	Interview Partner
Document thoroughly!	*„Auch das Thema "ungelöstes Pflege und Wartungskonzept": Wie erfolgt eine Aktualisierung der Daten? Die Gültigkeit der Informationsketten muss beachtet werden und dementsprechend muss der Digital Twin aktualisiert werden. Beim DT gibt es eine gewisse Gefahr, dass es zu einem Moloch an Informationen kommt, die irgendwie vernetzt sind, wobei es dann sehr unsicher wird.“*	*“Also the topic "unresolved care and maintenance concept": How is an update of the data done? The validity of the information chains must be respected and, accordingly, the Digital Twin must be updated. With Digital Twins, there is a certain risk of a jungle of information that is somehow networked, in which case it becomes very uncertain.”*	Team Lead - Electrical Equipment Company

A7 Addressed Challenges and Proposed Solution Elements

Table A 9: Summarized Challenges and Proposed Solution Elements. The Challenges are Sorted According to their Criticality as Investigated by Trauer, Mutschler, et al. (2022).

Addressed Challenges	Proposed Solution Element
“Development and deployment time and resources required” *“Combining product lifecycle management, manufacturing execution systems and operations”* *“Difficulties in setting up a strategy for the implementation of Digital Twin use cases”* *“Lack of suitable procedures for an efficient implementation”*	**Procedure Model**
“Identifying clear and valid value propositions associated with the Digital Twin solution” *“Setting realistic expectations and trust.”*	**Business Modelling Approach**
“Identifying clear and valid value	**Use Case Catalogue**

Addressed Challenges	Proposed Solution Element
propositions associated with the Digital Twin solution" *"No systematic approach for identifying promising use cases"*	
"Identifying clear and valid value propositions associated with the Digital Twin solution"	**Value Map**
"Integration of Digital Twin in legacy system" *"Difficulties in setting up a strategy for the implementation of Digital Twin use cases"* *"IT infrastructure"*	**Use Case Template**
"Setting realistic expectations and trust." *"Bureaucracy, cultural inertia, and knowledge assessment"*	**Trust Framework**

A8 Additional Material on the Digital Twin Toolbox for Implementation and Design

Table A 10: The Core Vocabulary of Design Support (adapted from Gericke et al., 2017).

Term	Explanation
Design Methodology	*"In design, a clearly and explicitly articulated approach to producing designs for a class of systems, that specifies in more or less detail the activities to be carried out, the relationship and sequencing of the activities, the methods to be used for particular activities, the information artefacts to be produced by the activities and used as inputs to other activities, and how the process is to be managed, as well as (tacitly or explicitly) the paradigm for thinking about the design problem and the priorities given to particular decisions or aspects of the design or ways of thinking about the design."*
Design Process	*"In design, (1) A formally specified sequence of activities to be carried out in developing a particular design, or a class of designs, which will often be an application or customization of a methodology to a particular problem. (2) The actual sequence of activities carried out in the development of a design, which may correspond more or less well to any formally specified process."*

Term	Explanation
Design Method	*“A specification of how a specified result is to be achieved. This may include specifications of how information is to be shown, what information is to be used as inputs to the method, what tools are to be used, what actions are to be performed and how, and how the task should be decomposed and how actions should be sequenced.”*
Guideline	*“In design, a statement of what to do when, or what should be the case under particular circumstances. A should only be violated for good reason, with a careful consideration of the consequences.”*
Tool	*An object, artefact or software that is used to perform some action (for example to produce new design information). Tools might be based on particular methods, guidelines, processes or approaches or can be generic environments that can be used in conjunction with many methods.”*

A8.1 Additional Material of the Procedure Model

The Steps of the Procedure Model

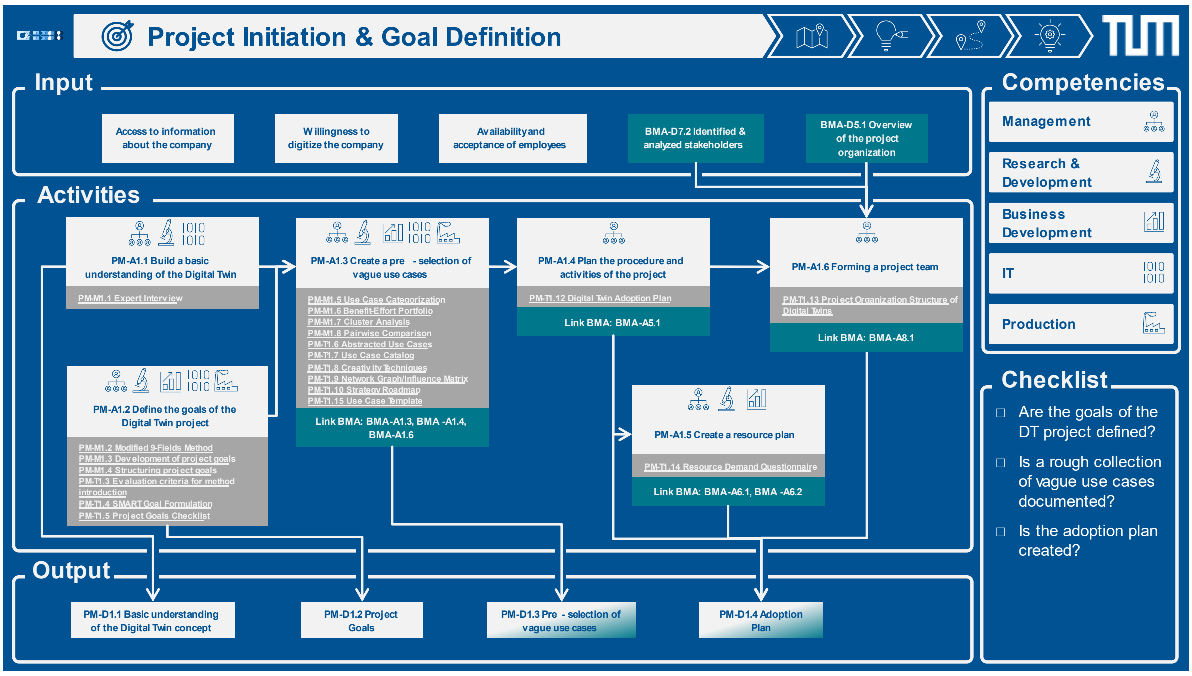


Figure A 30: Overview of “Step 1 – Project Initiation & Goal Definition” of the Digital Twin Procedure Model.

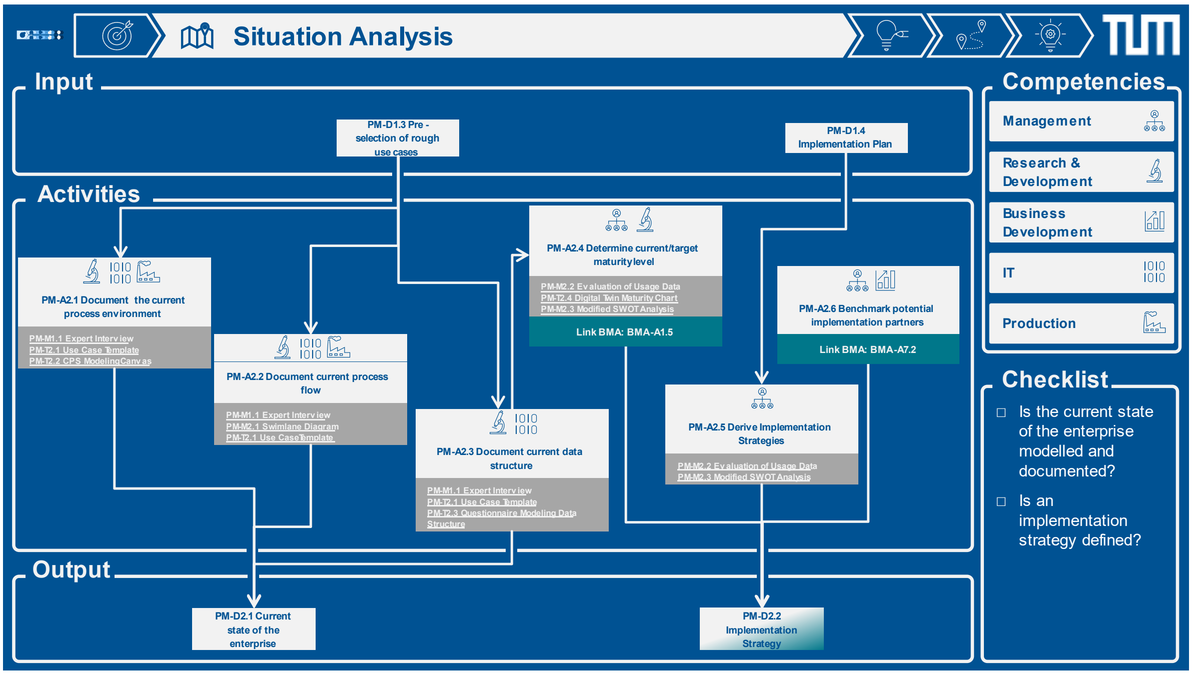


Figure A 31: Overview of "Step 2 – Situation Analysis" of the Digital Twin Procedure Model.

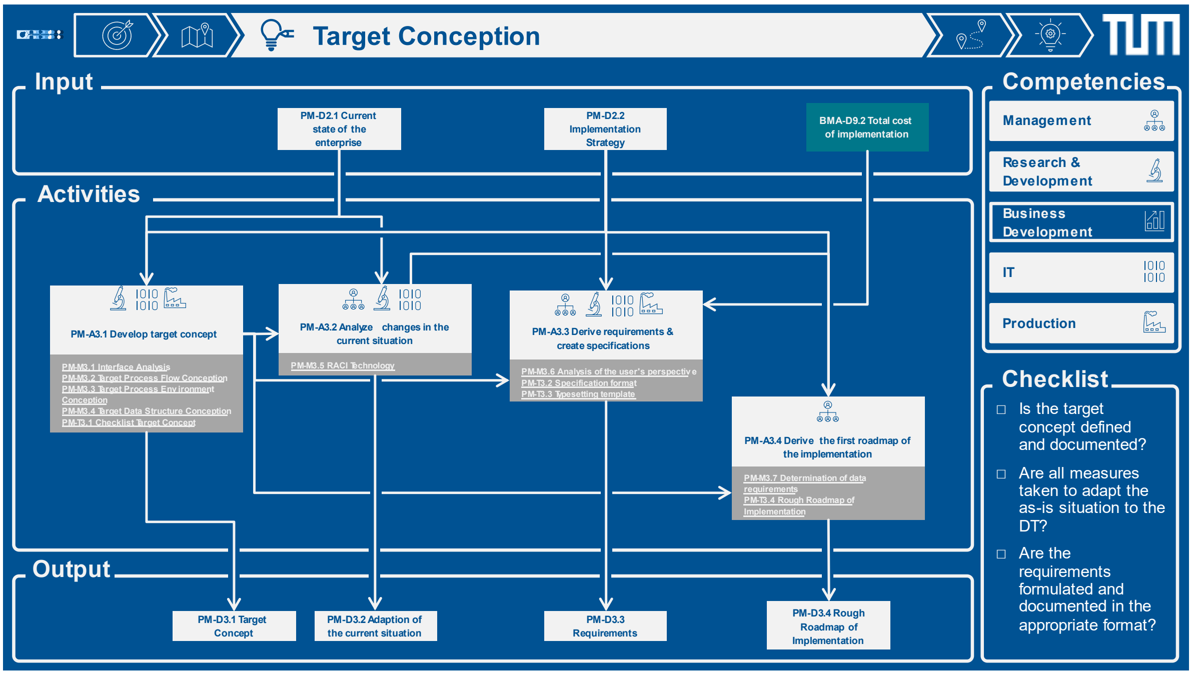


Figure A 32: Overview of "Step 3 – Target Conception" of the Digital Twin Procedure Model.

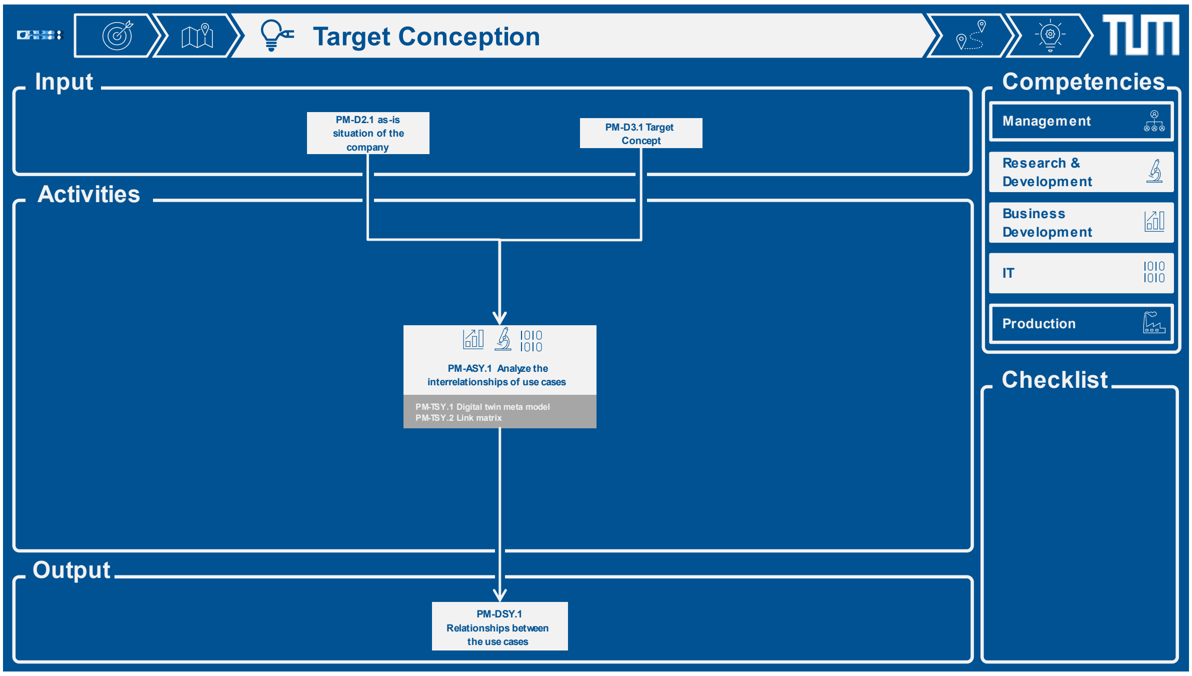


Figure A 33: Overview of the First Synchronisation Point as Part of Step 3 of the Digital Twin Procedure Model.

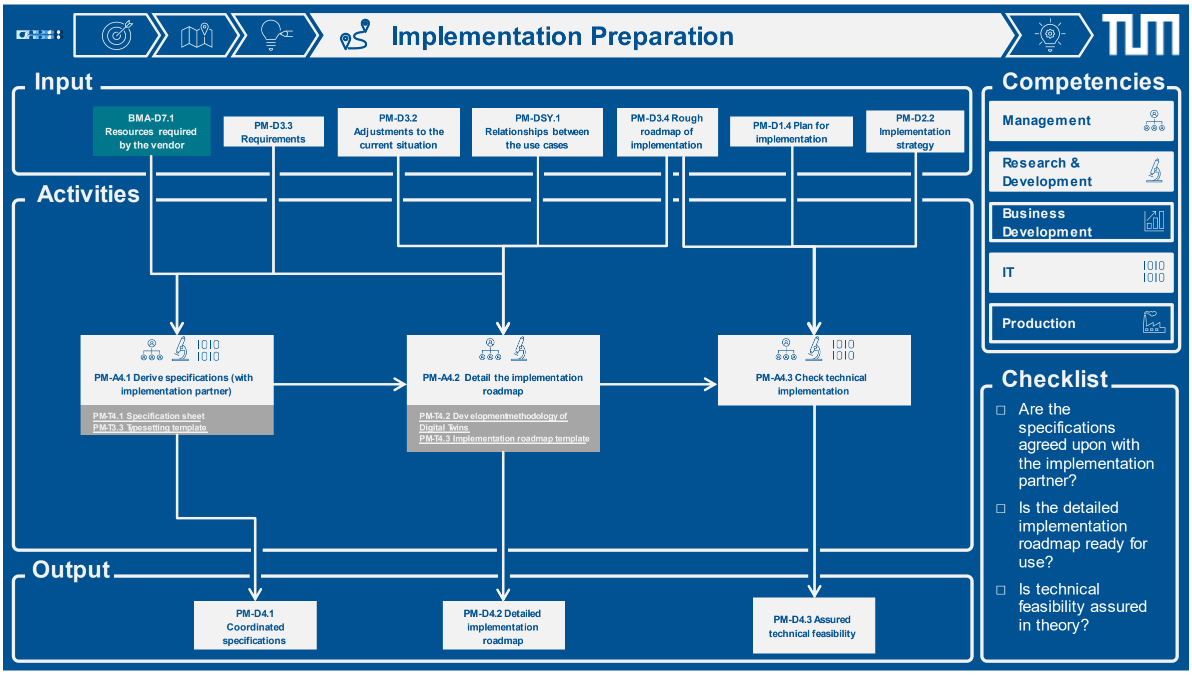


Figure A 34: Overview of "Step 4 – Implementation Preparation" of the Digital Twin Procedure Model.

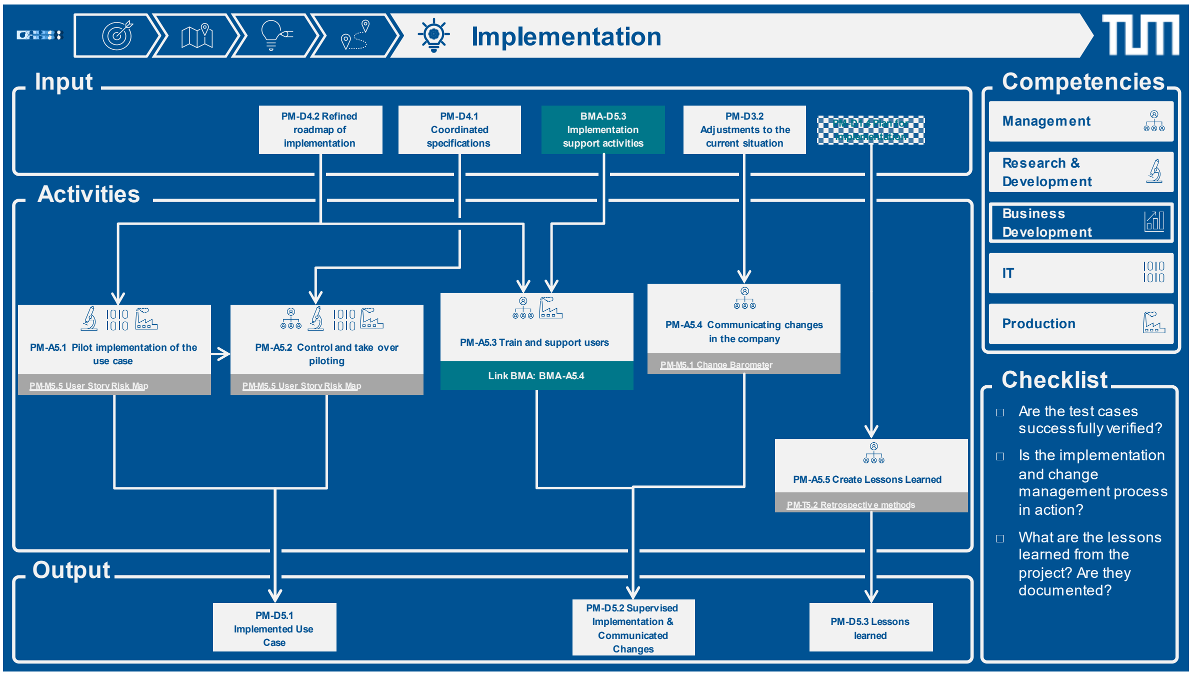


Figure A 35: Overview of "Step 5 – Implementation" of the Digital Twin Procedure Model.

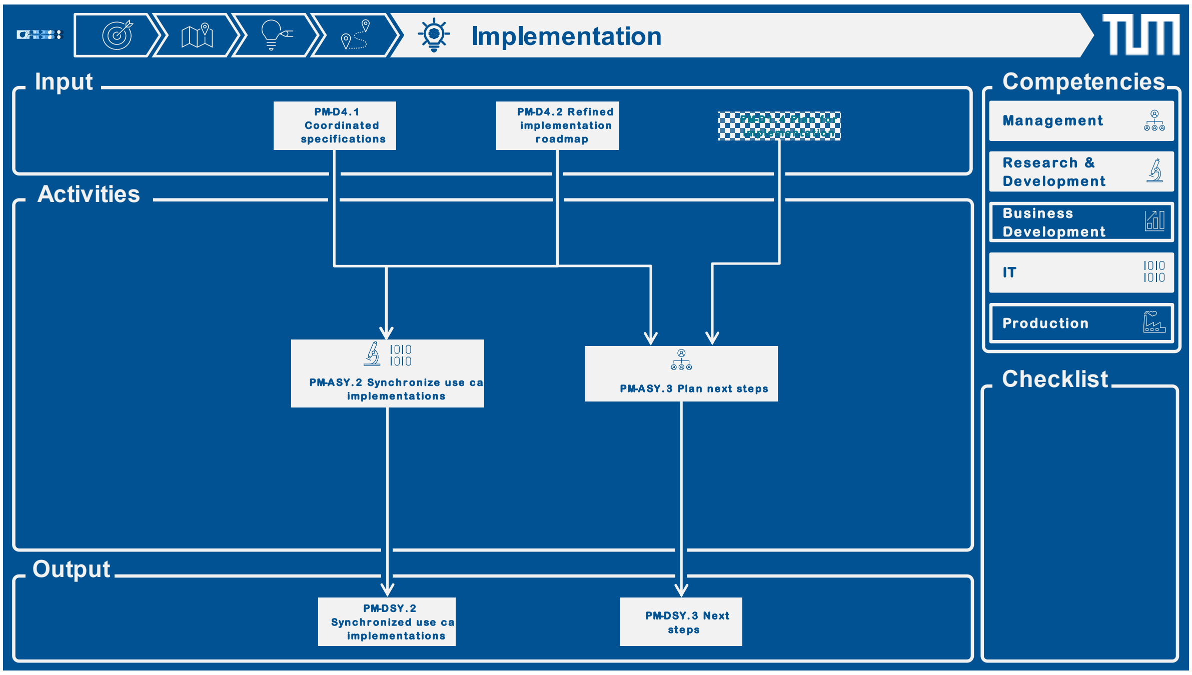


Figure A 36: Overview of the Second Synchronisation Point as Part of Step 5 of the Digital Twin Procedure Model.

The Activities of the Procedure Model

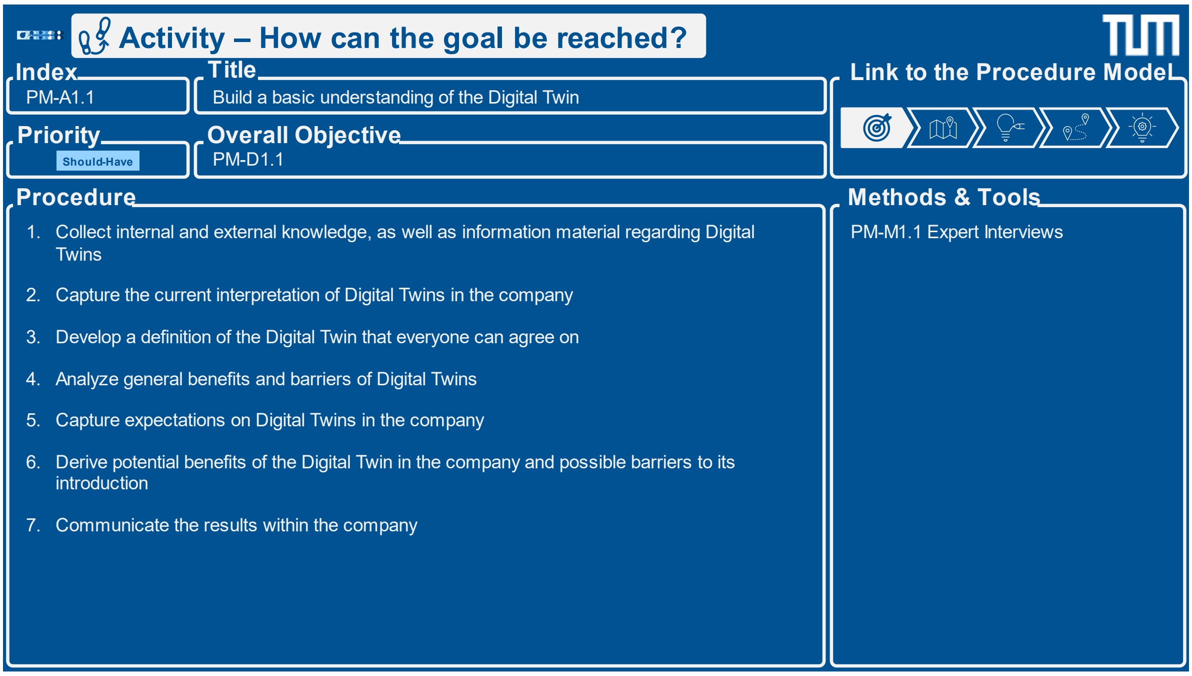


Figure A 37: Activity PM-A1.1 of the Digital Twin Procedure Model.

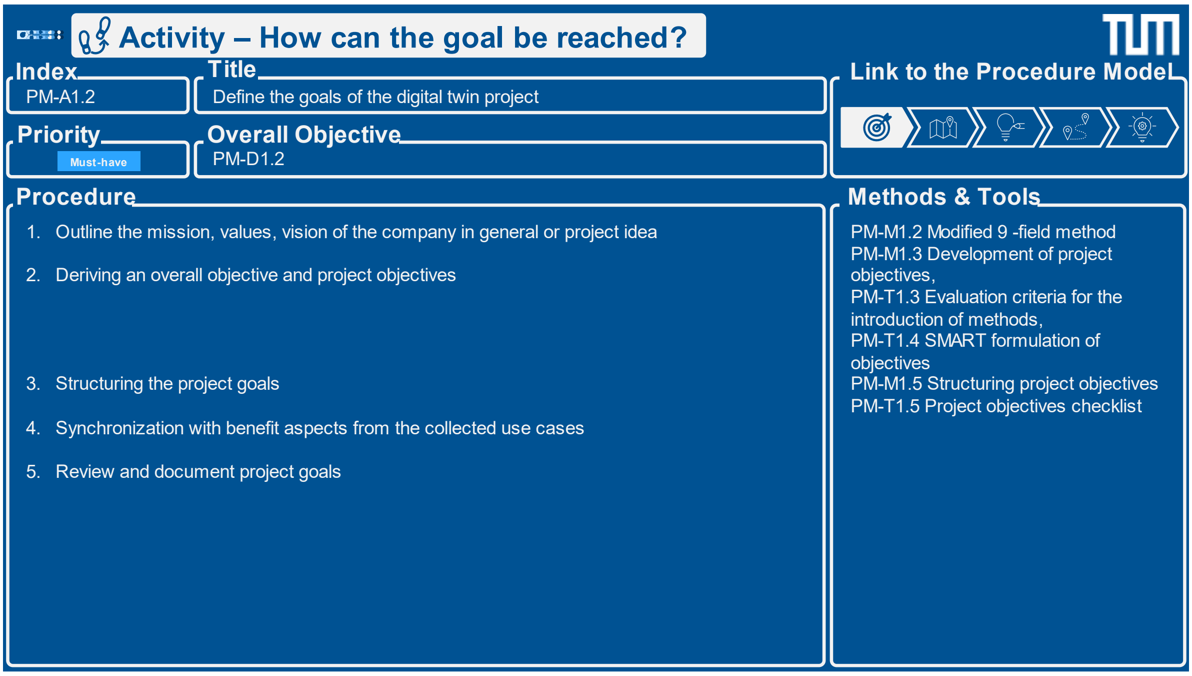


Figure A 38: Activity PM-A1.2 of the Digital Twin Procedure Model.

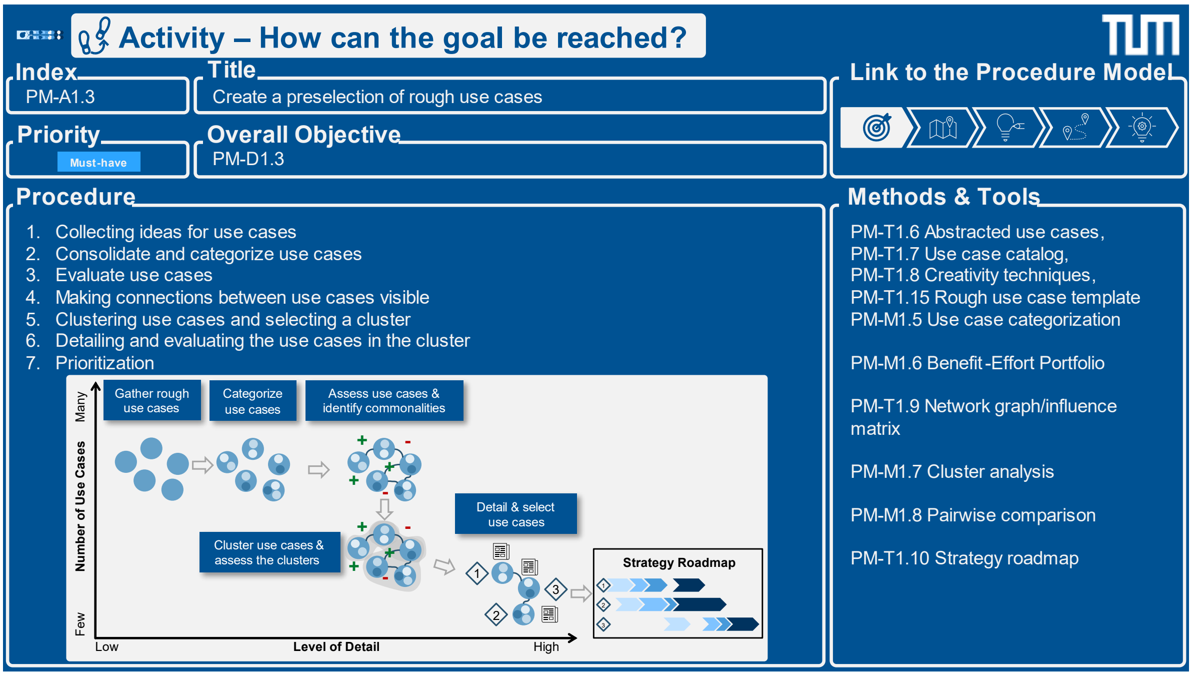


Figure A 39: Activity PM-A1.3 of the Digital Twin Procedure Model.

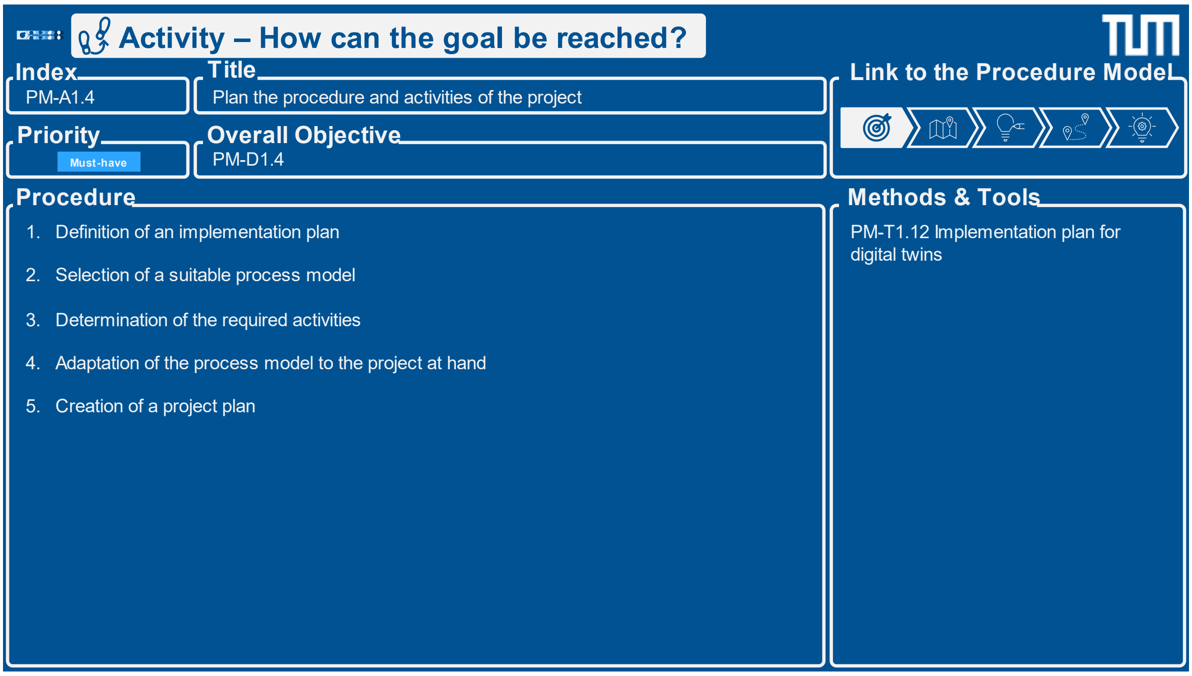


Figure A 40: Activity PM-A1.4 of the Digital Twin Procedure Model.

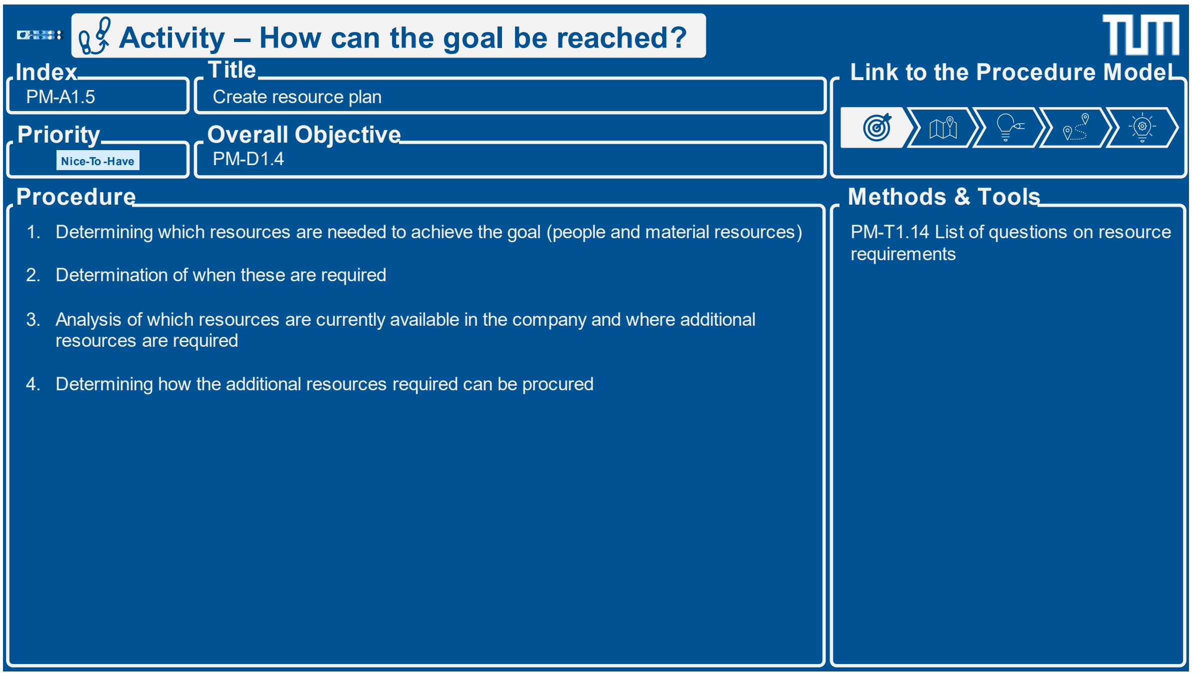


Figure A 41: Activity PM-A1.5 of the Digital Twin Procedure Model.

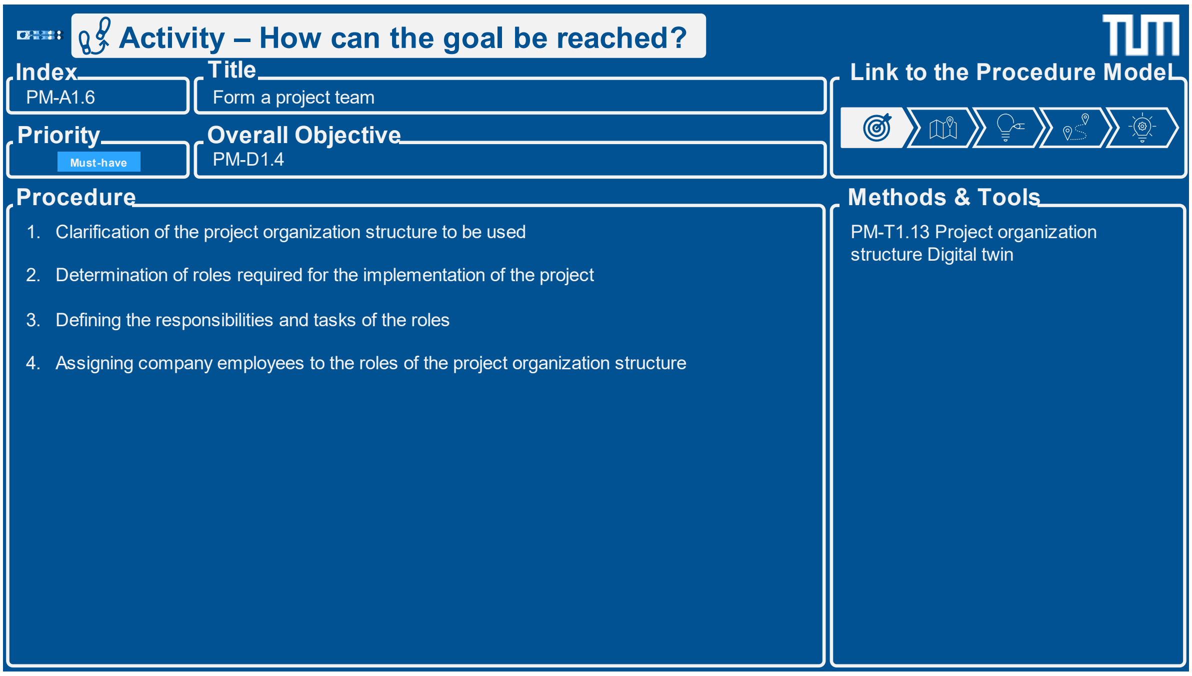


Figure A 42: Activity PM-A1.6 of the Digital Twin Procedure Model.

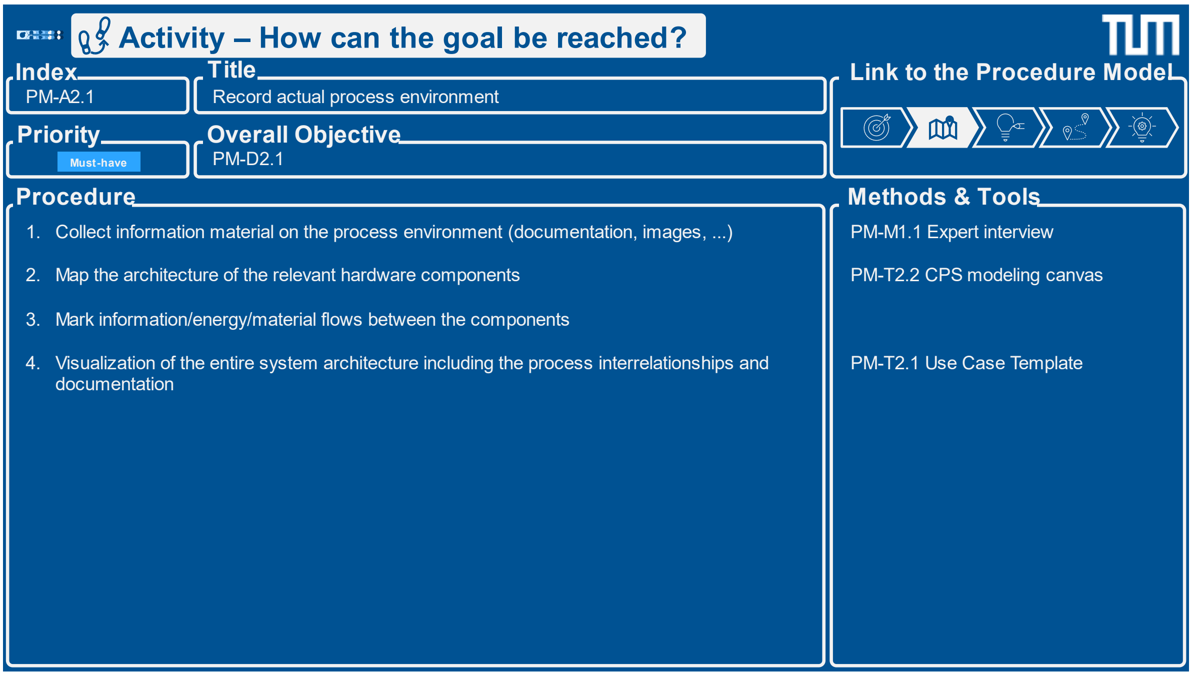


Figure A 43: Activity PM-A2.1 of the Digital Twin Procedure Model.

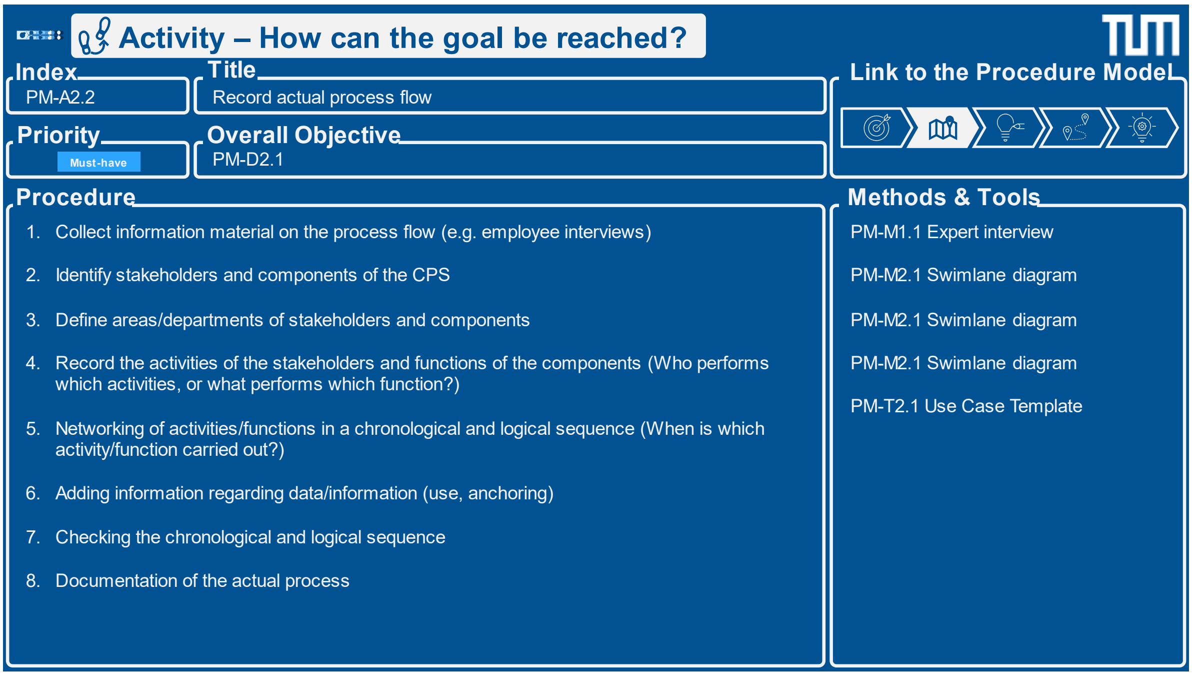


Figure A 44: Activity PM-A2.2 of the Digital Twin Procedure Model.

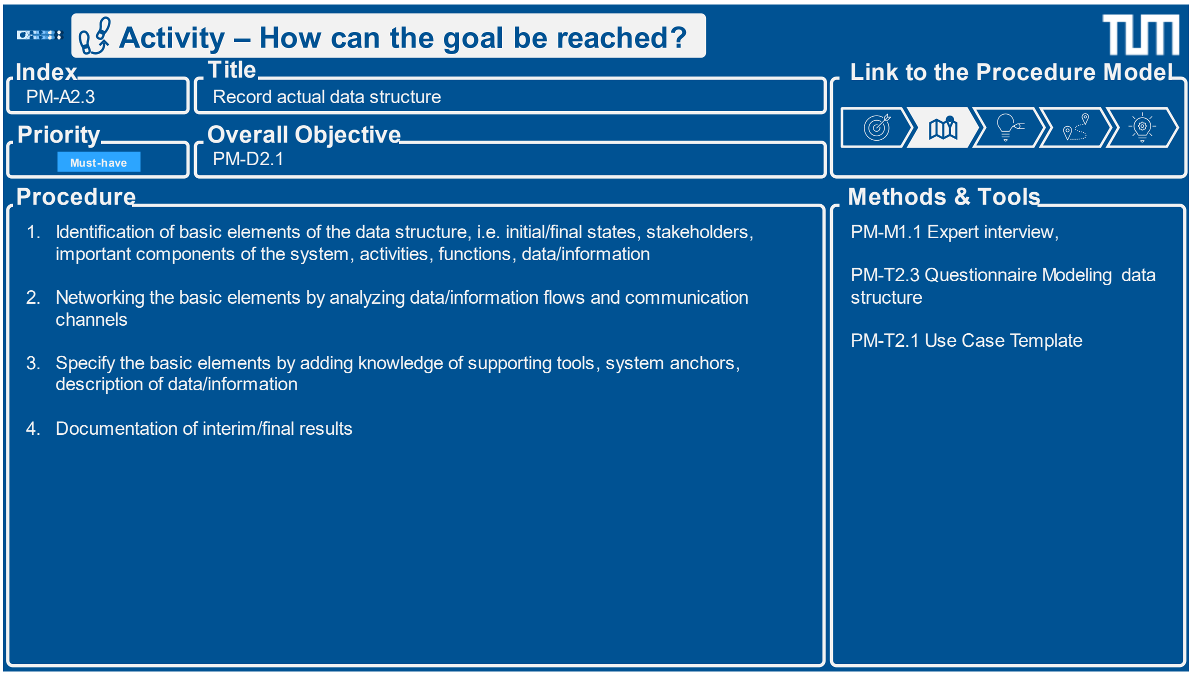


Figure A 45: Activity PM-A2.3 of the Digital Twin Procedure Model.

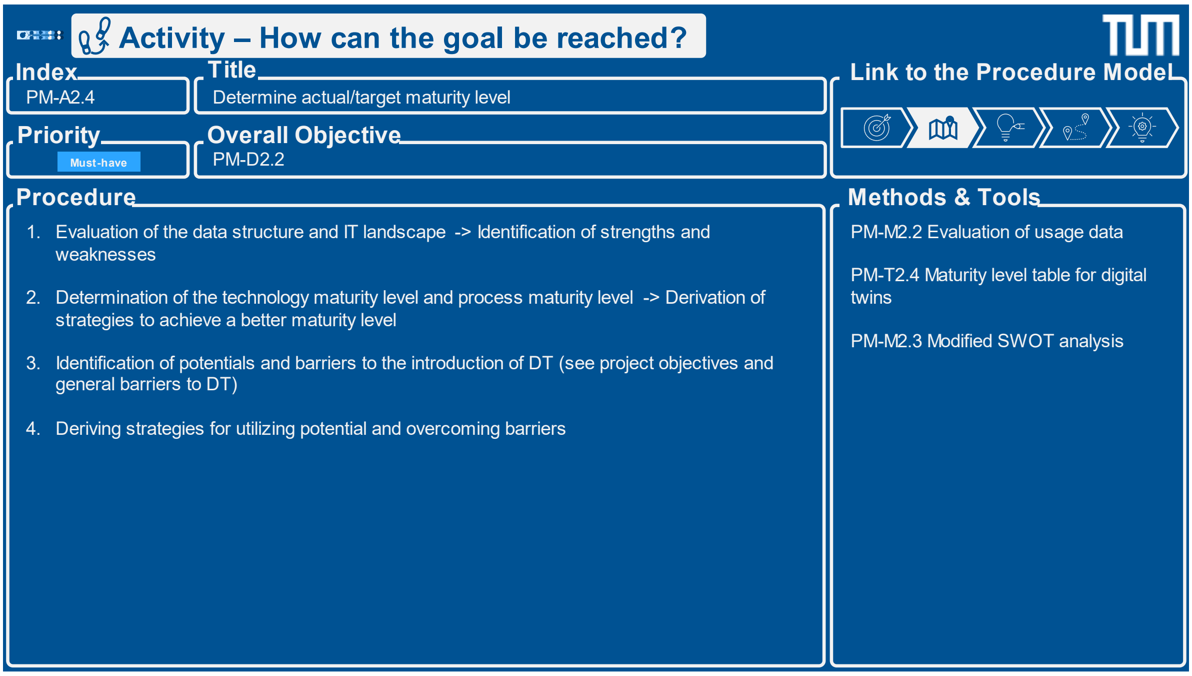


Figure A 46: Activity PM-A2.4 of the Digital Twin Procedure Model.

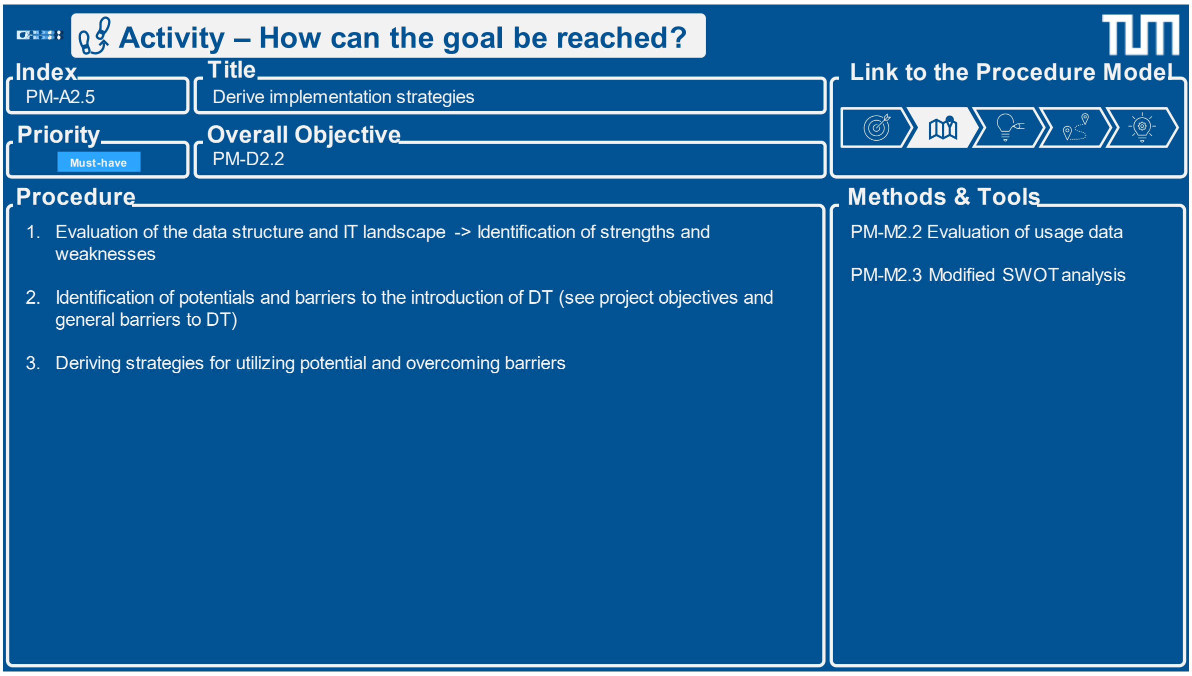


Figure A 47: Activity PM-A2.5 of the Digital Twin Procedure Model.

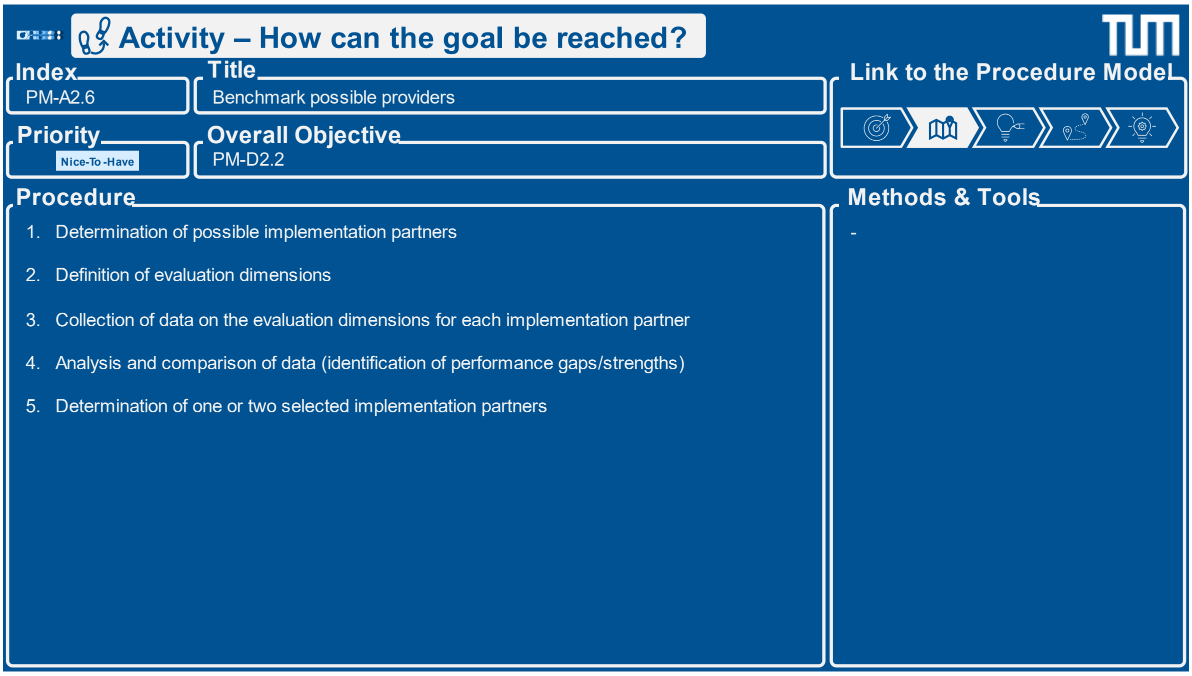


Figure A 48: Activity PM-A2.6 of the Digital Twin Procedure Model.

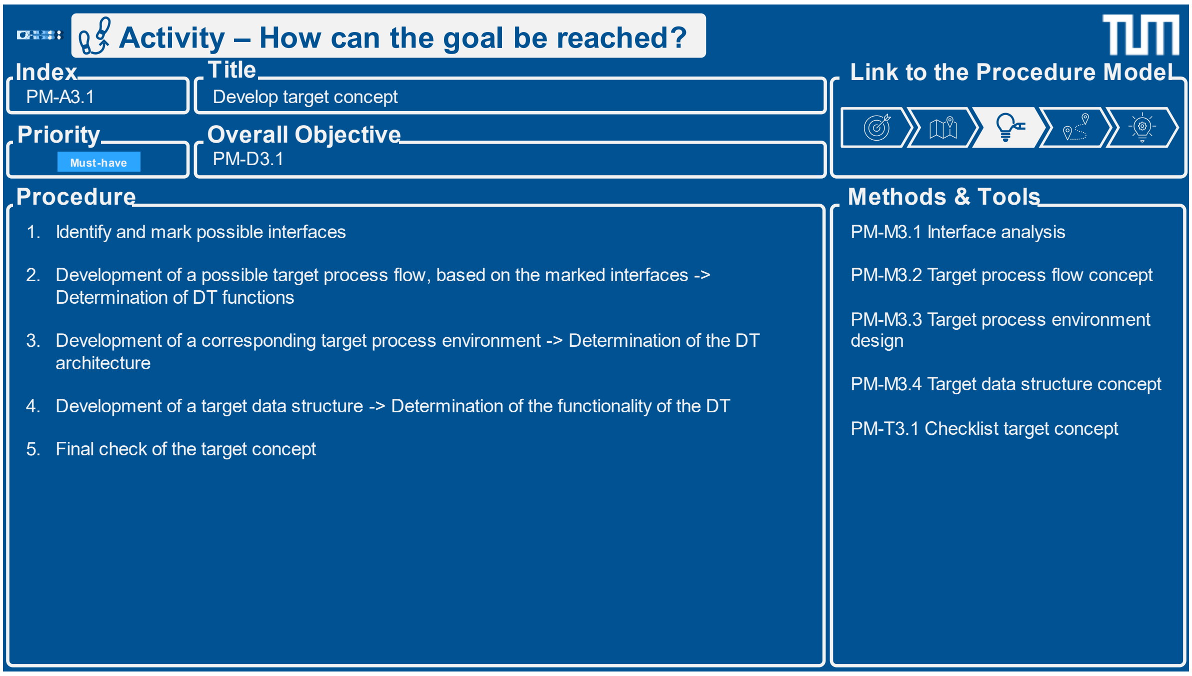


Figure A 49: Activity PM-A3.1 of the Digital Twin Procedure Model.

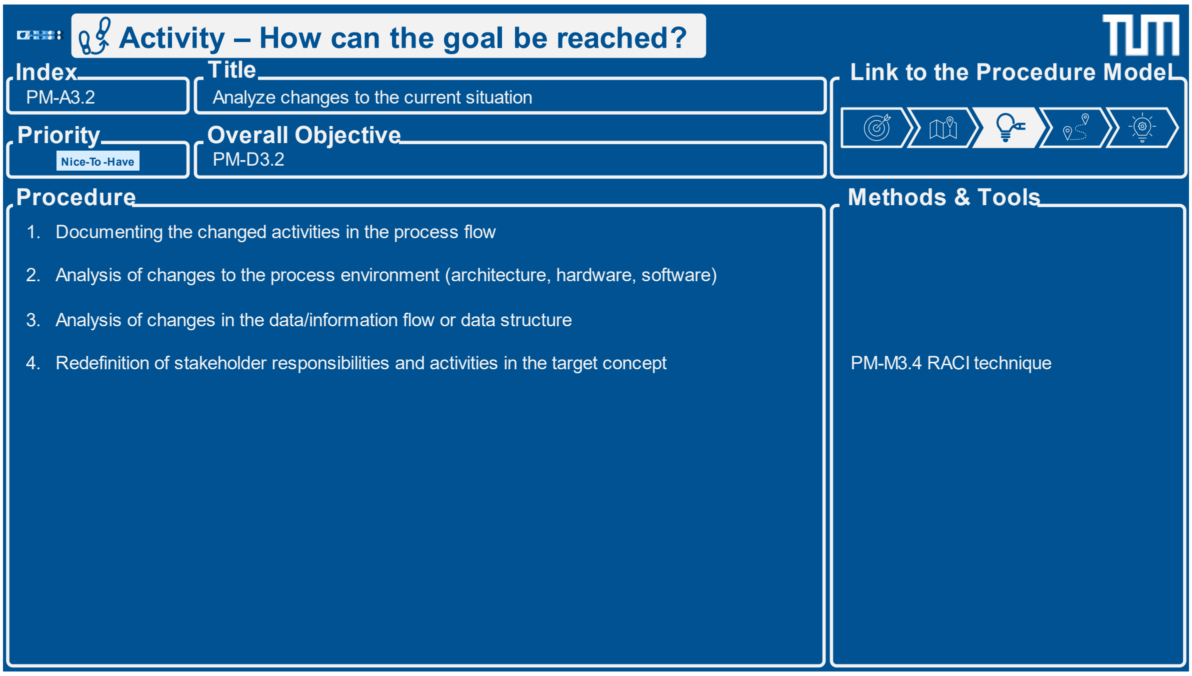


Figure A 50: Activity PM-A3.2 of the Digital Twin Procedure Model.

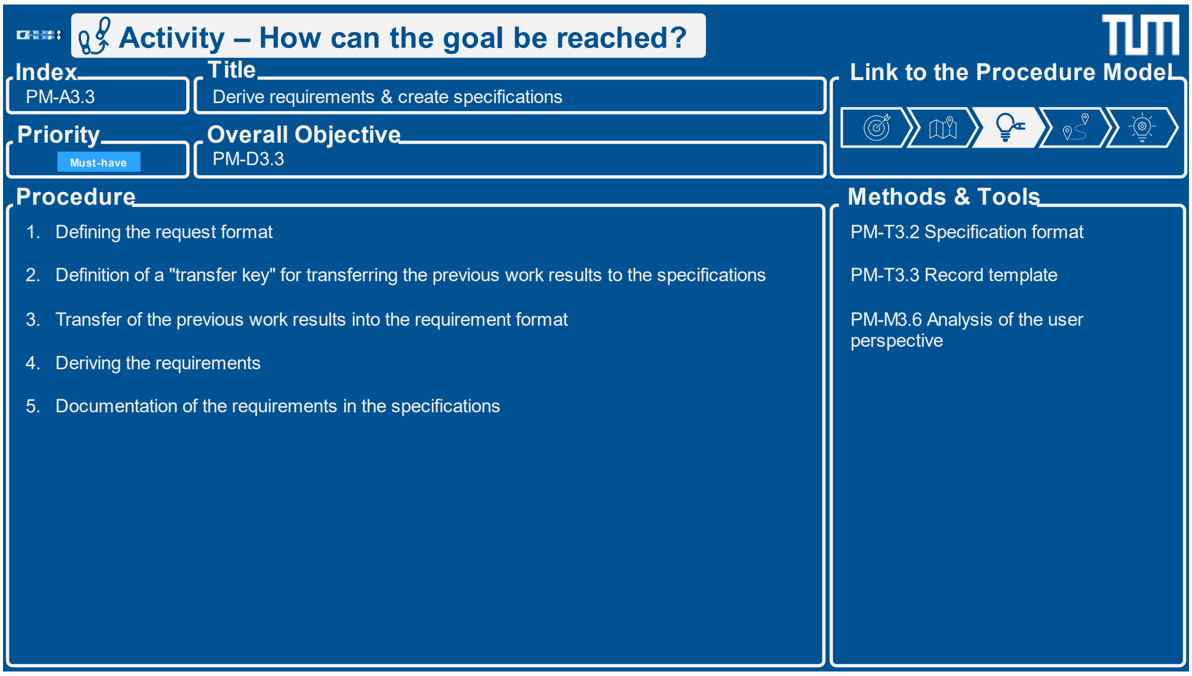


Figure A 51: Activity PM-A3.3 of the Digital Twin Procedure Model.

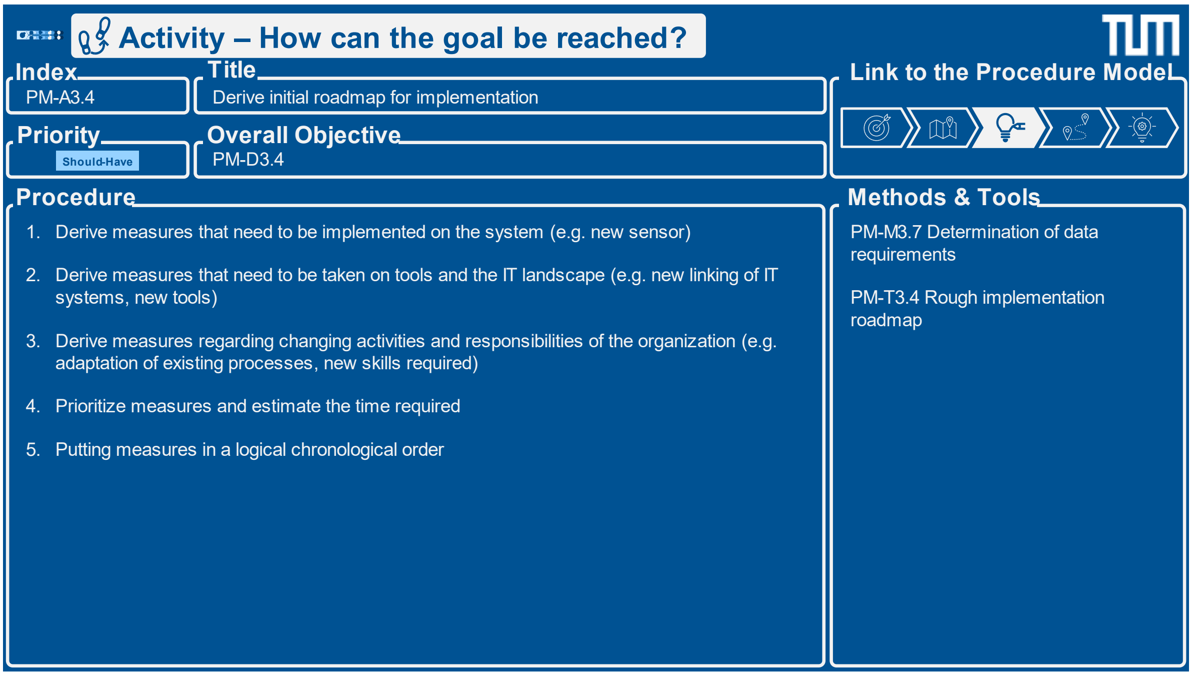


Figure A 52: Activity PM-A3.4 of the Digital Twin Procedure Model.

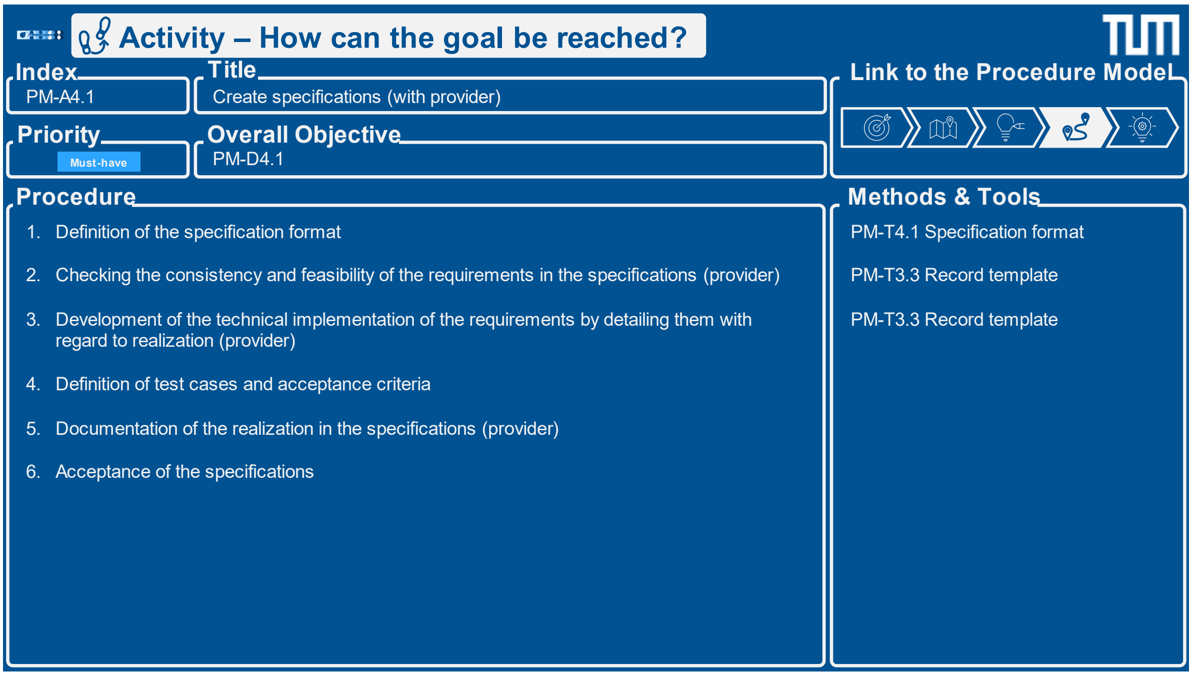


Figure A 53: Activity PM-A4.1 of the Digital Twin Procedure Model.

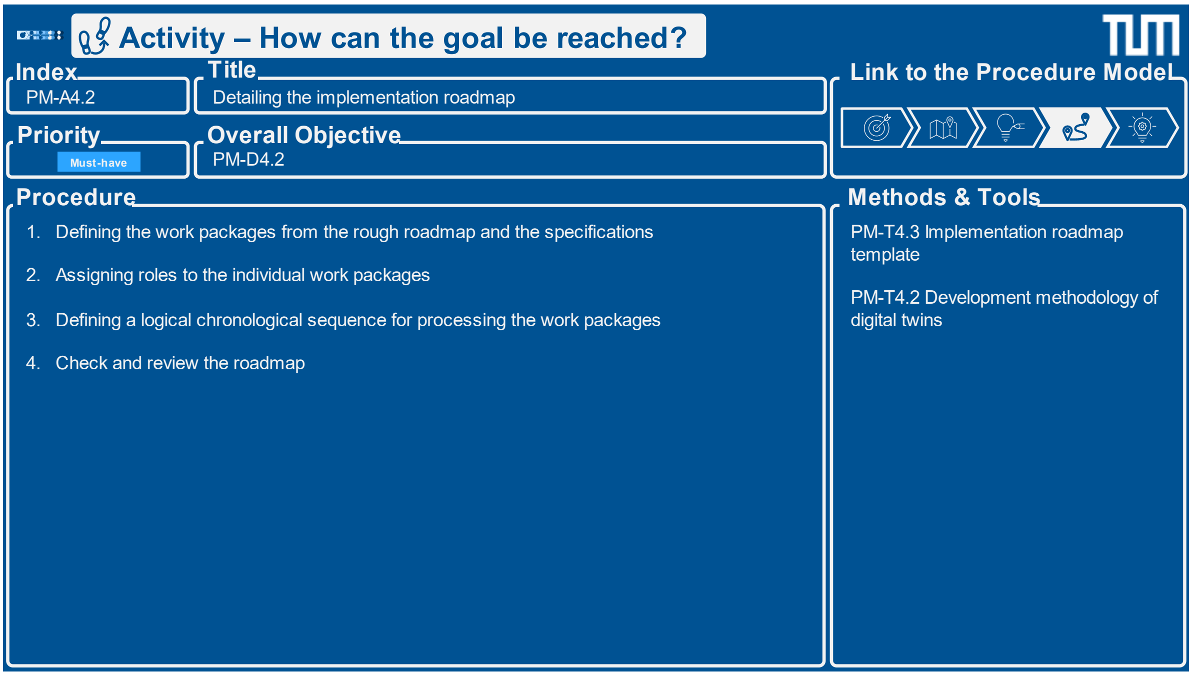


Figure A 54: Activity PM-A4.2 of the Digital Twin Procedure Model.

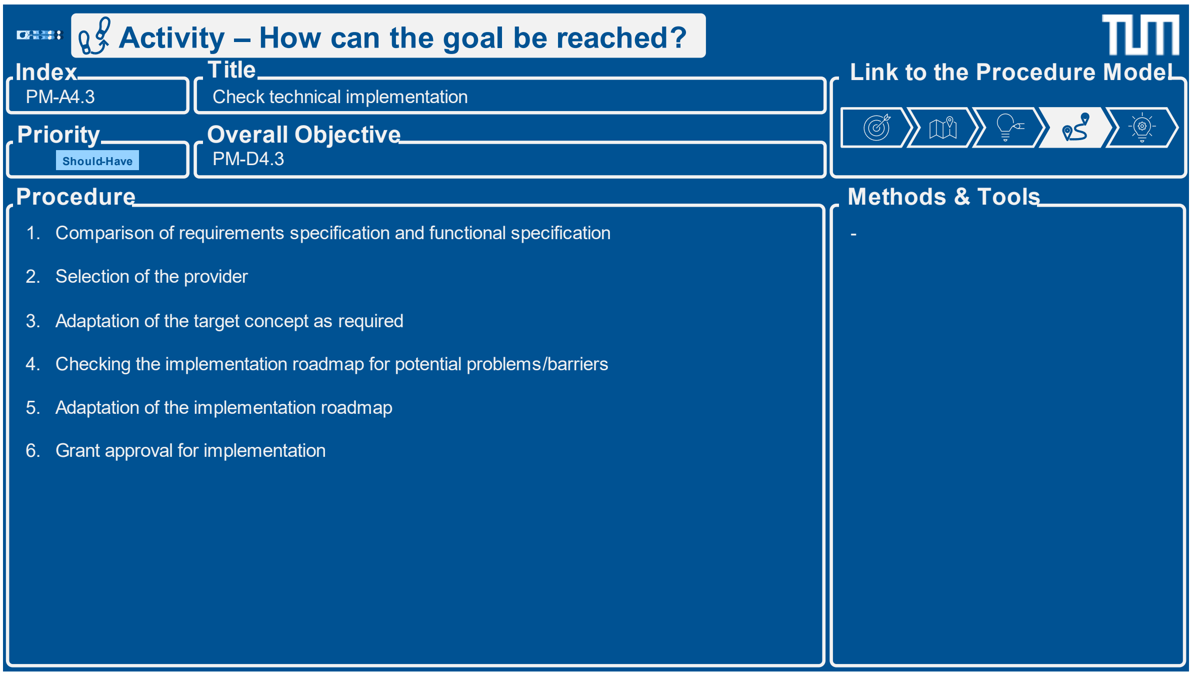


Figure A 55: Activity PM-A4.3 of the Digital Twin Procedure Model.

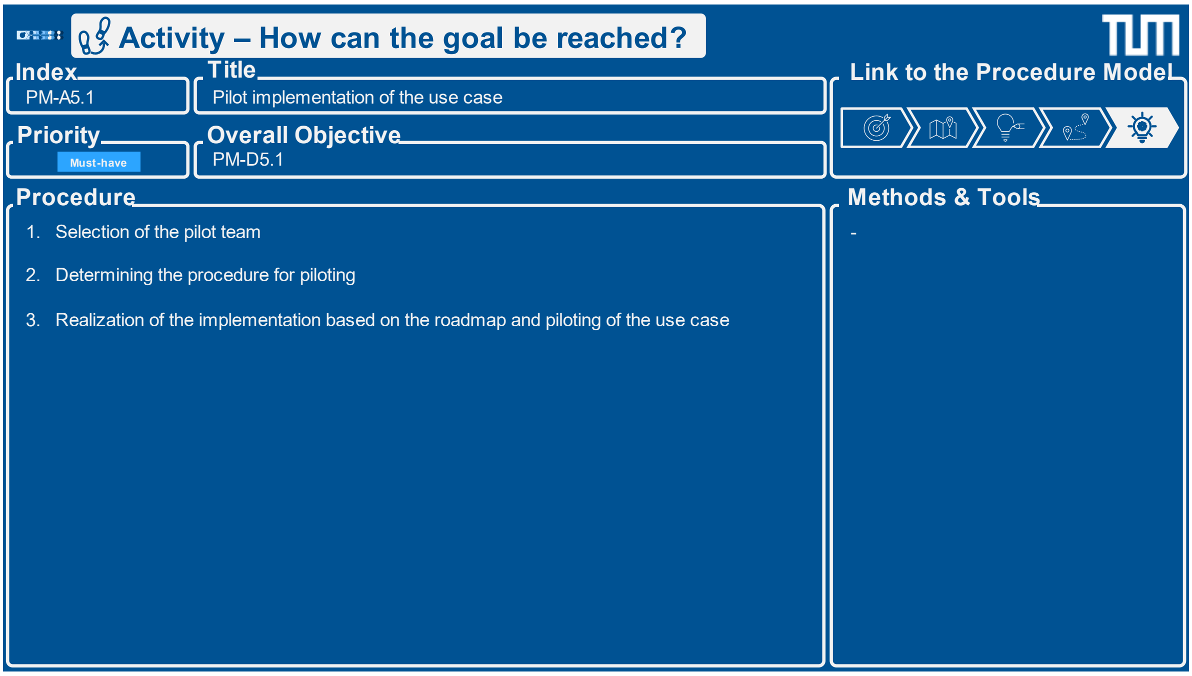


Figure A 56: Activity PM-A5.1 of the Digital Twin Procedure Model.

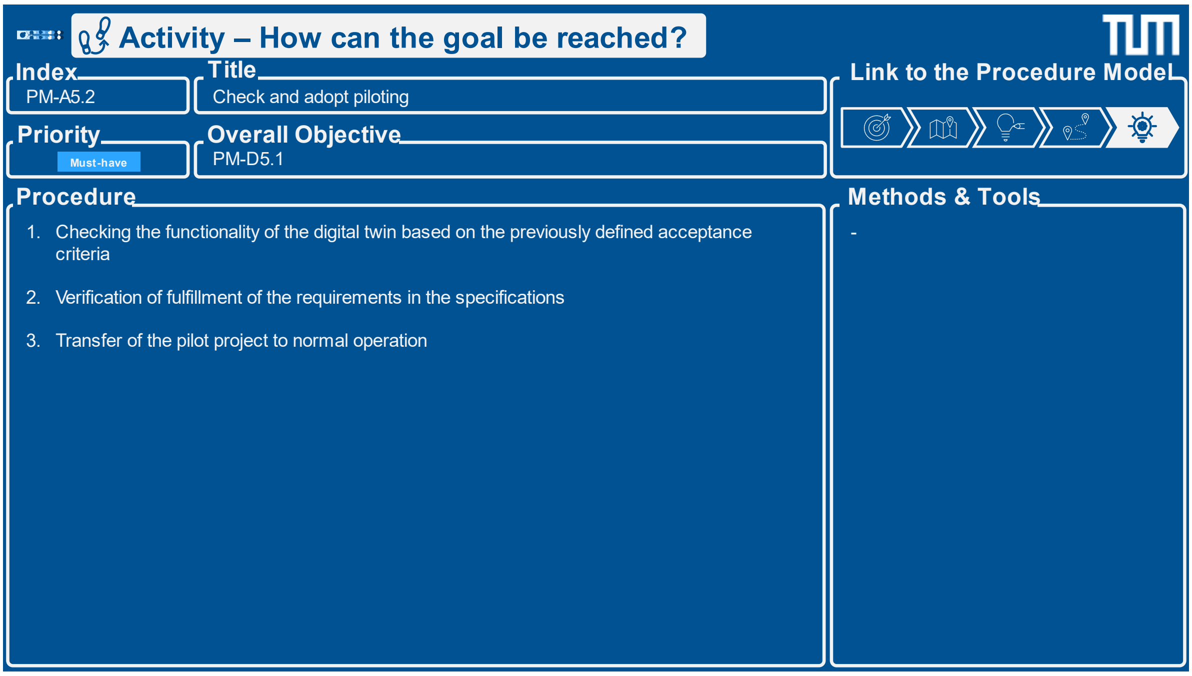


Figure A 57: Activity PM-A5.2 of the Digital Twin Procedure Model.

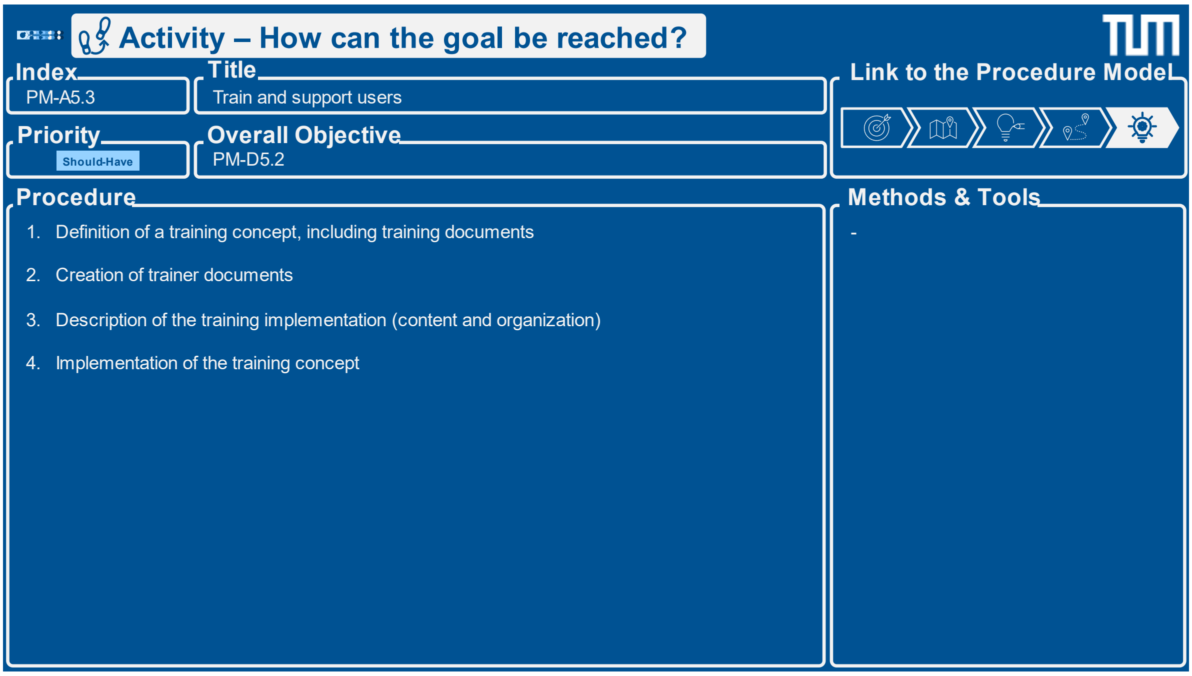


Figure A 58: Activity PM-A5.3 of the Digital Twin Procedure Model.

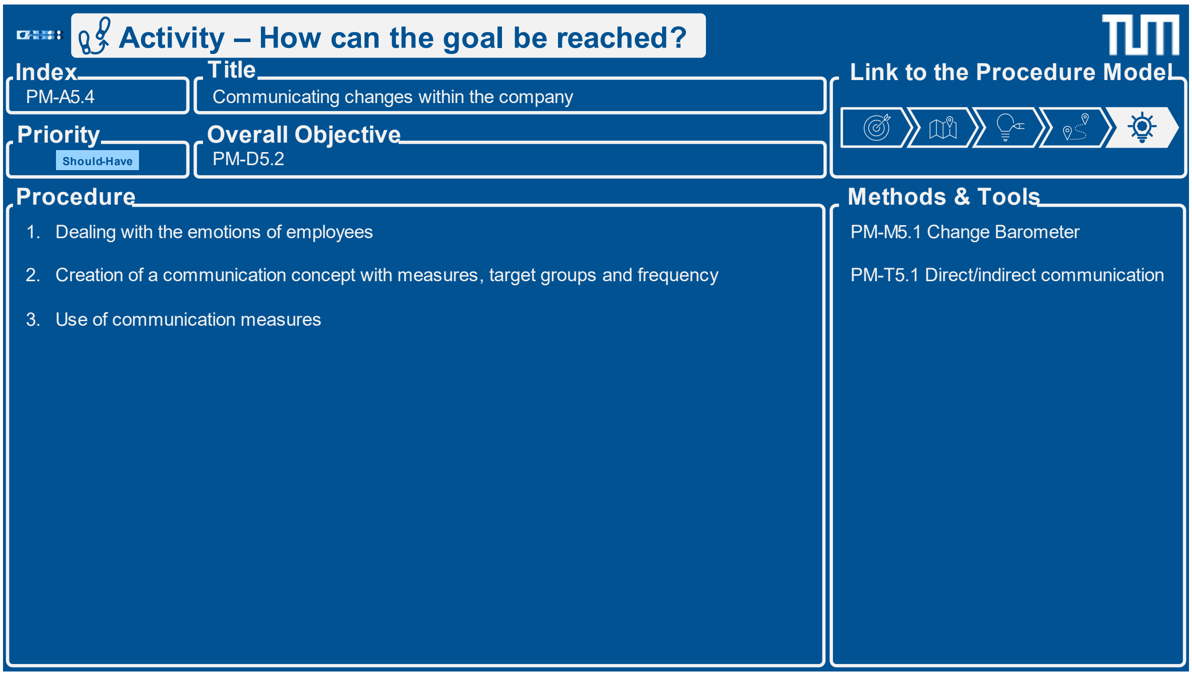


Figure A 59: Activity PM-A5.4 of the Digital Twin Procedure Model.

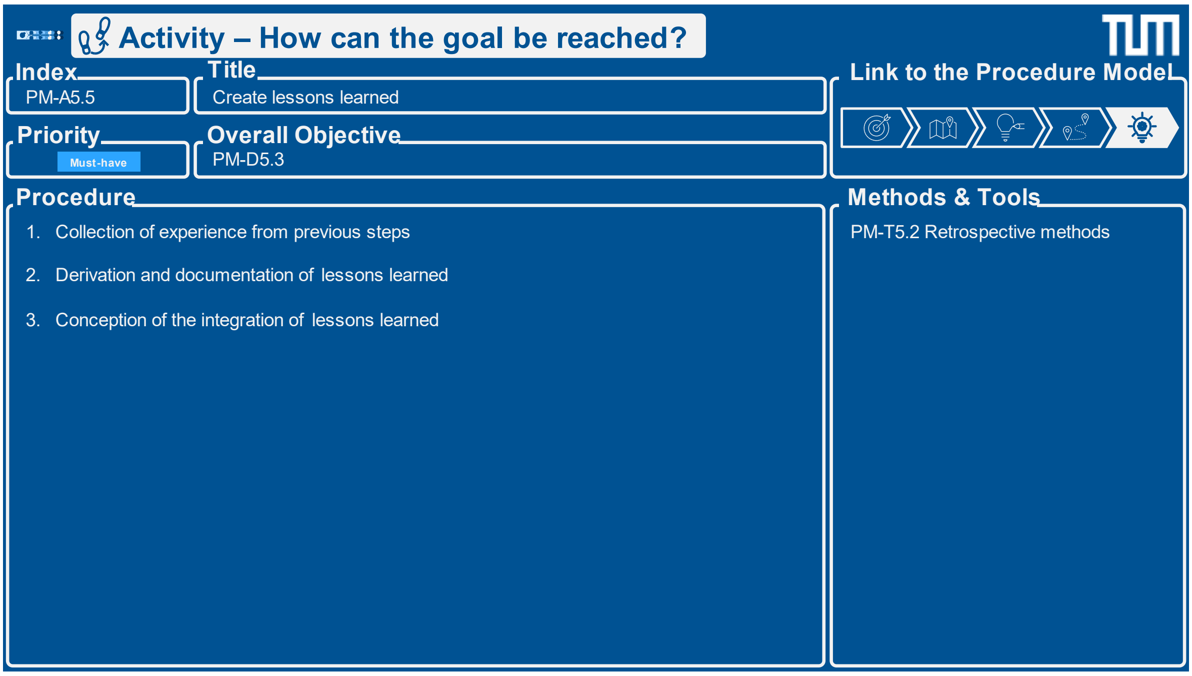


Figure A 60: Activity PM-A5.5 of the Digital Twin Procedure Model.

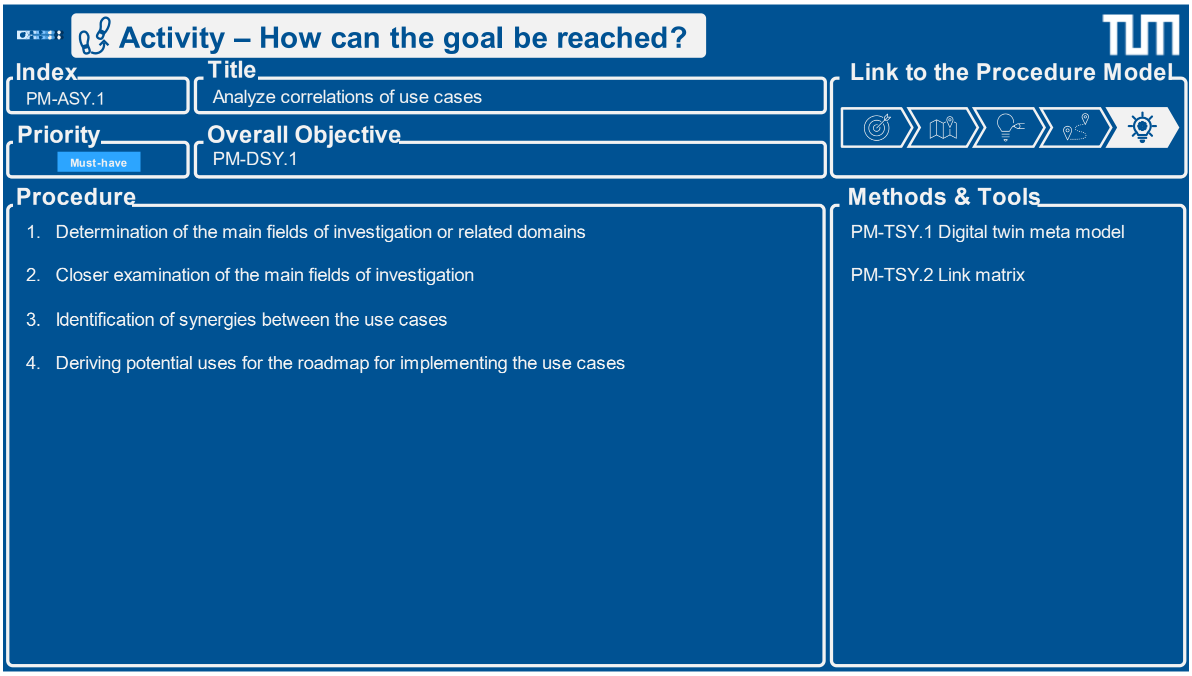


Figure A 61: Activity PM-ASY.1 of the Digital Twin Procedure Model.

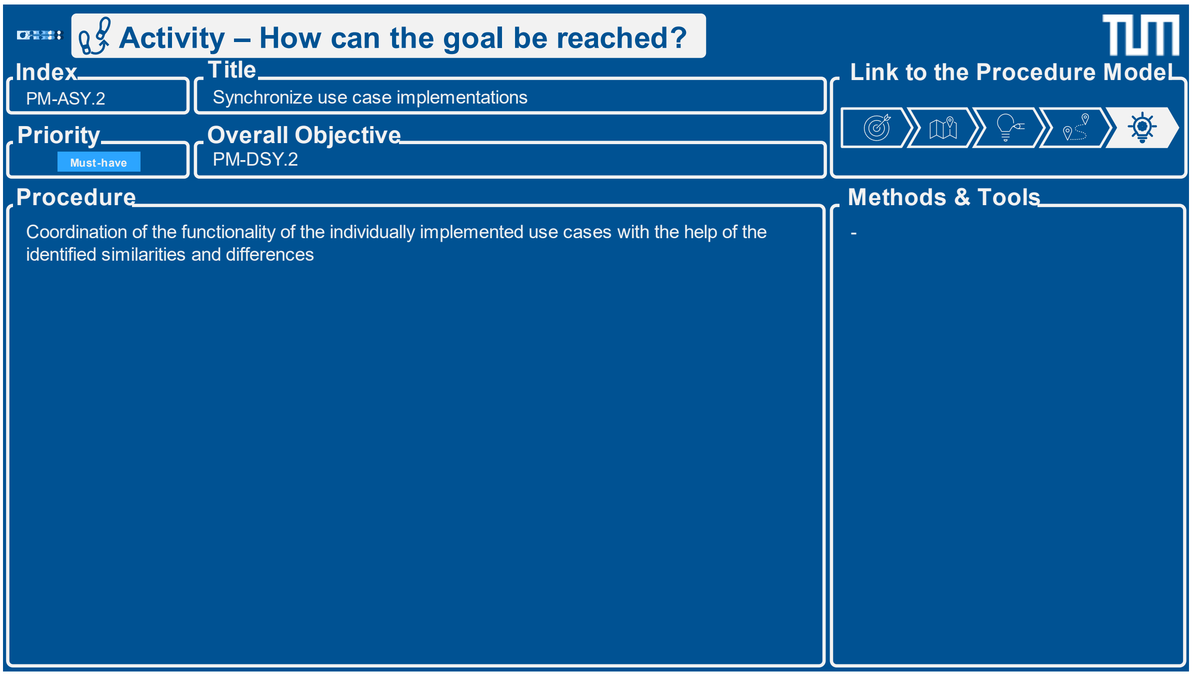


Figure A 62: Activity PM-ASY.2 of the Digital Twin Procedure Model.

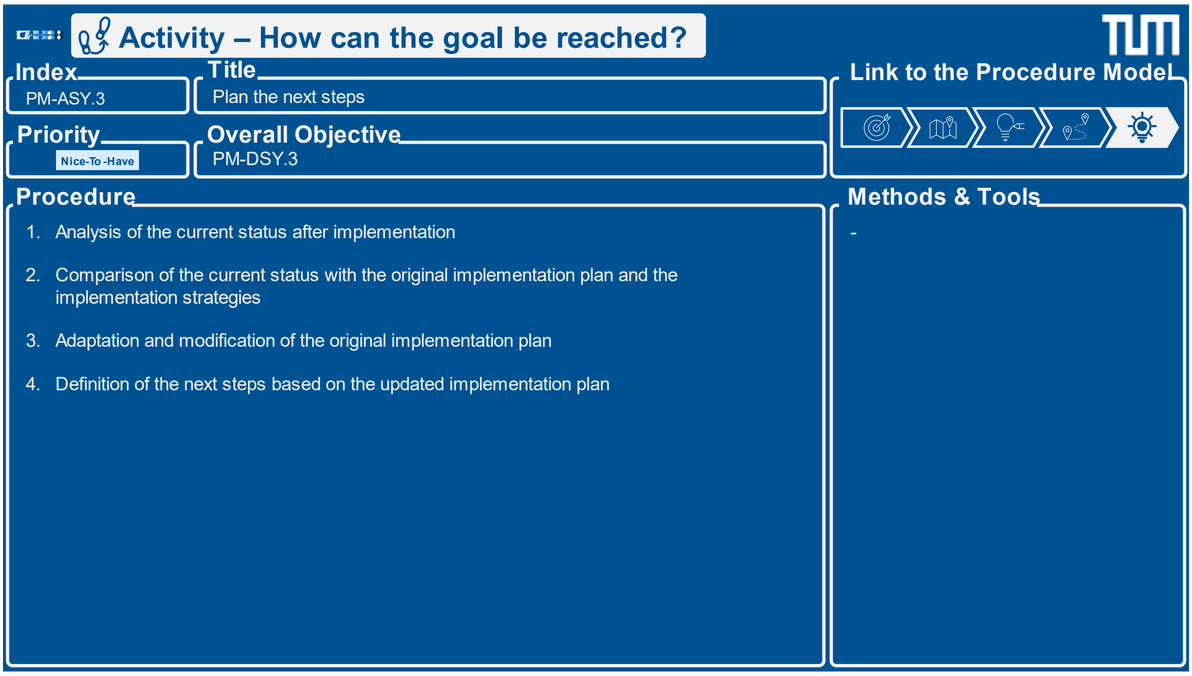


Figure A 63: Activity PM-ASY.3 of the Digital Twin Procedure Model.

The Methods and Tools of the Procedure Model

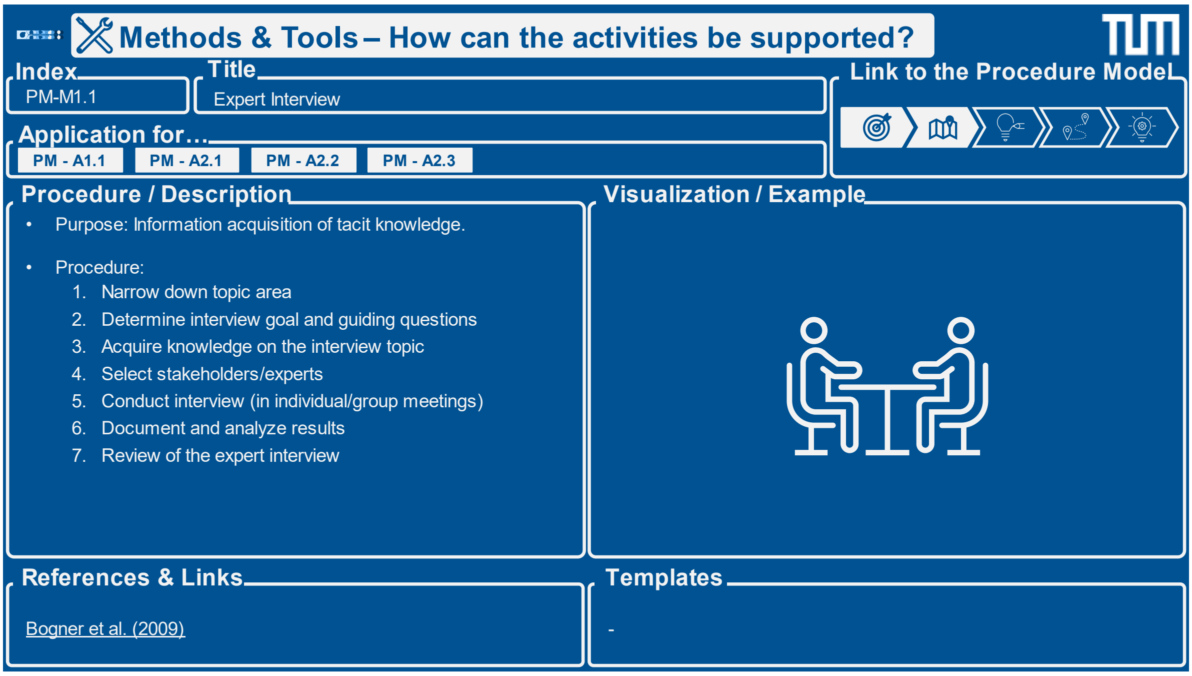


Figure A 64: Method PM-M1.1 of the Digital Twin Procedure Model.

Methods & Tools – How can the activities be supported?

Index: PM-M1.2

Title: Modified 9-field method

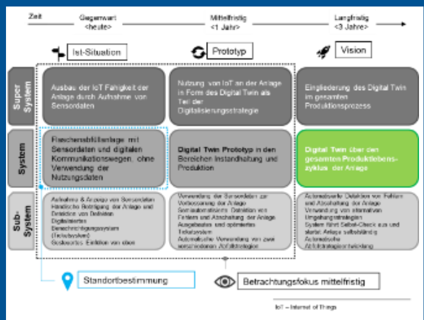
Link to the Procedure Model

Application for…: PM-A1.2

Procedure / Description

1. Determine the current situation of the system in the company based on the definition of the digital twin (tile in the middle left)
2. Abstraction at super-system level and concretization at sub-system level
3. Defining the medium-term and long-term position of the digital twin in the company

Visualization / Example



Based on [Mahlau, 2018 p.67]

References & Links

[Ehrlenspiel, 2017 p.549ff], [Mahlau, 2018 p.66f]

Templates

PM-M1.2 Modified 9-field method

Figure A 65: Method PM-M1.2 of the Digital Twin Procedure Model.

Methods & Tools – How can the activities be supported?

Index: PM-M1.3

Title: Development of project goals

Link to the Procedure Model

Application for…: PM-A1.2

Procedure / Description

1. Definition of a global/coarse target
2. Derive further project objectives under the key question: WHAT is to be achieved within the framework of the project?

Global/coarse target:
Brief, concise description of the project task that characterizes the final state to be achieved [Kuster.2008 p.356].

- What is to be achieved? (quality, functionality, scope)
- Who should achieve this? (person, group of persons)
- When should this be achieved? (Time limit)
- How is this to be achieved? (cost framework)

Visualization / Example

Global/coarse target:
Reducing the spread of damage to the pump in the event of defects occurring in the system. Implementation of the project within six months with a project manager and a core team consisting of business, engineering and IT specialists.

Project goals:
Automatic stop of the system if a defect is detected.

Improving trust in digitalization technologies, including digital twins.

References & Links

[Kuster, 2008 p.352ff]

Templates

-

Figure A 66: Method PM-M1.3 of the Digital Twin Procedure Model.

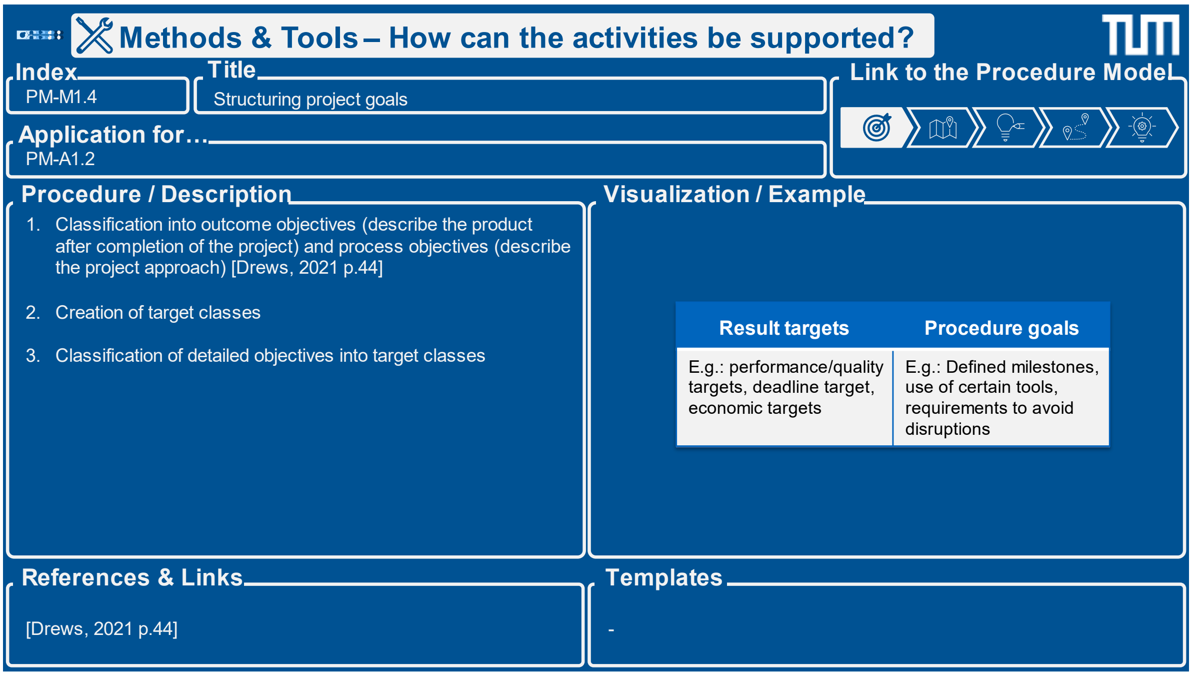


Figure A 67: Method PM-M1.4 of the Digital Twin Procedure Model.

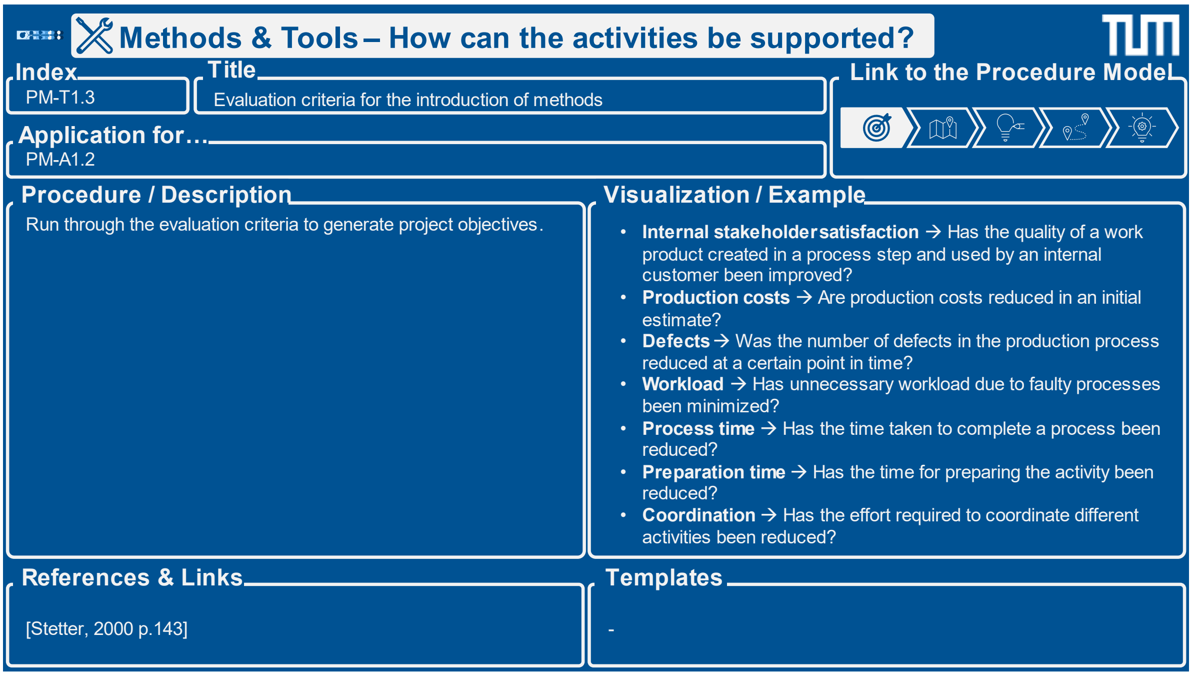


Figure A 68: Tool PM-T1.3 of the Digital Twin Procedure Model.

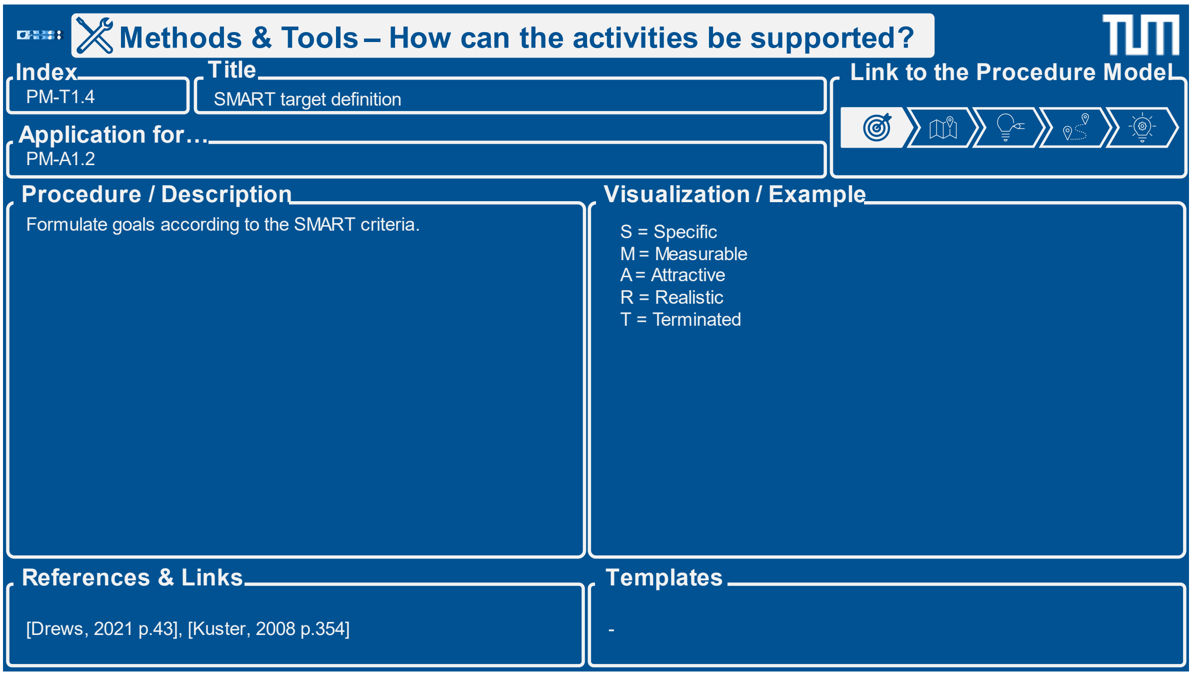


Figure A 69: Tool PM-T1.4 of the Digital Twin Procedure Model.

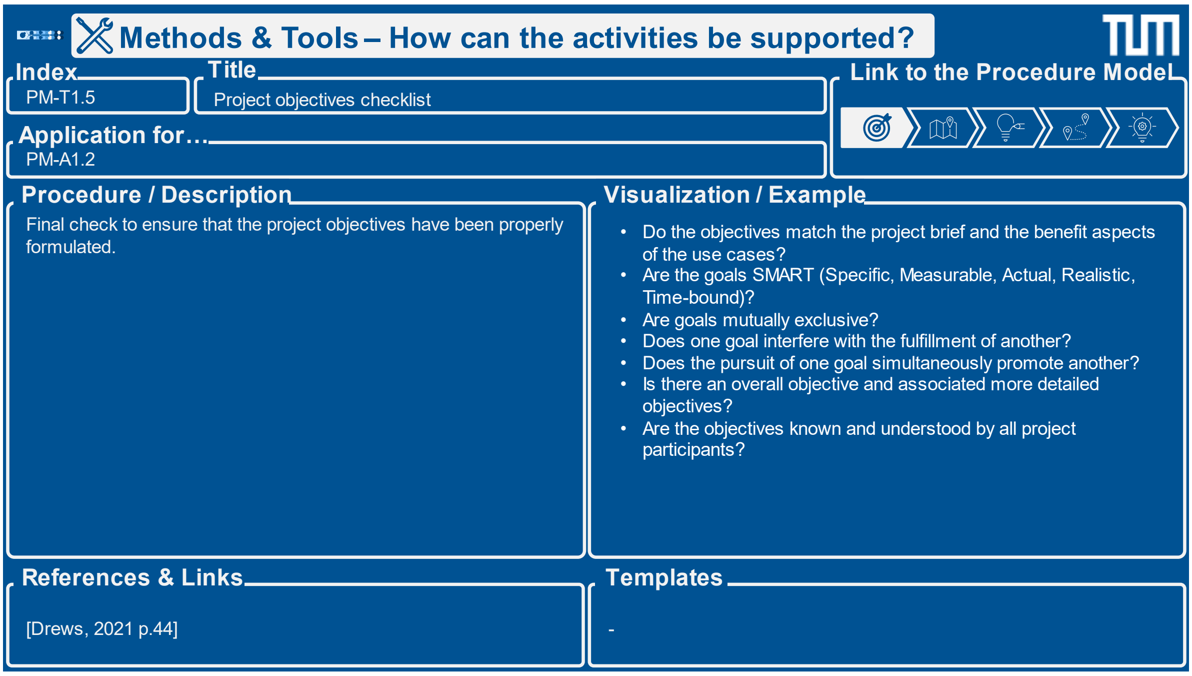


Figure A 70: Tool PM-T1.5 of the Digital Twin Procedure Model.

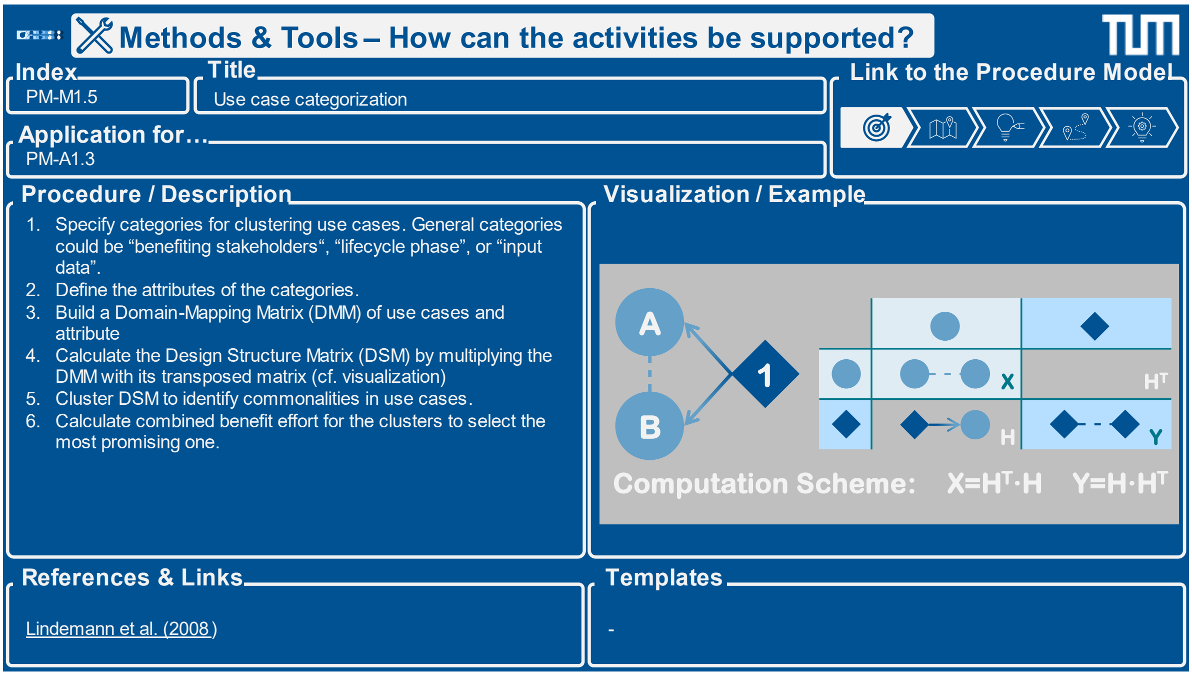


Figure A 71: Method PM-M1.5 of the Digital Twin Procedure Model.

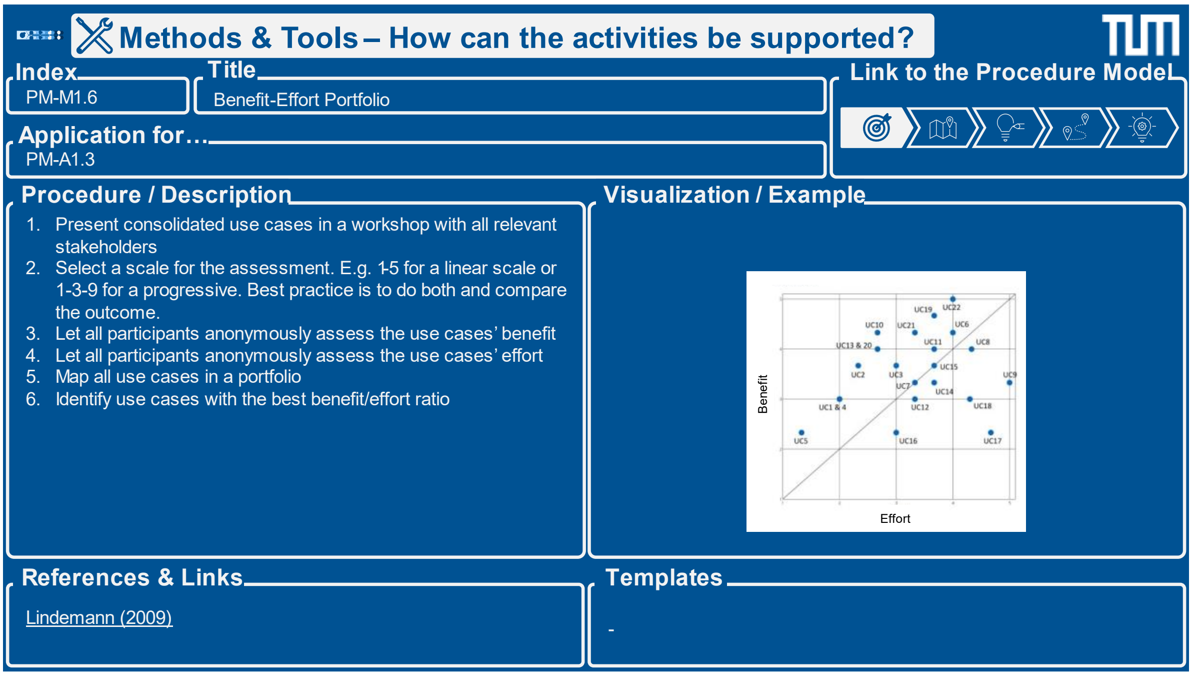


Figure A 72: Method PM-M1.6 of the Digital Twin Procedure Model.

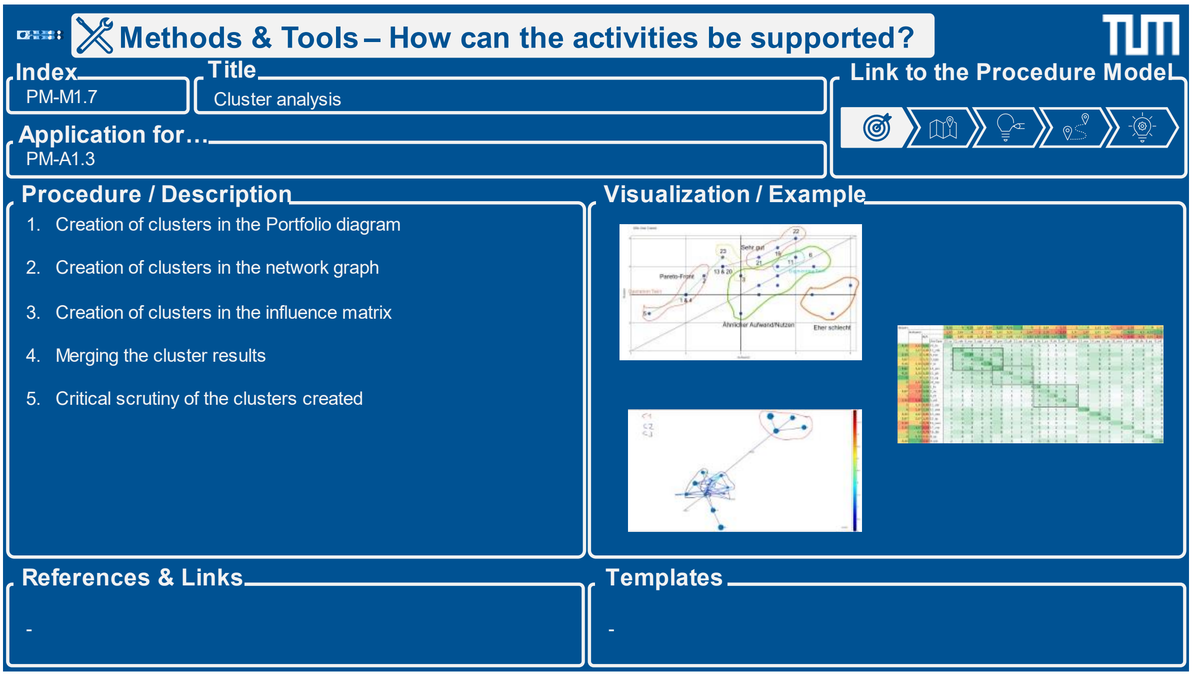


Figure A 73: Method PM-M1.7 of the Digital Twin Procedure Model.

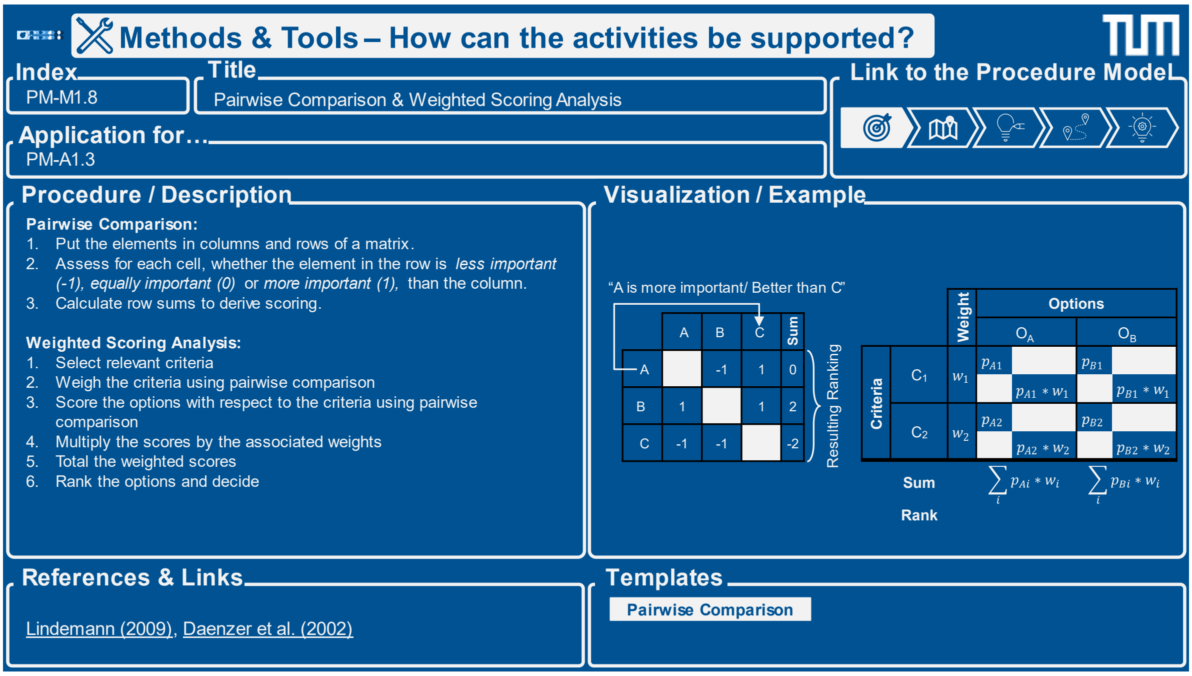


Figure A 74: Method PM-M1.8 of the Digital Twin Procedure Model.

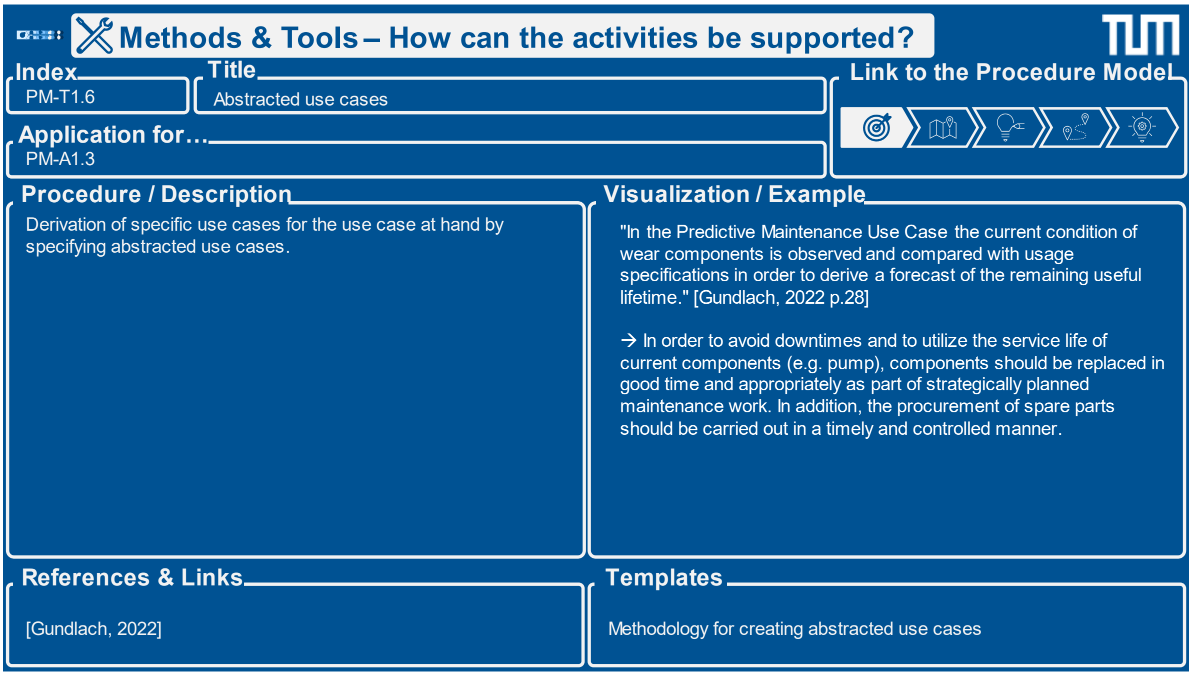


Figure A 75: Tool PM-T1.6 of the Digital Twin Procedure Model.

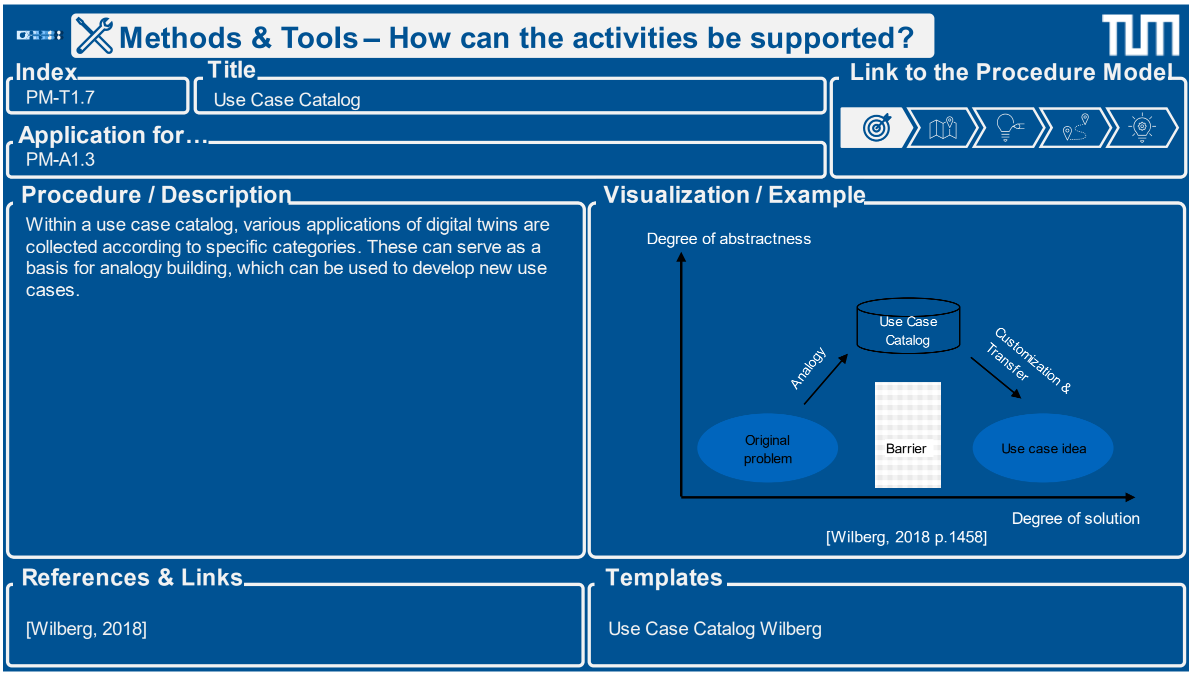


Figure A 76: Tool PM-T1.7 of the Digital Twin Procedure Model.

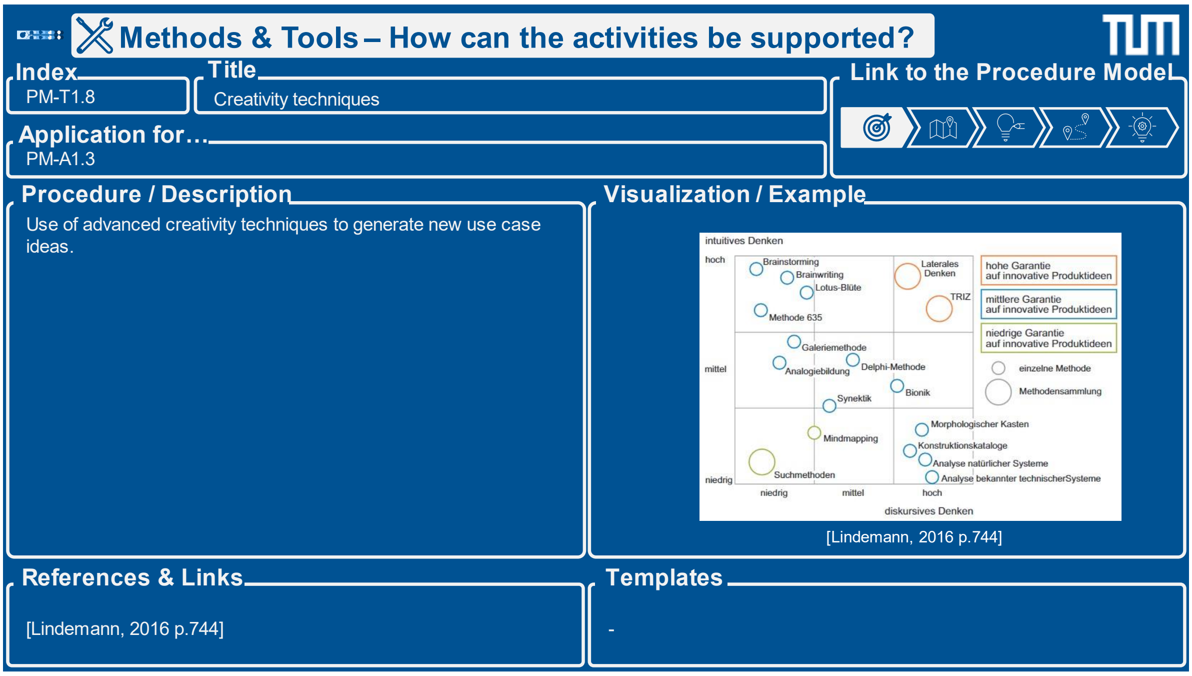


Figure A 77: Tool PM-T1.8 of the Digital Twin Procedure Model.

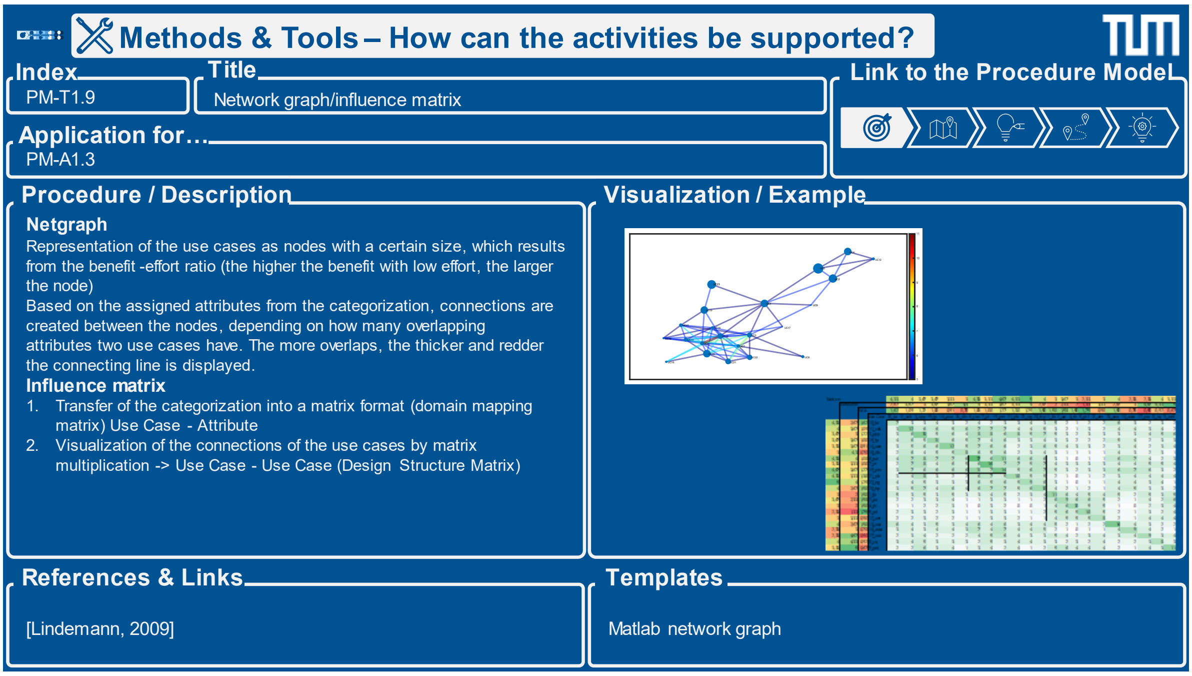


Figure A 78: Tool PM-T1.9 of the Digital Twin Procedure Model.

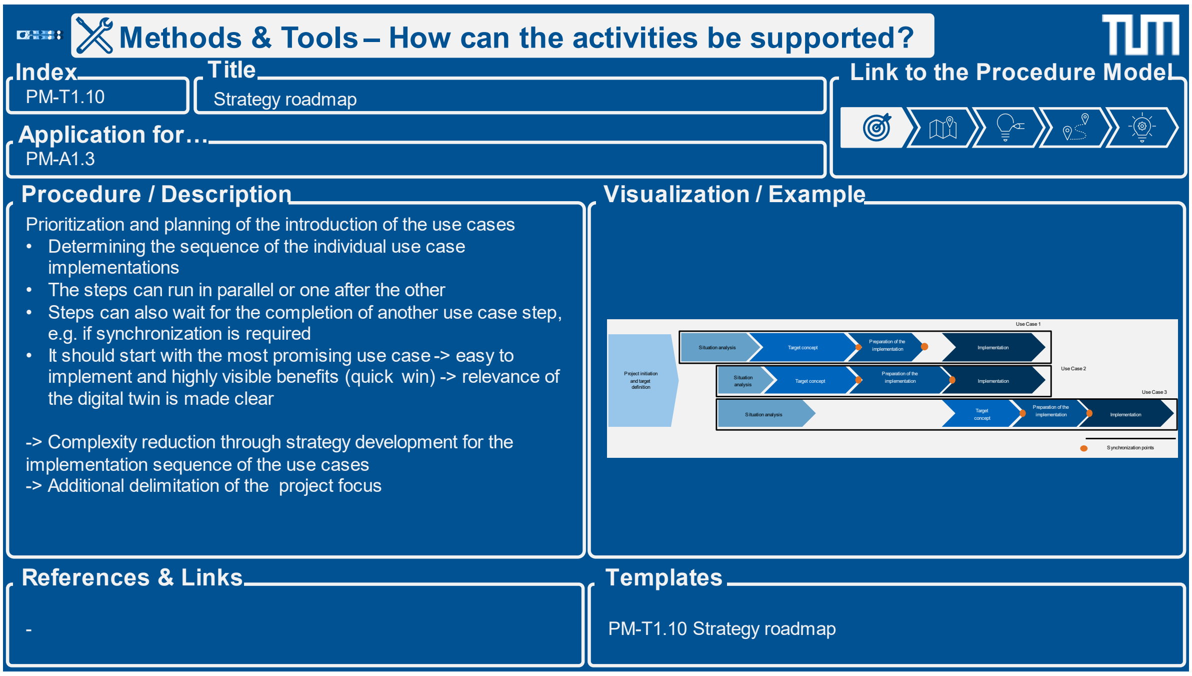


Figure A 79: Tool PM-T1.10 of the Digital Twin Procedure Model.

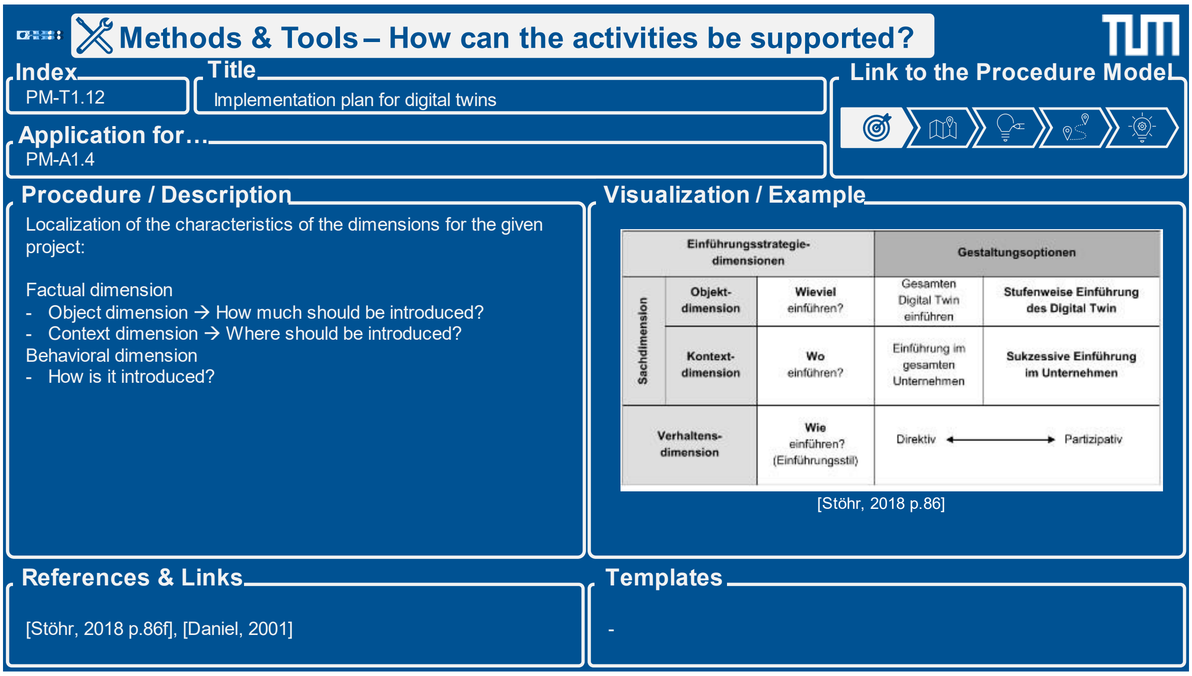


Figure A 80: Tool PM-T1.12 of the Digital Twin Procedure Model.

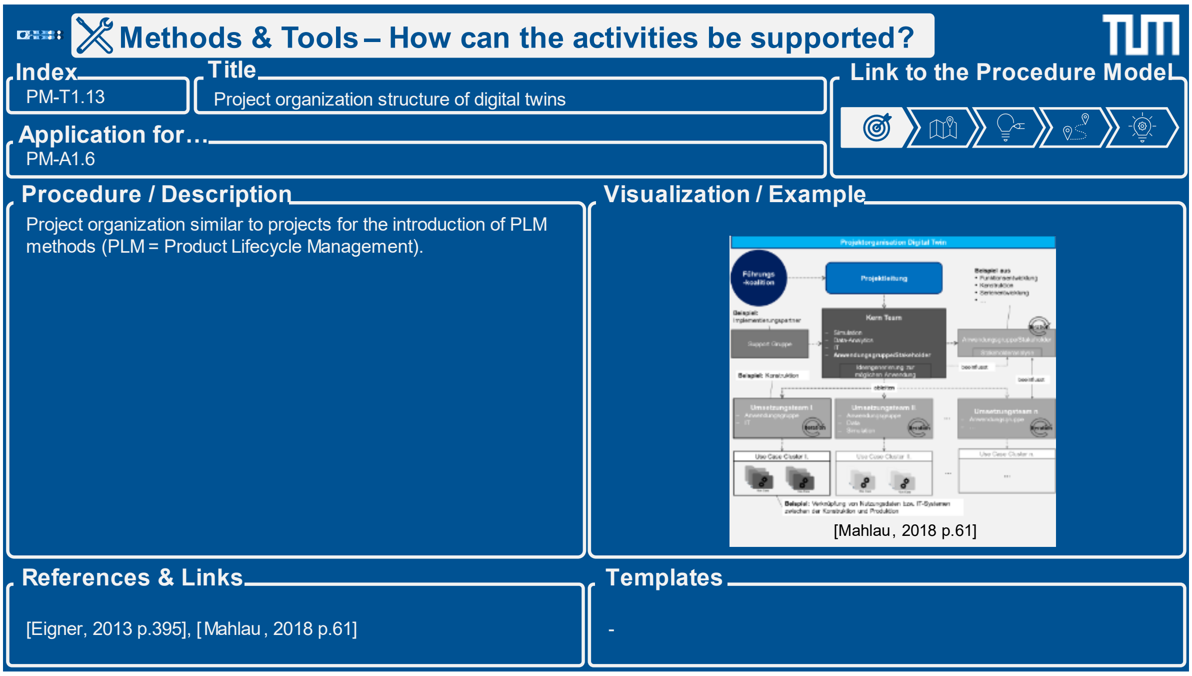


Figure A 81: Tool PM-T1.13 of the Digital Twin Procedure Model.

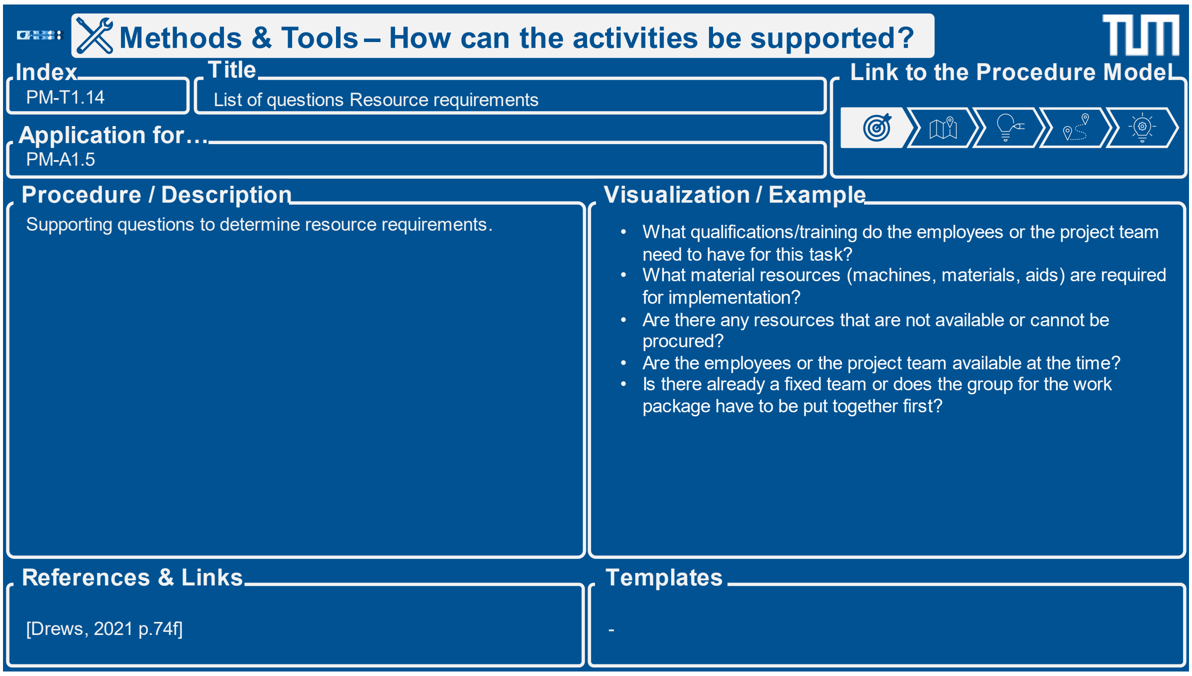


Figure A 82: Tool PM-T1.14 of the Digital Twin Procedure Model.

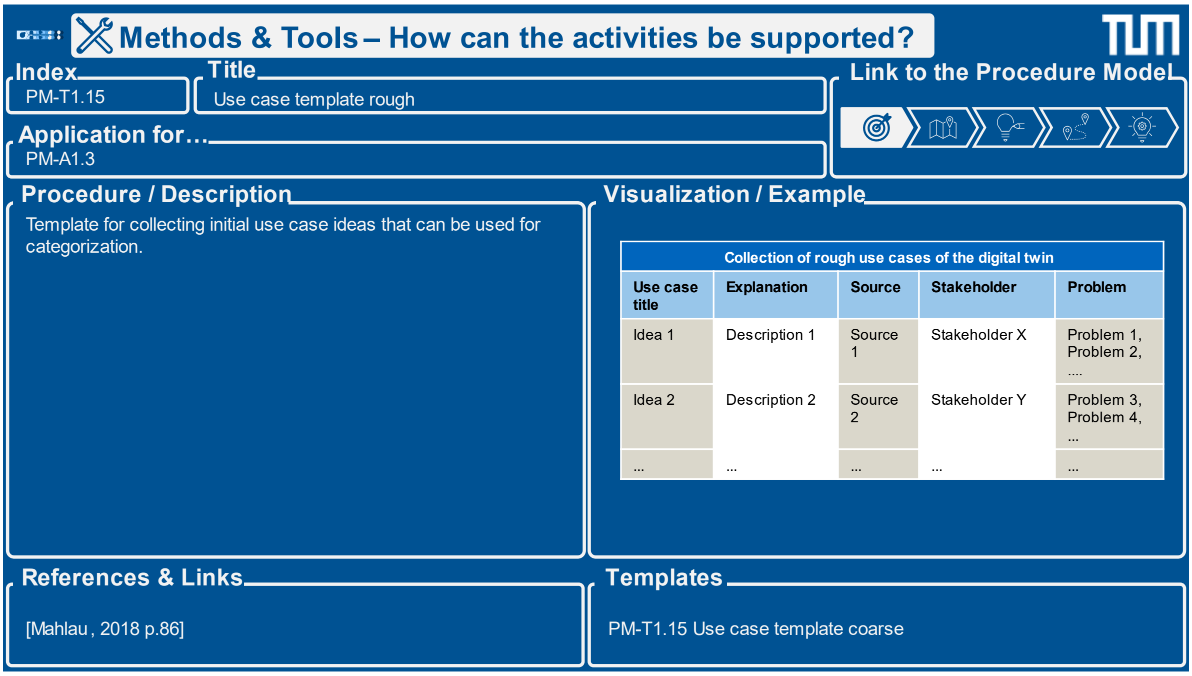


Figure A 83: Tool PM-T1.15 of the Digital Twin Procedure Model.

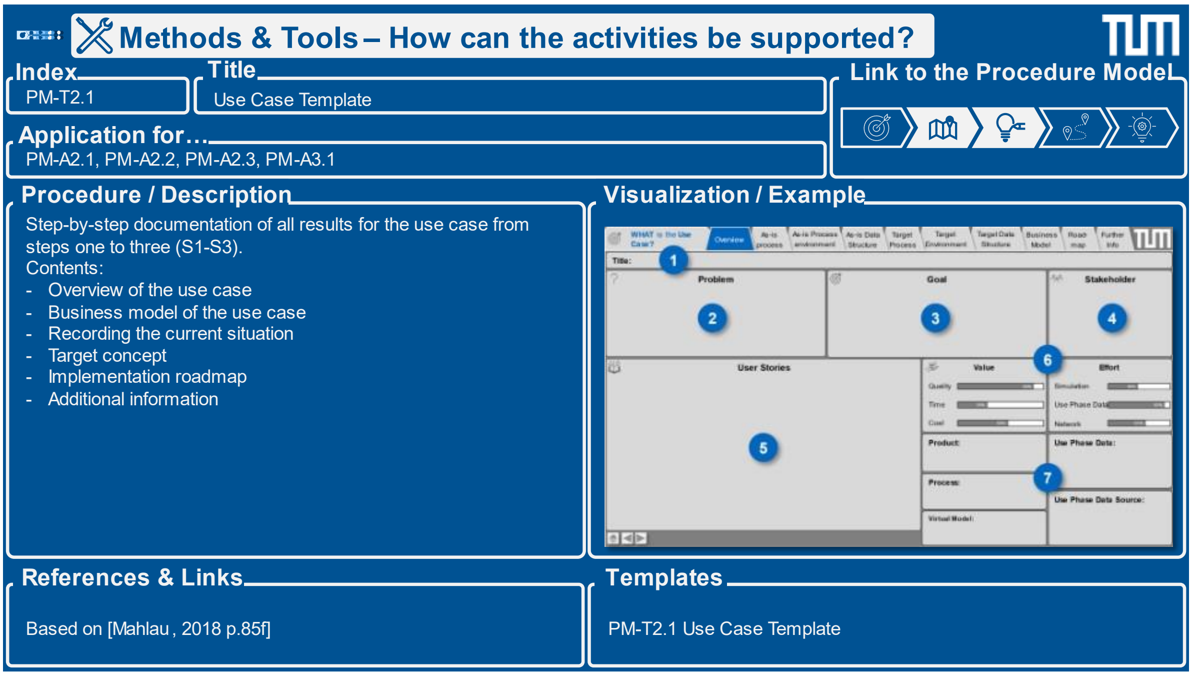


Figure A 84: Tool PM-T2.1 of the Digital Twin Procedure Model.

Methods & Tools – How can the activities be supported?

Index
PM-T2.2

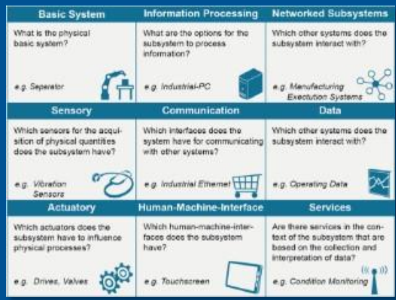
Title
CPS Modeling Kanvas

Application for…
PM-A2.1

Link to the Procedure Model

Procedure / Description
To create the digital twin environment, the questions from the CPS modeling canvas can be answered in sequence. This allows the components of the digital twin to be systematically developed.

Visualization / Example



[Westermann, 2018 p.3045]

References & Links
[Westermann, 2018]

Templates
-

Figure A 85: Tool PM-T2.2 of the Digital Twin Procedure Model.

Methods & Tools – How can the activities be supported?

Index
PM-T2.3

Title
Questionnaire Modeling data structure

Application for…
PM-A2.3

Link to the Procedure Model

Procedure / Description
Run through the questionnaire as a support for recording the elements and linking the data structure.

Visualization / Example

Prioritization	Questions
Primary - Basic elements	• Which events/states are associated with the use case at the beginning and at the end (e.g. normal operation, system failure, ...)? • ...
Primary - Networking	• Where does the data/information required for activities/functions come from? • ...
Secondary - Specification	• How can the data/information be described in terms of content and form? • ...

Based on [Mahlau, 2018 p.75f]

References & Links
Based on [Mahlau, 2018 p.75f]

Templates
PM-T2.3 Questionnaire Modeling data structure,

Figure A 86: Tool PM-T2.3 of the Digital Twin Procedure Model.

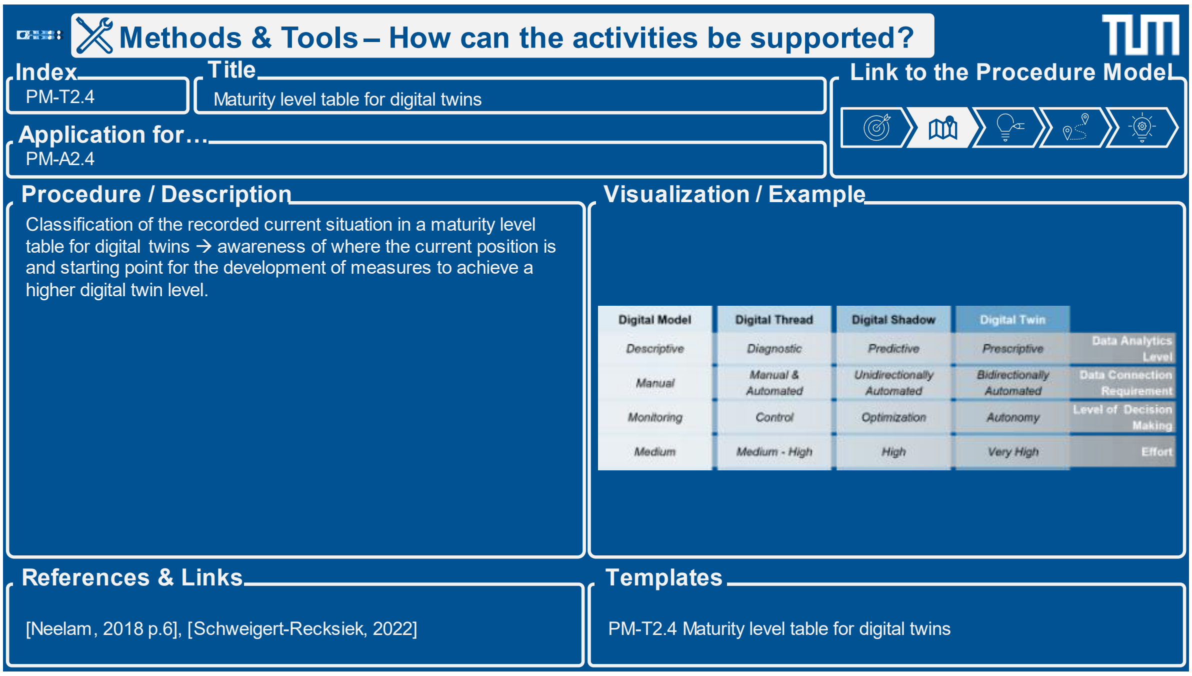


Figure A 87: Tool PM-T2.4 of the Digital Twin Procedure Model.

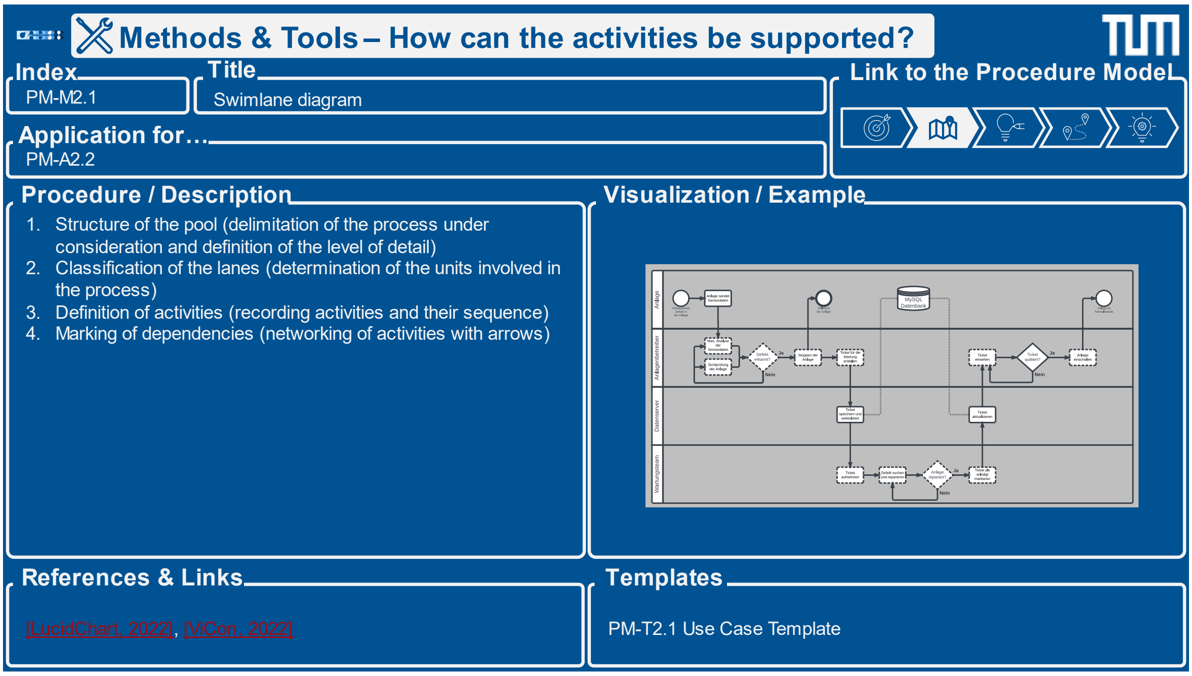


Figure A 88: Method PM-M2.1 of the Digital Twin Procedure Model.

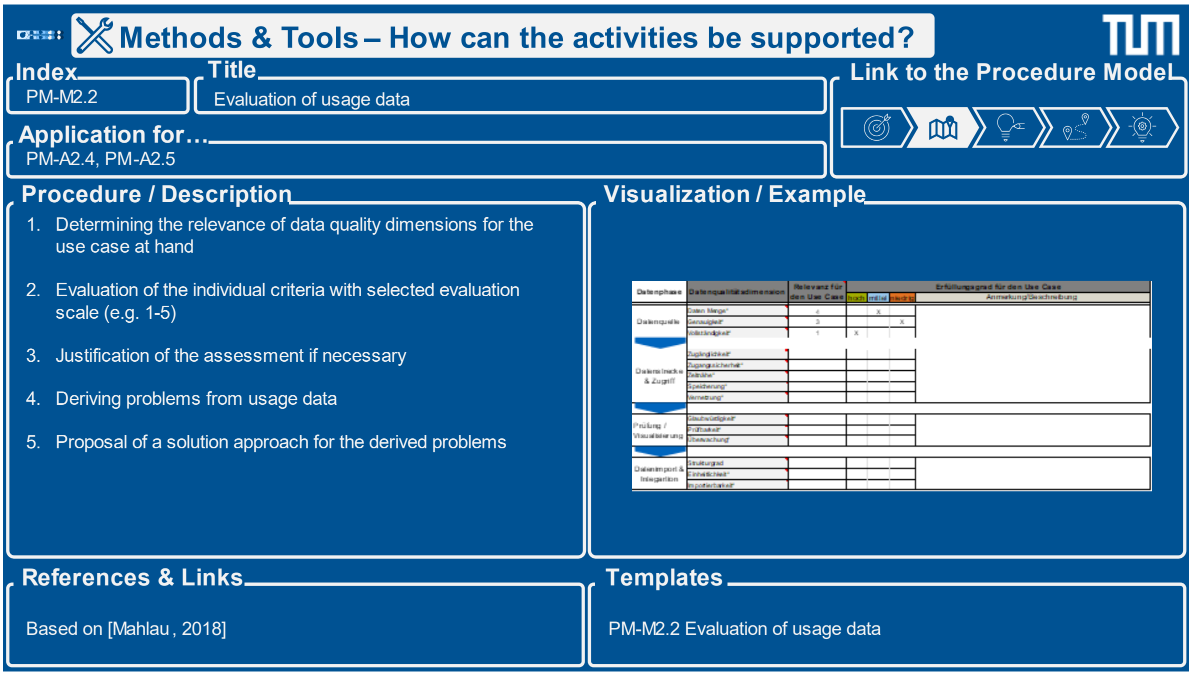


Figure A 89: Method PM-M2.2 of the Digital Twin Procedure Model.

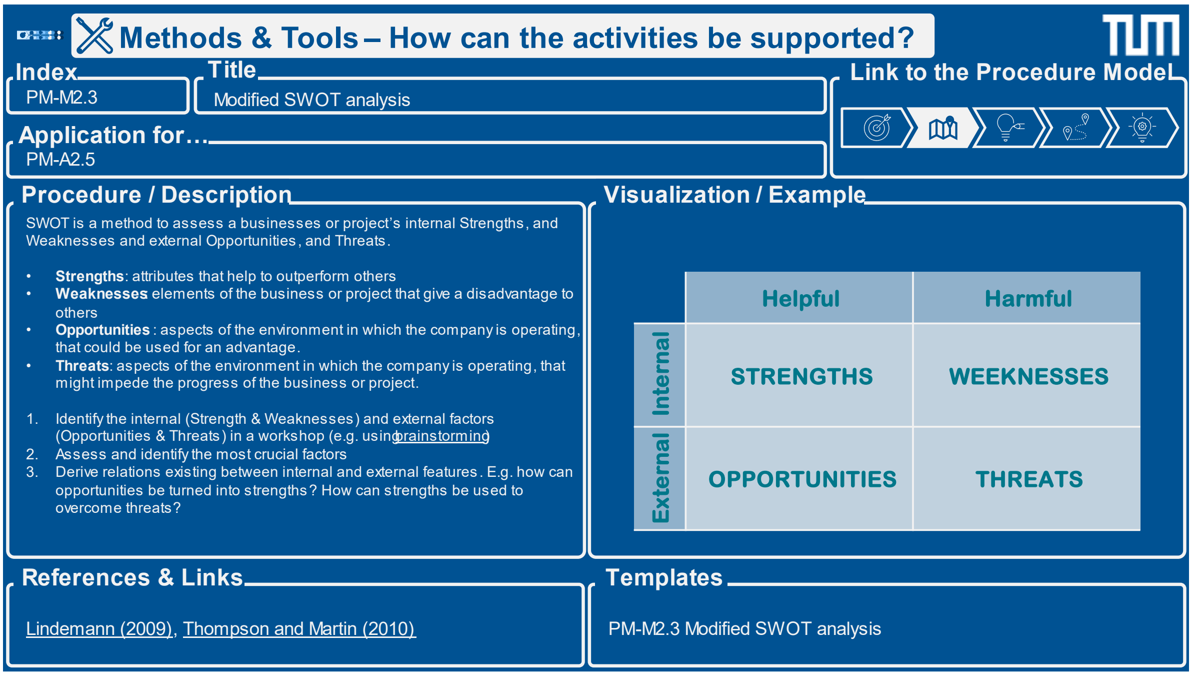


Figure A 90: Method PM-M2.3 of the Digital Twin Procedure Model.

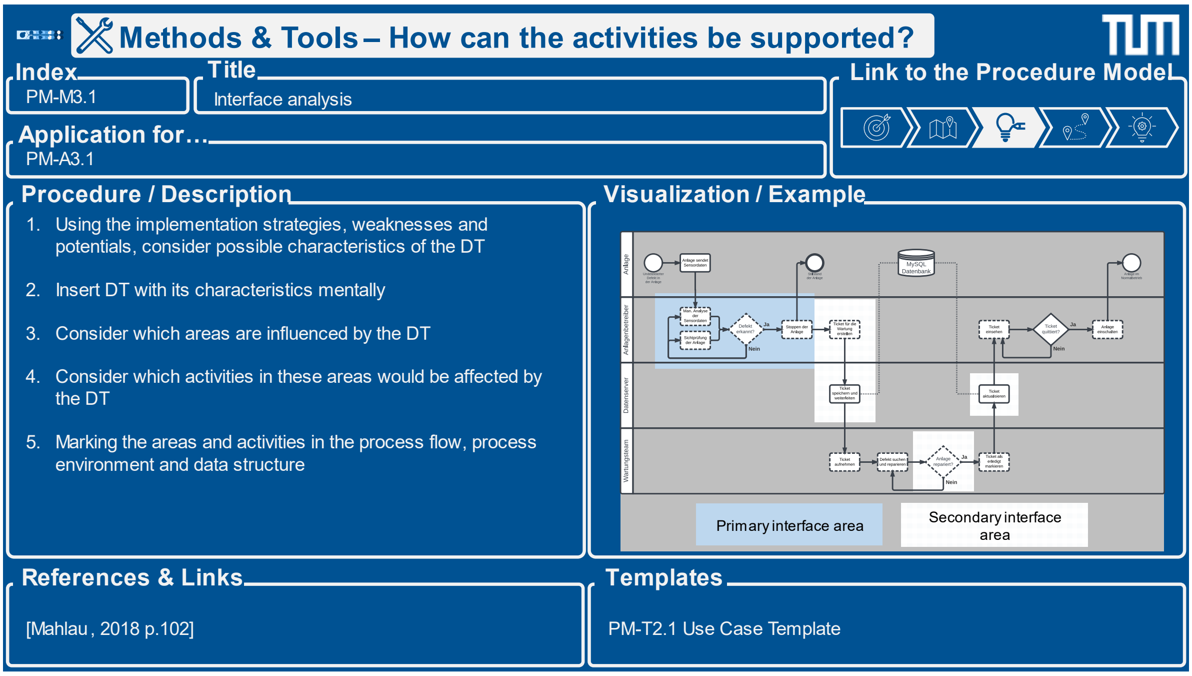


Figure A 91: Method PM-M3.1 of the Digital Twin Procedure Model.

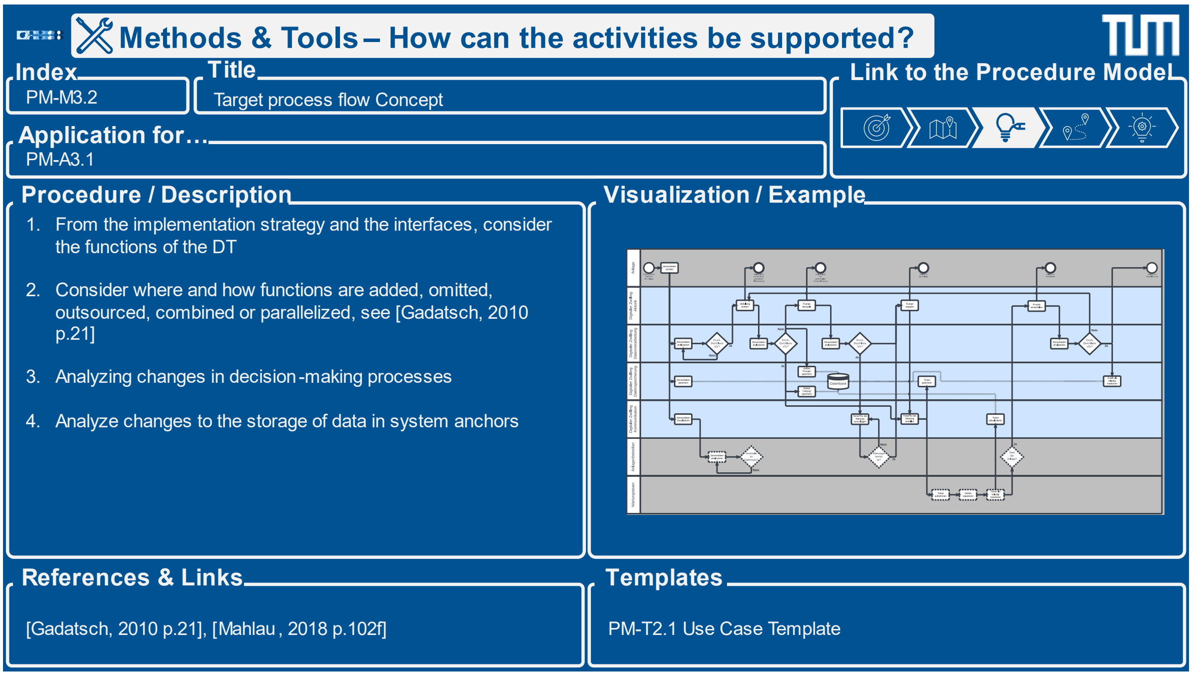


Figure A 92: Method PM-M3.2 of the Digital Twin Procedure Model.

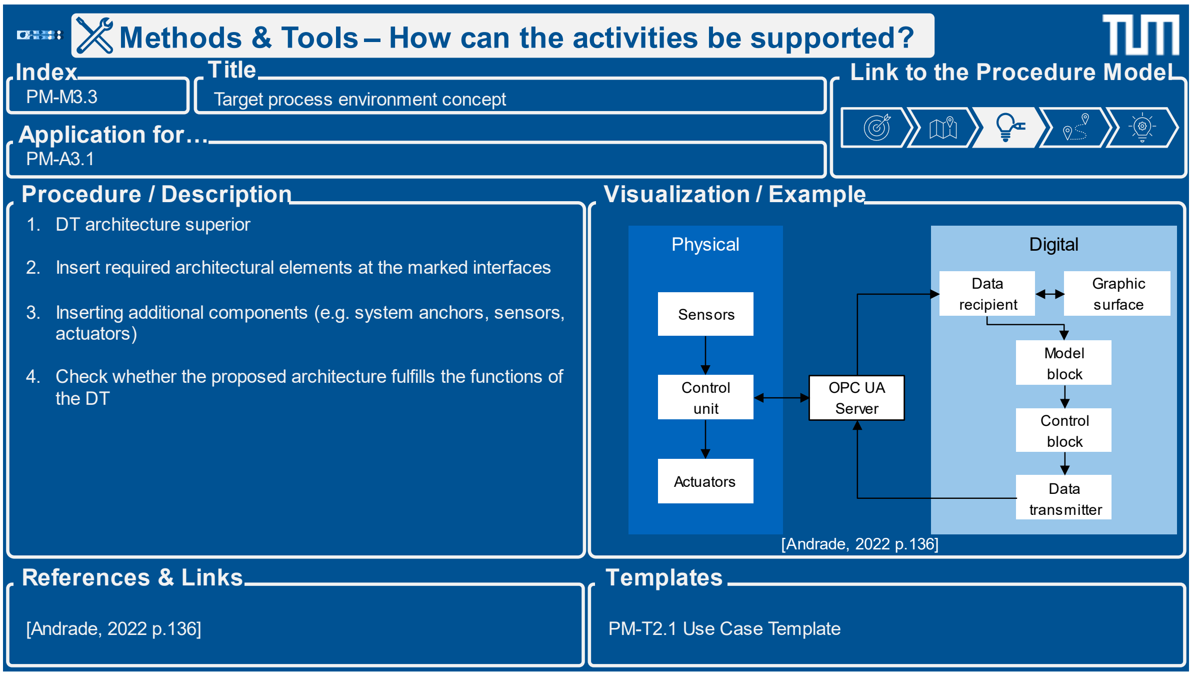


Figure A 93: Method PM-M3.3 of the Digital Twin Procedure Model.

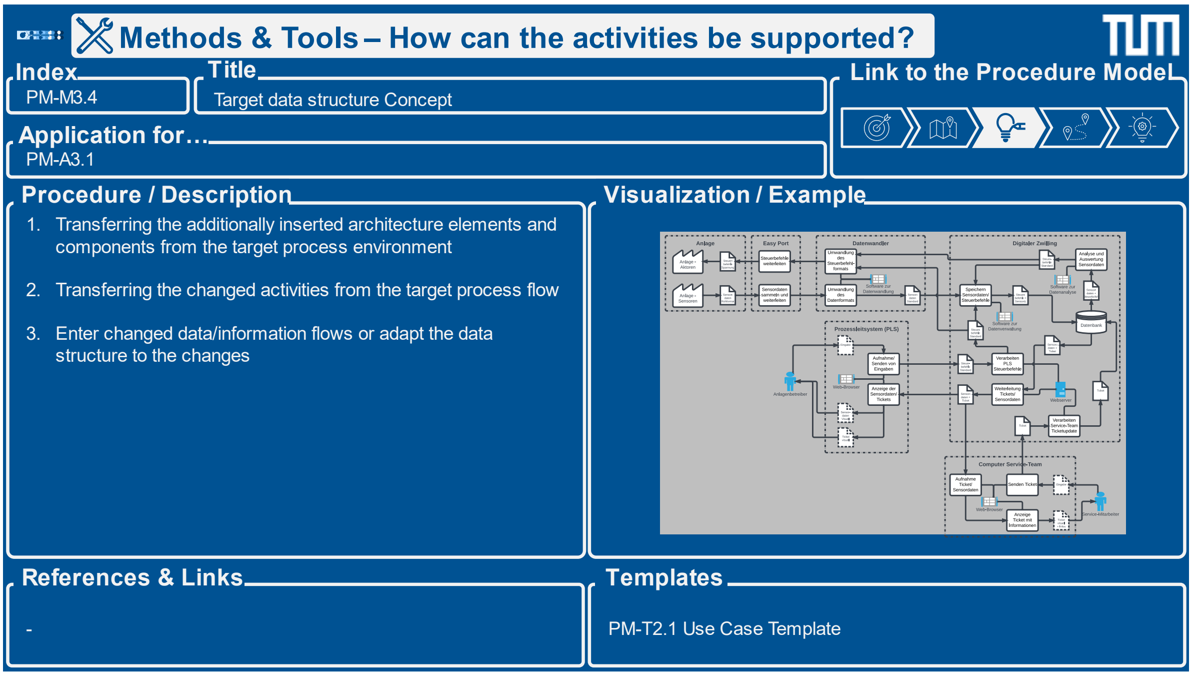


Figure A 94: Method PM-M3.4 of the Digital Twin Procedure Model.

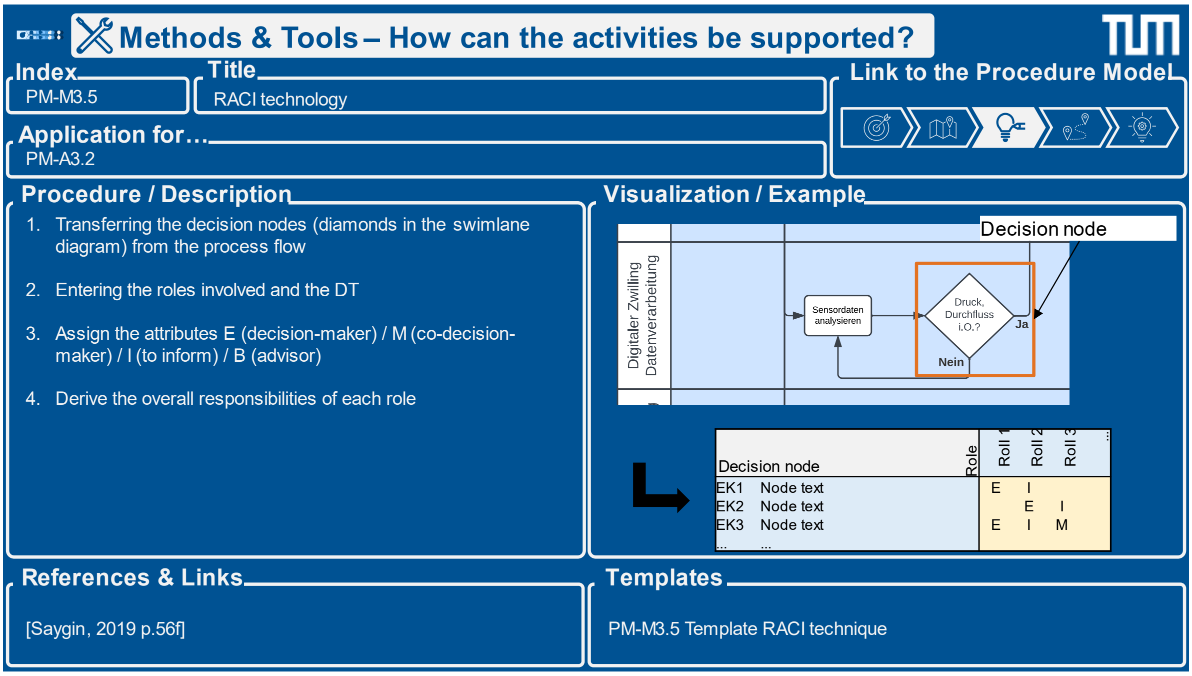


Figure A 95: Method PM-M3.5 of the Digital Twin Procedure Model.

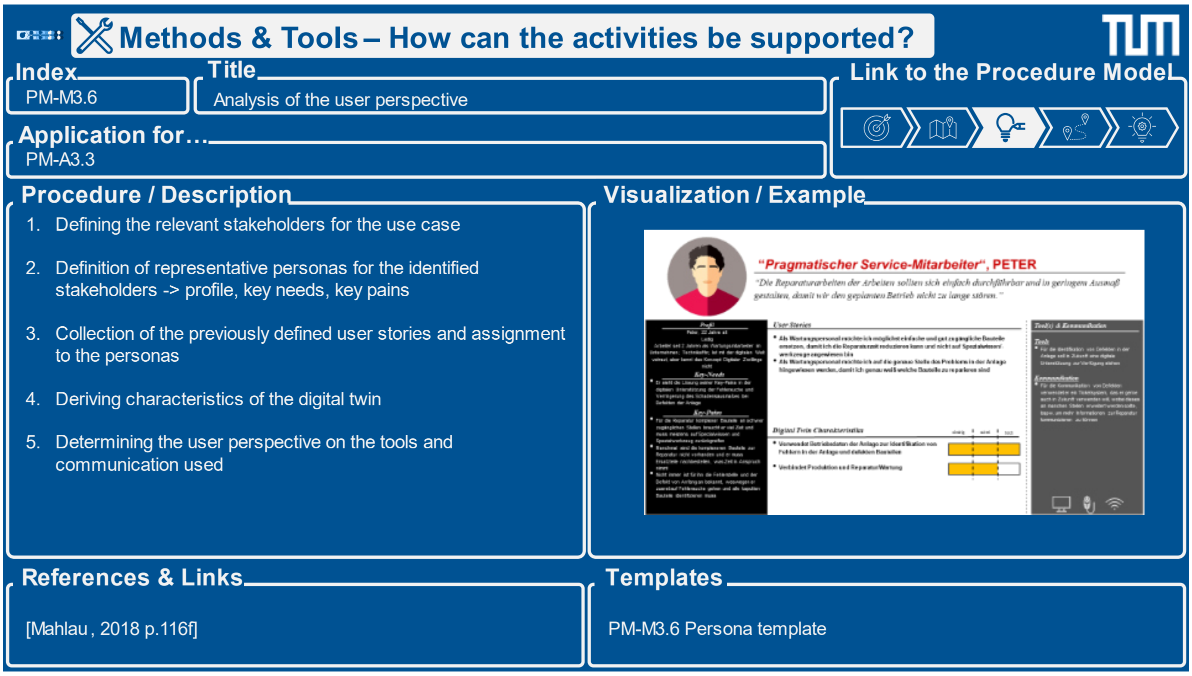


Figure A 96: Method PM-M3.6 of the Digital Twin Procedure Model.

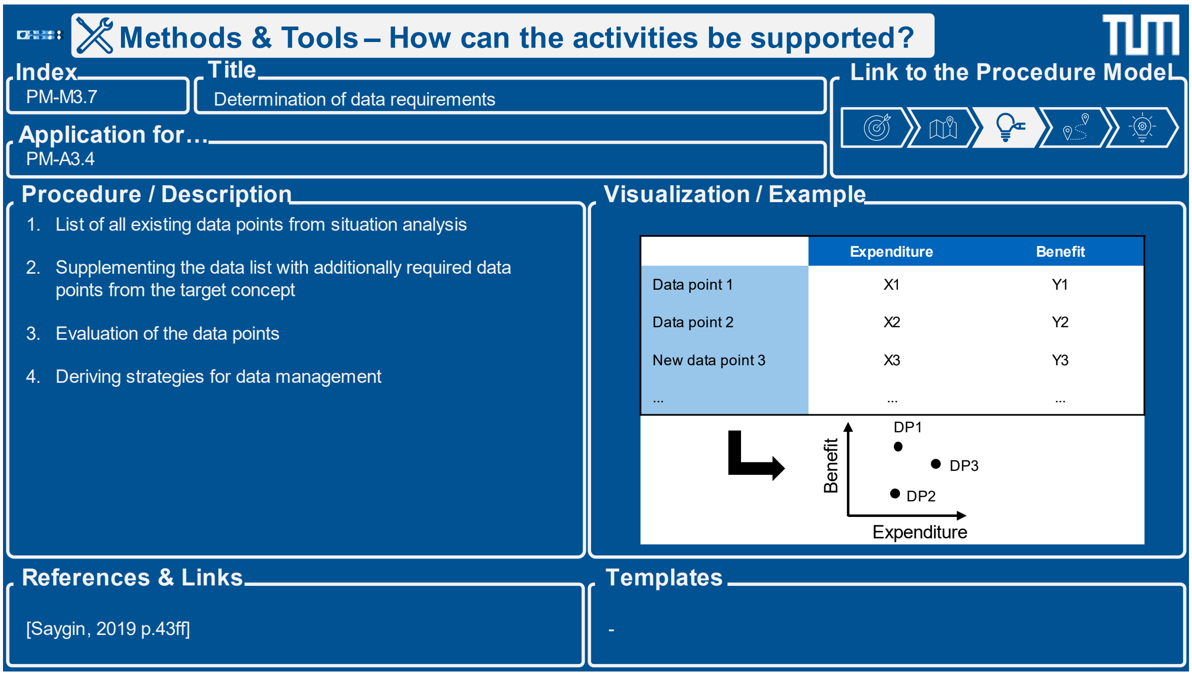


Figure A 97: Method PM-M3.7 of the Digital Twin Procedure Model.

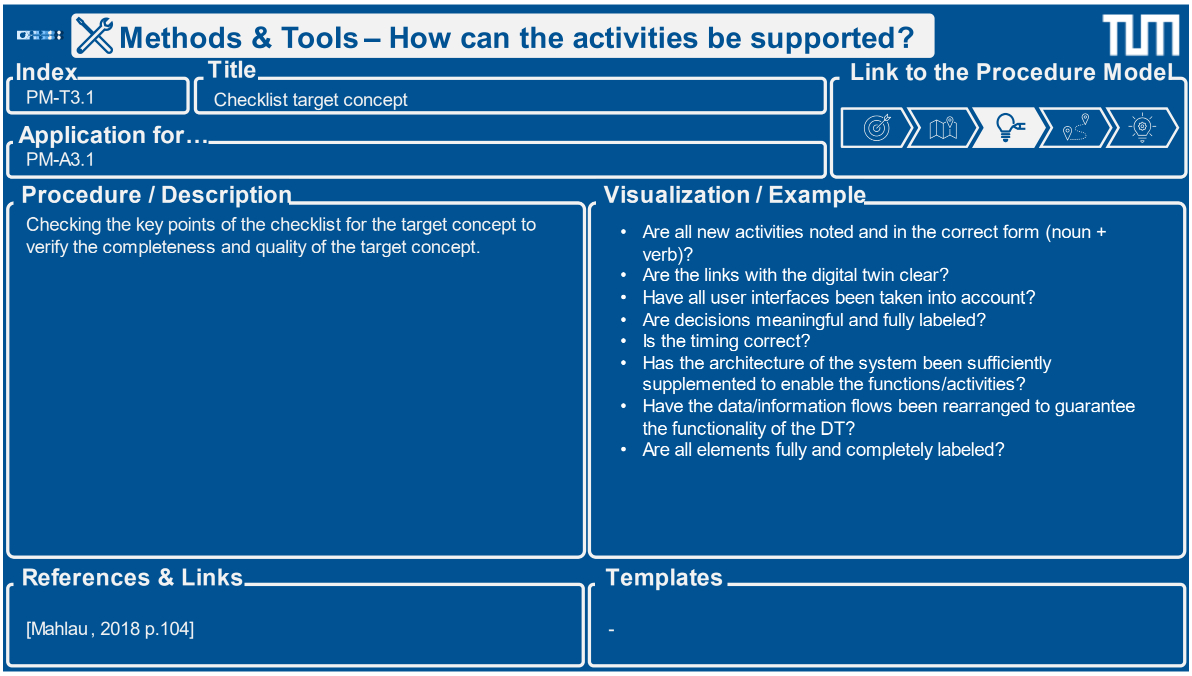


Figure A 98: Tool PM-T3.1 of the Digital Twin Procedure Model.

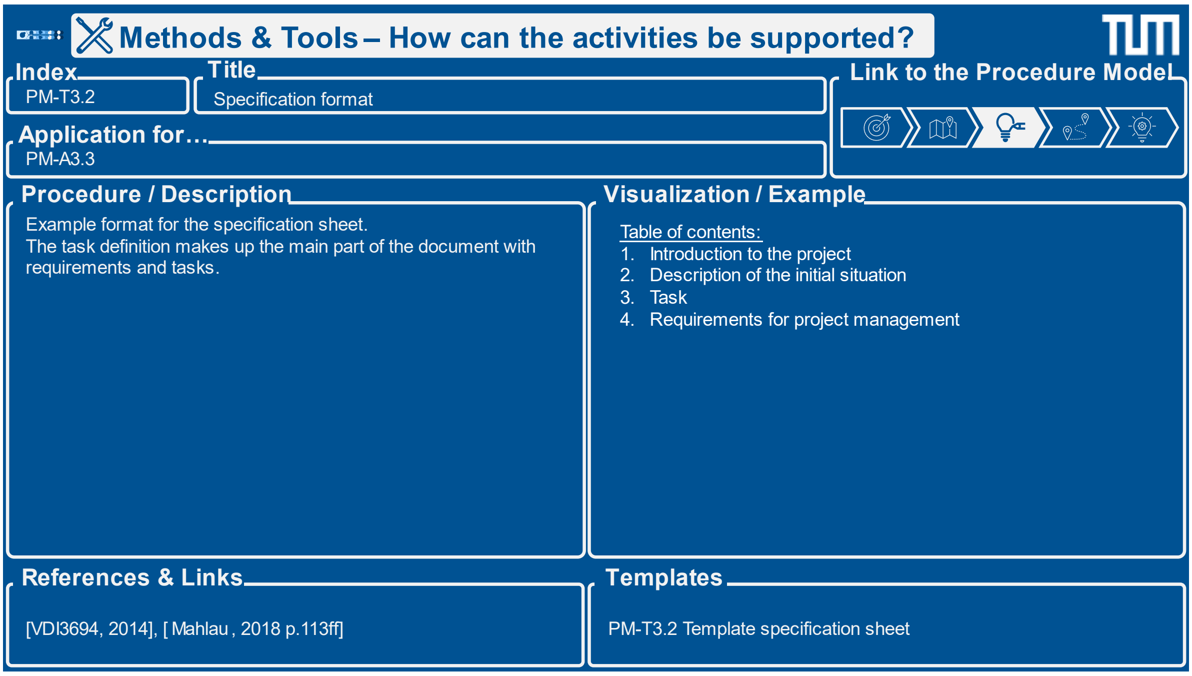


Figure A 99: Tool PM-T3.2 of the Digital Twin Procedure Model.

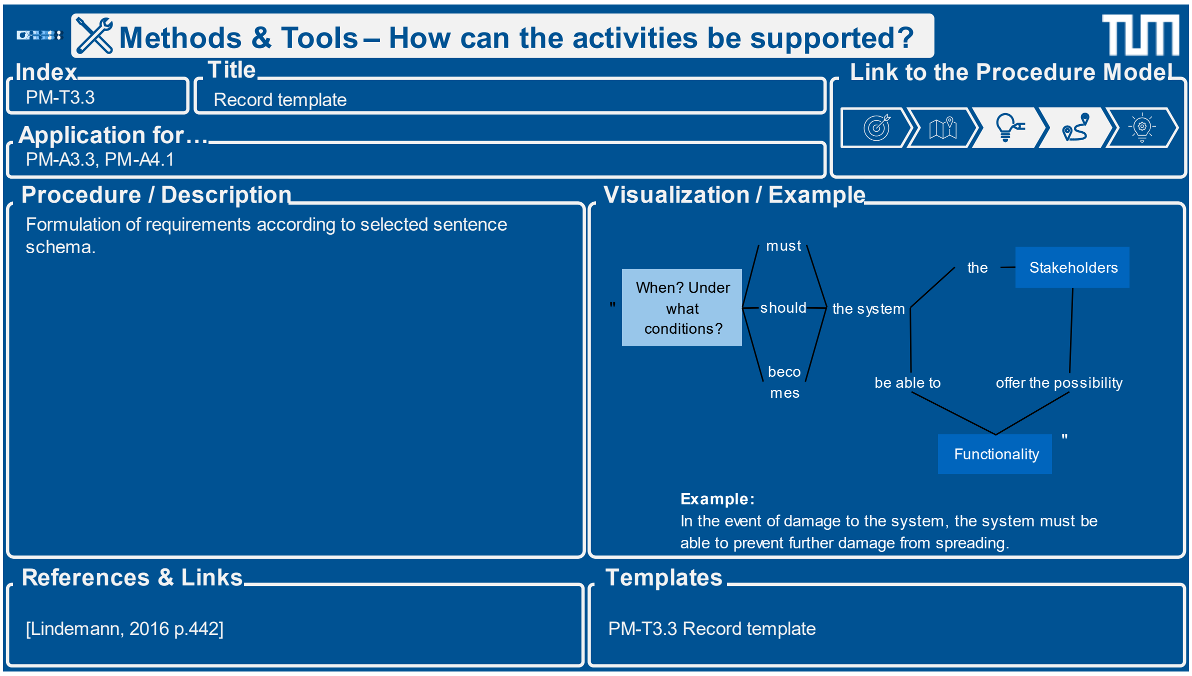


Figure A 100: Tool PM-T3. of the Digital Twin Procedure Model.

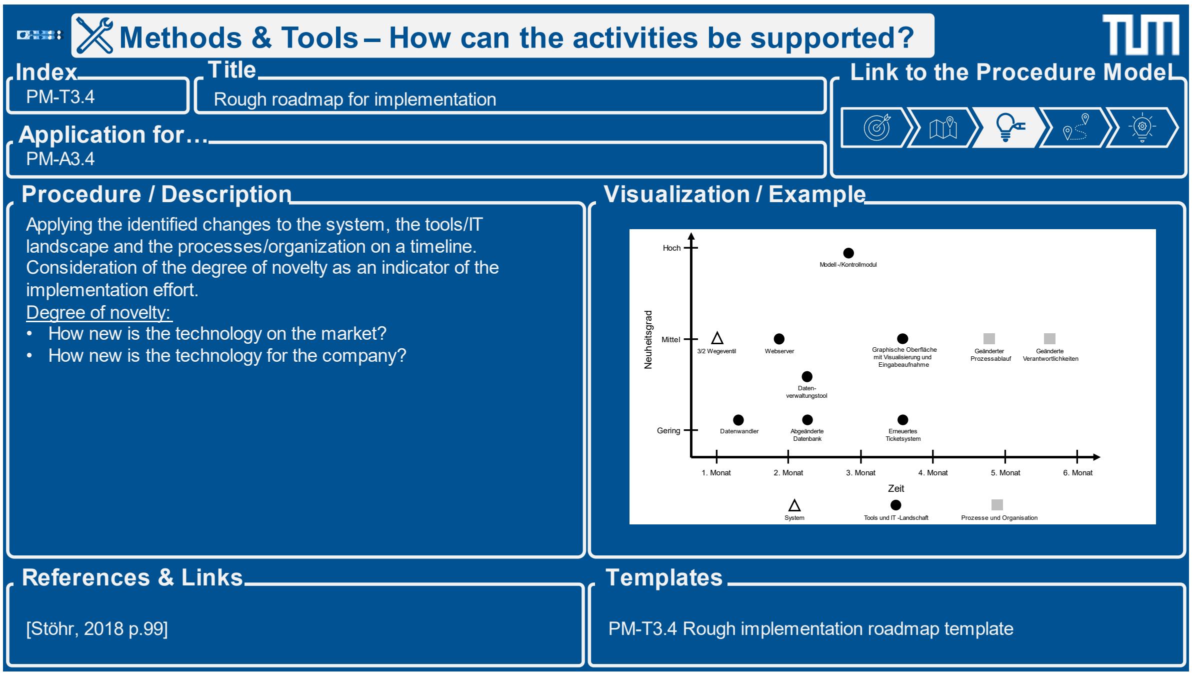


Figure A 101: Tool PM-T3.4 of the Digital Twin Procedure Model.

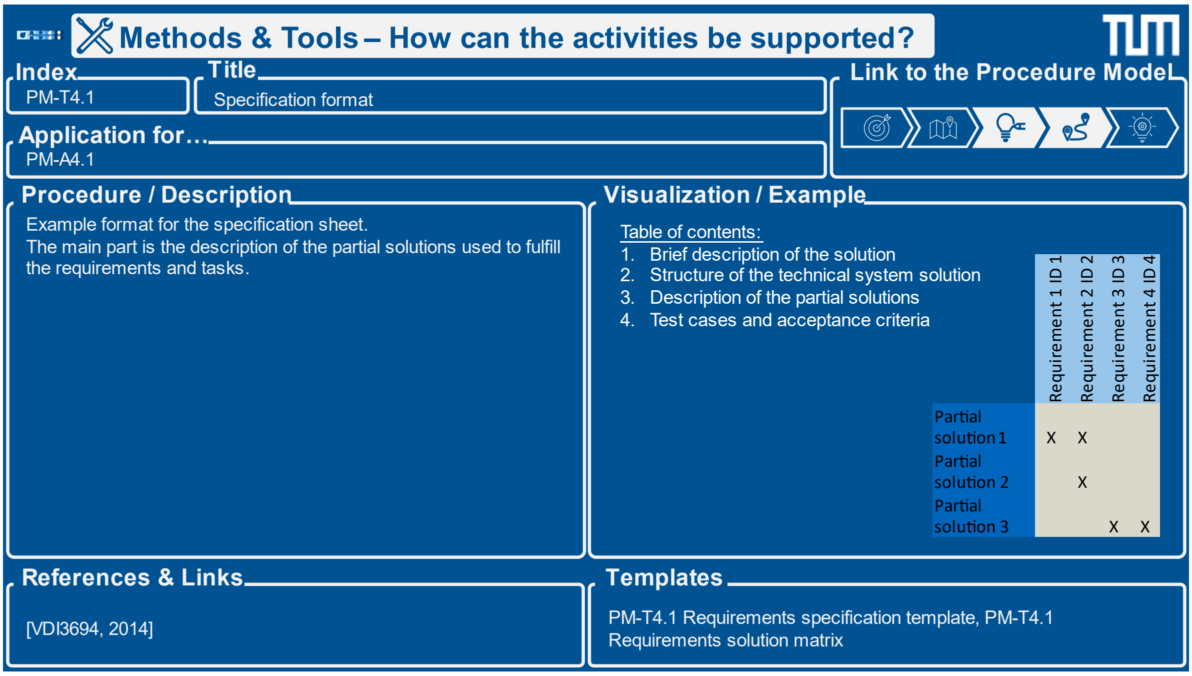


Figure A 102: Tool PM-T4.1 of the Digital Twin Procedure Model.

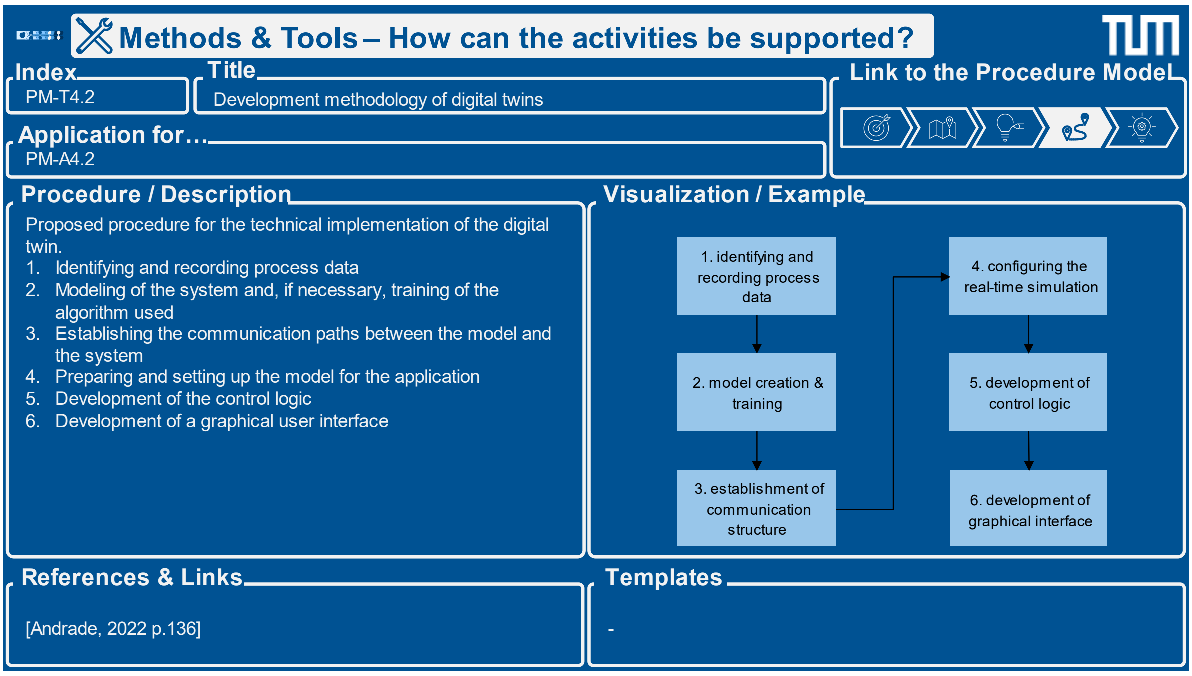


Figure A 103: Tool PM-T4.2 of the Digital Twin Procedure Model.

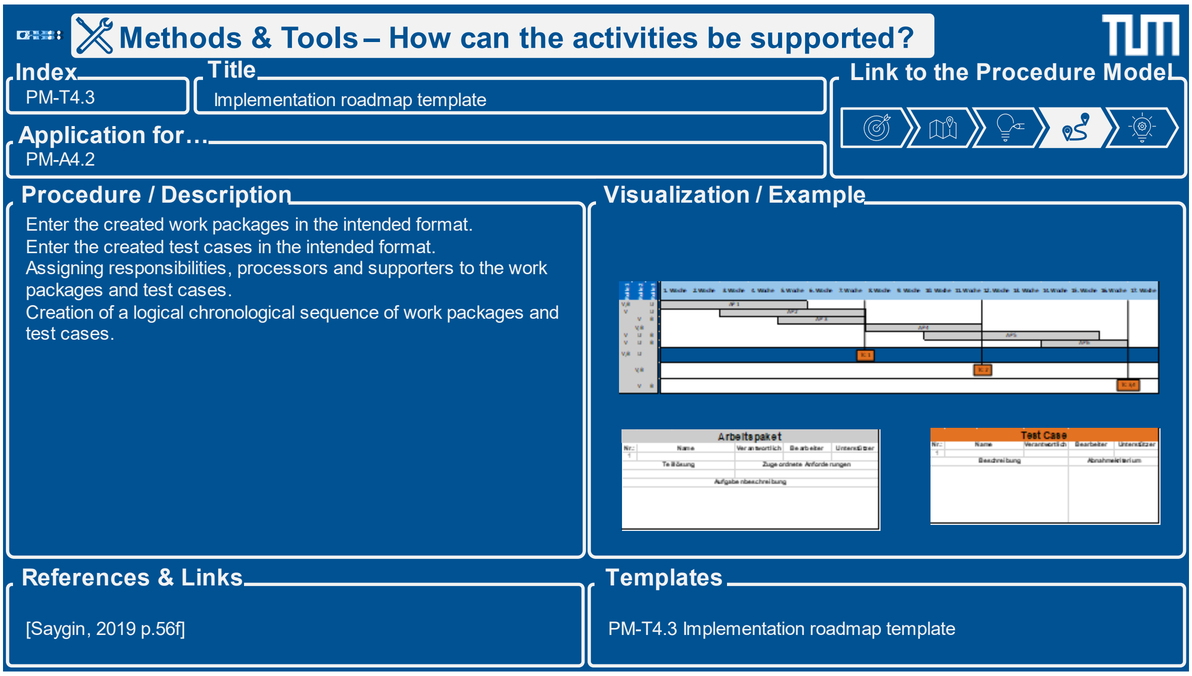


Figure A 104: Tool PM-T4.3 of the Digital Twin Procedure Model.

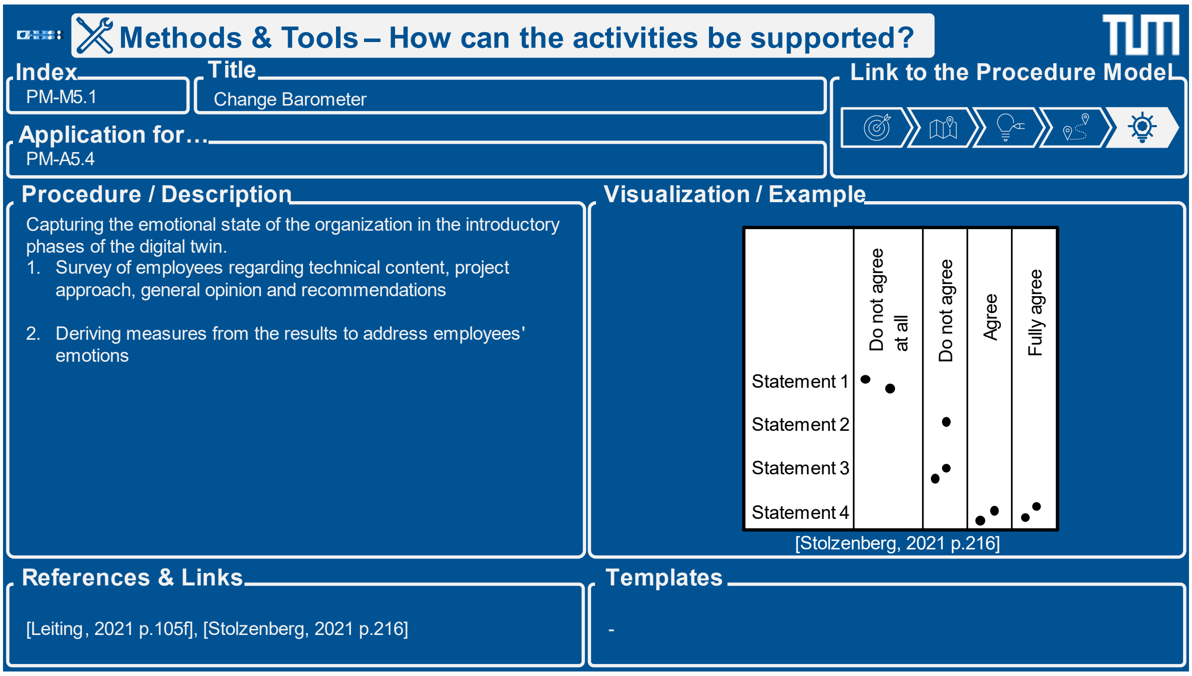


Figure A 105: Method PM-M5.1 of the Digital Twin Procedure Model.

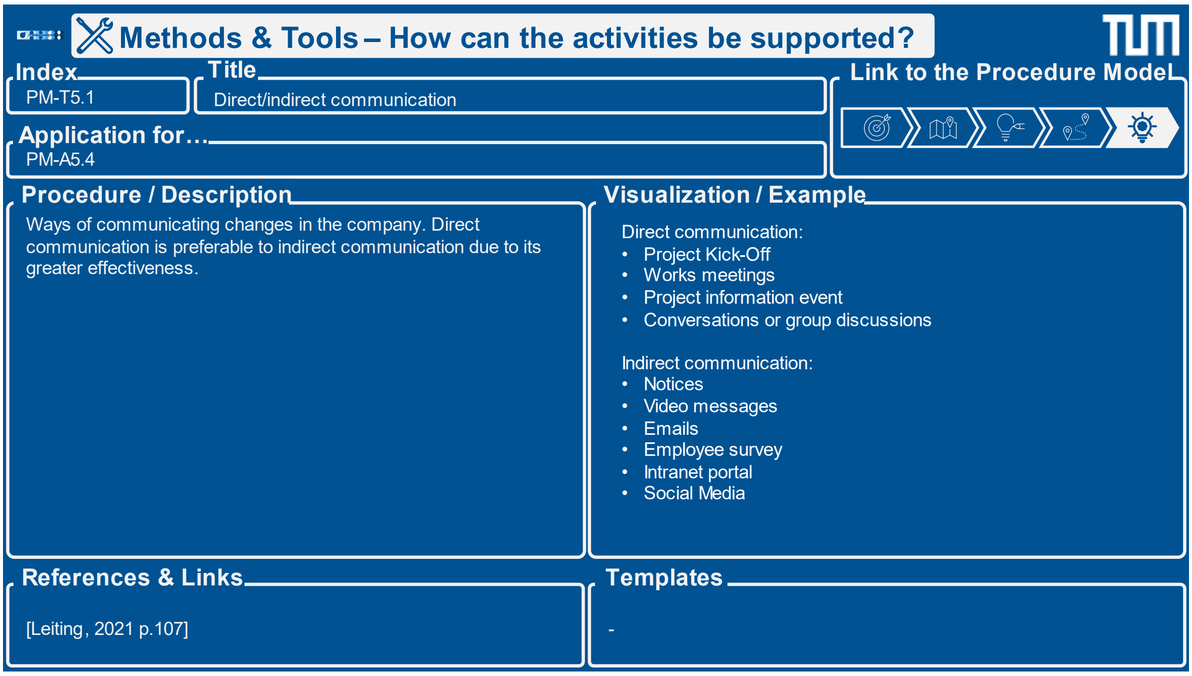


Figure A 106: Tool PM-T5.1 of the Digital Twin Procedure Model.

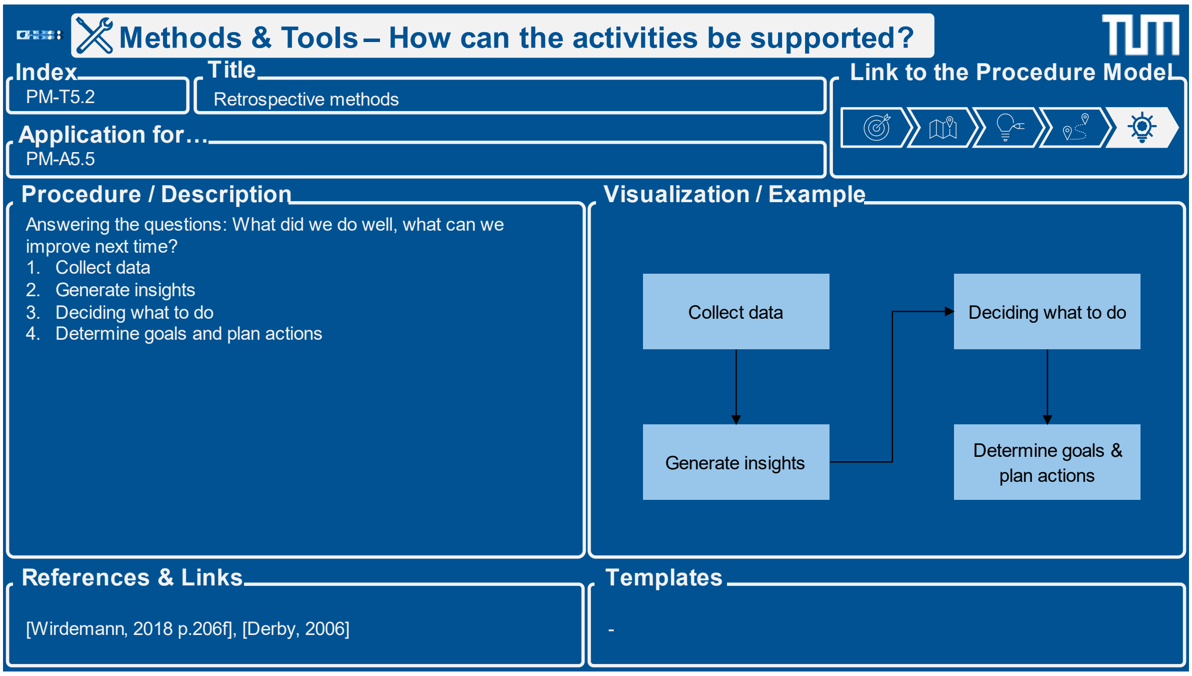


Figure A 107: Tool PM-T5.2 of the Digital Twin Procedure Model.

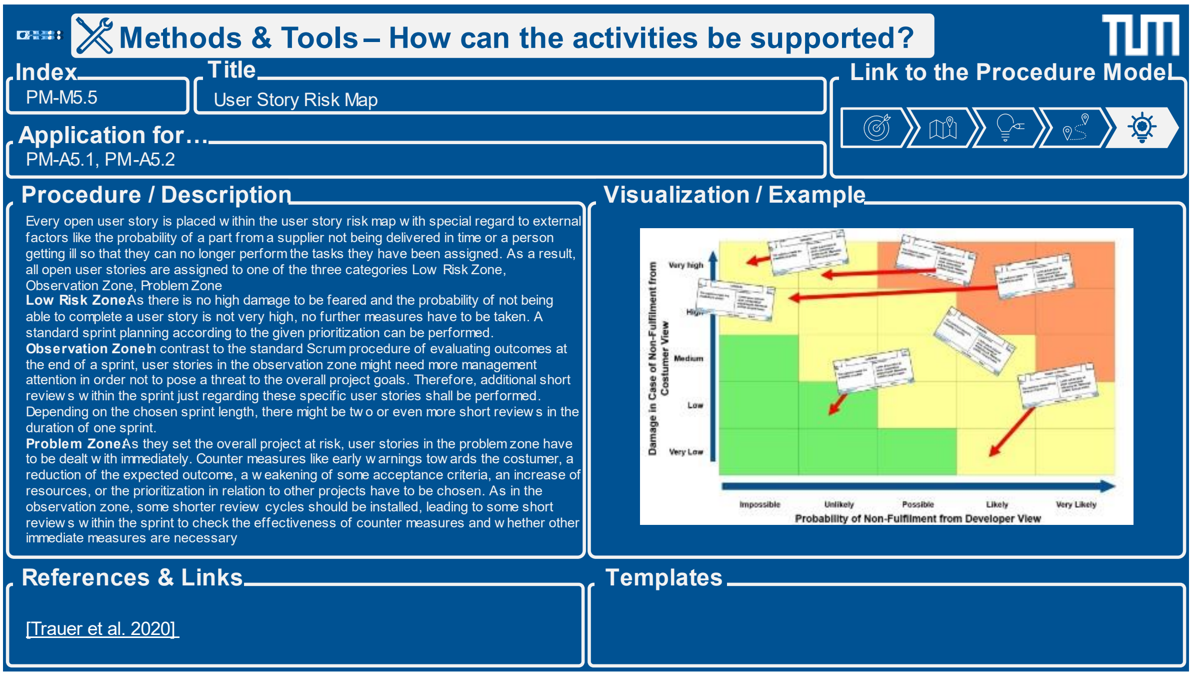


Figure A 108: Method PM-M5.5 of the Digital Twin Procedure Model.

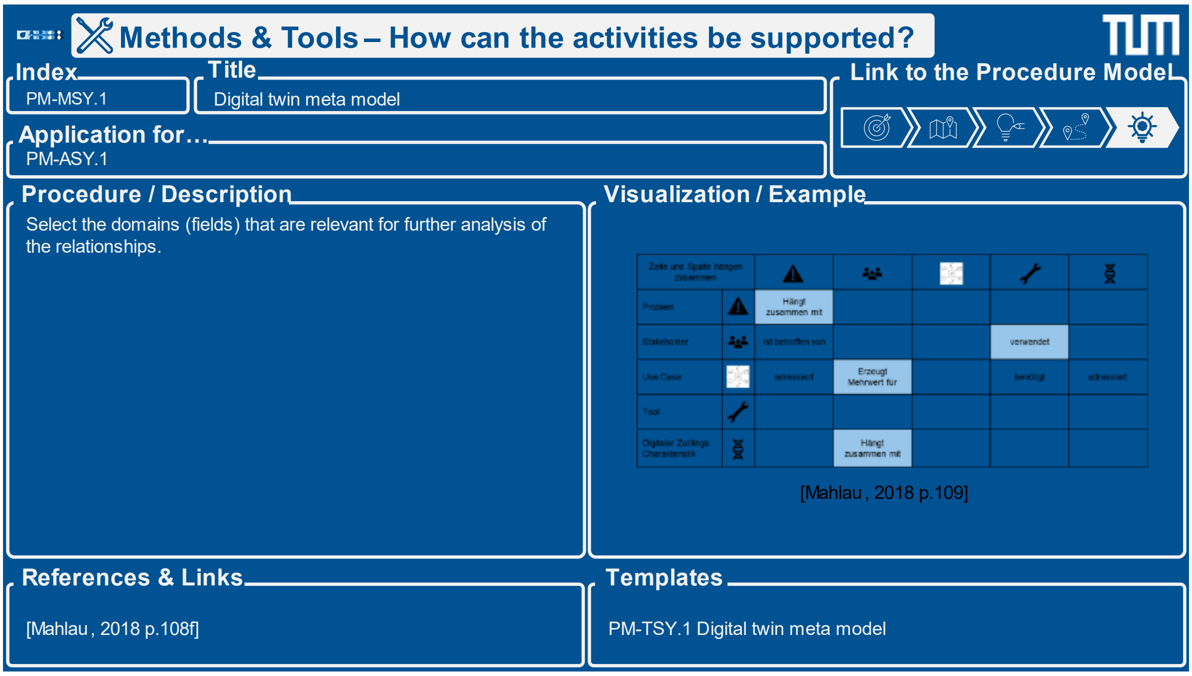


Figure A 109: Method PM-MSY.1 of the Digital Twin Procedure Model.

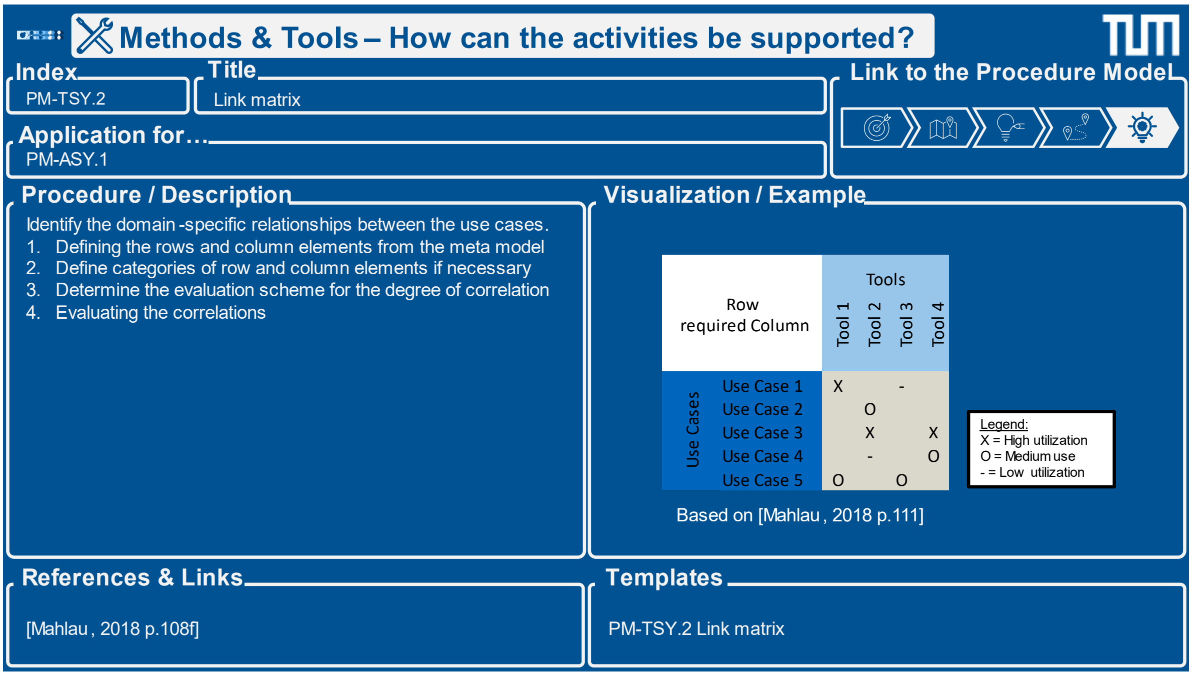


Figure A 110: Tool PM-TSY.2 of the Digital Twin Procedure Model.

The Deliverables of the Procedure Model

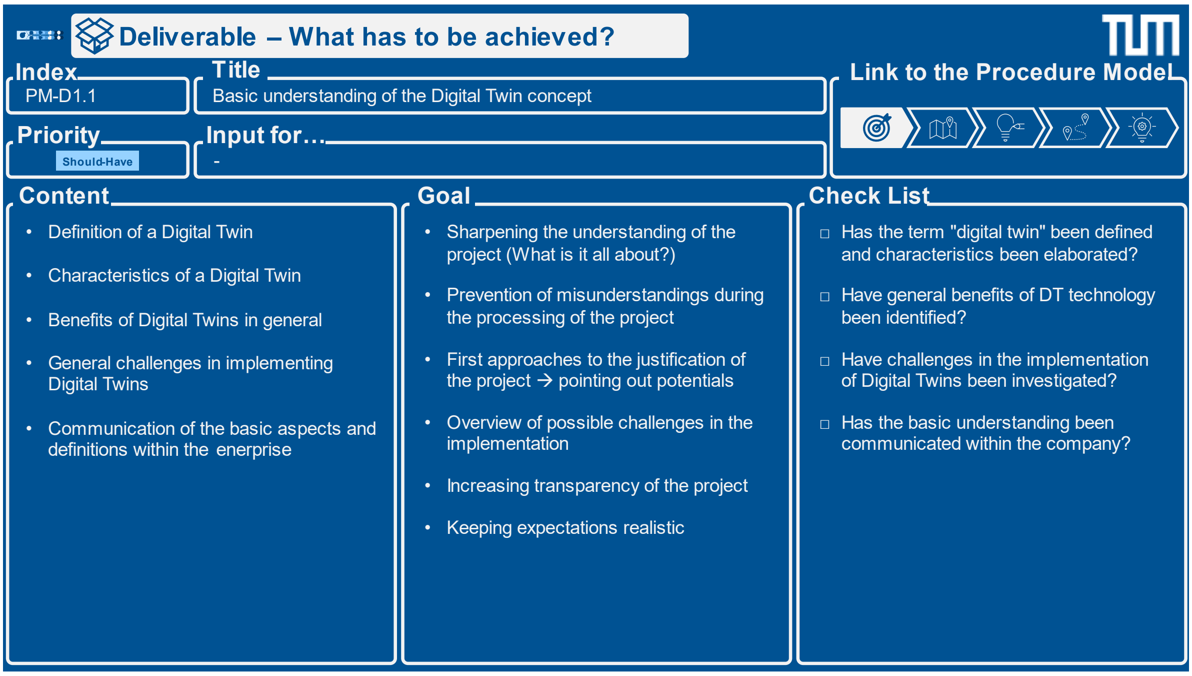


Figure A 111: Deliverable PM-D1.1 of the Digital Twin Procedure Model.

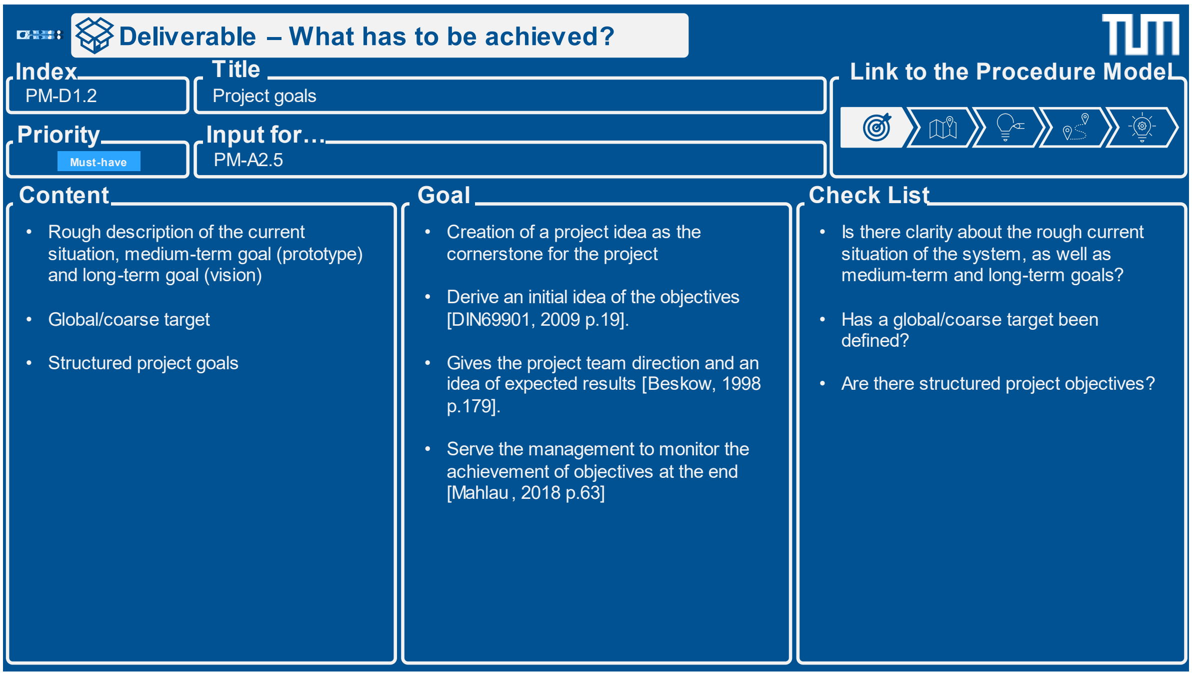


Figure A 112: Deliverable PM-D1.2 of the Digital Twin Procedure Model.

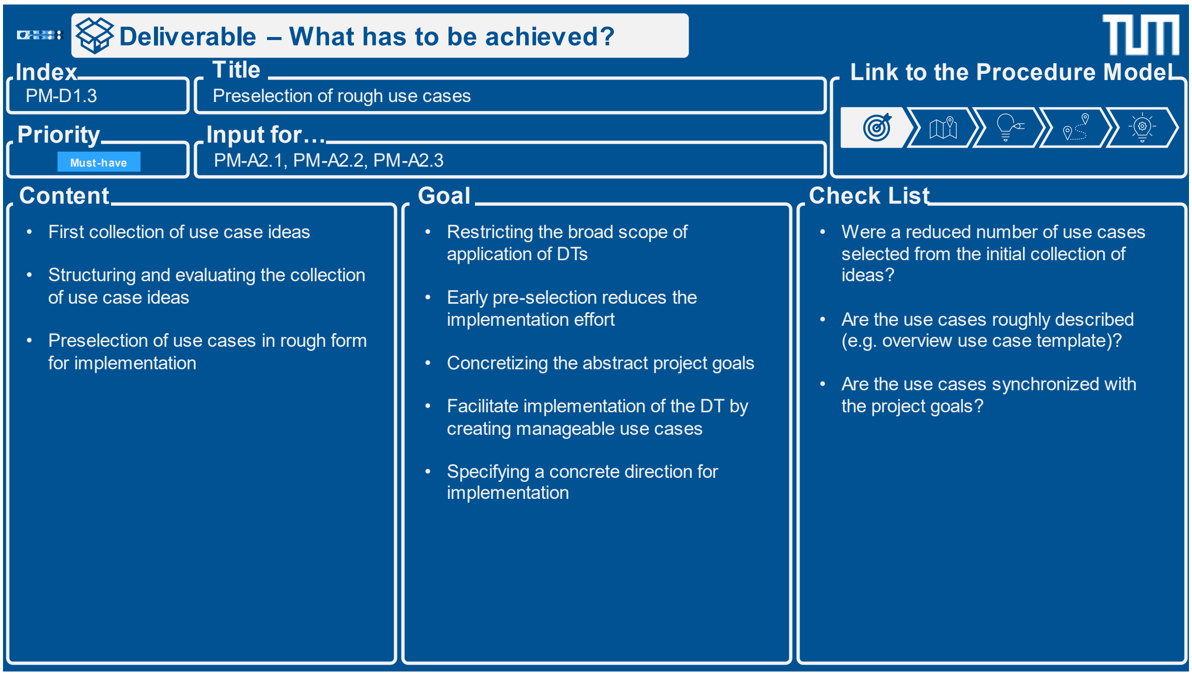


Figure A 113: Deliverable PM-D1.3 of the Digital Twin Procedure Model.

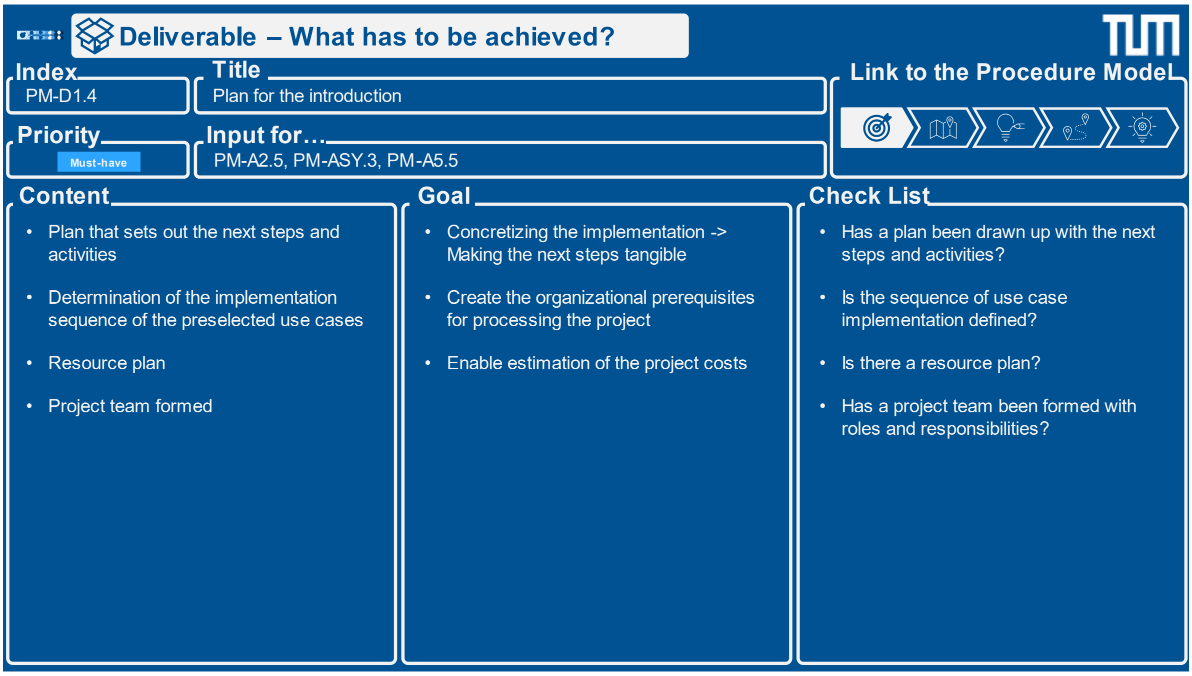


Figure A 114: Deliverable PM-D1.4 of the Digital Twin Procedure Model.

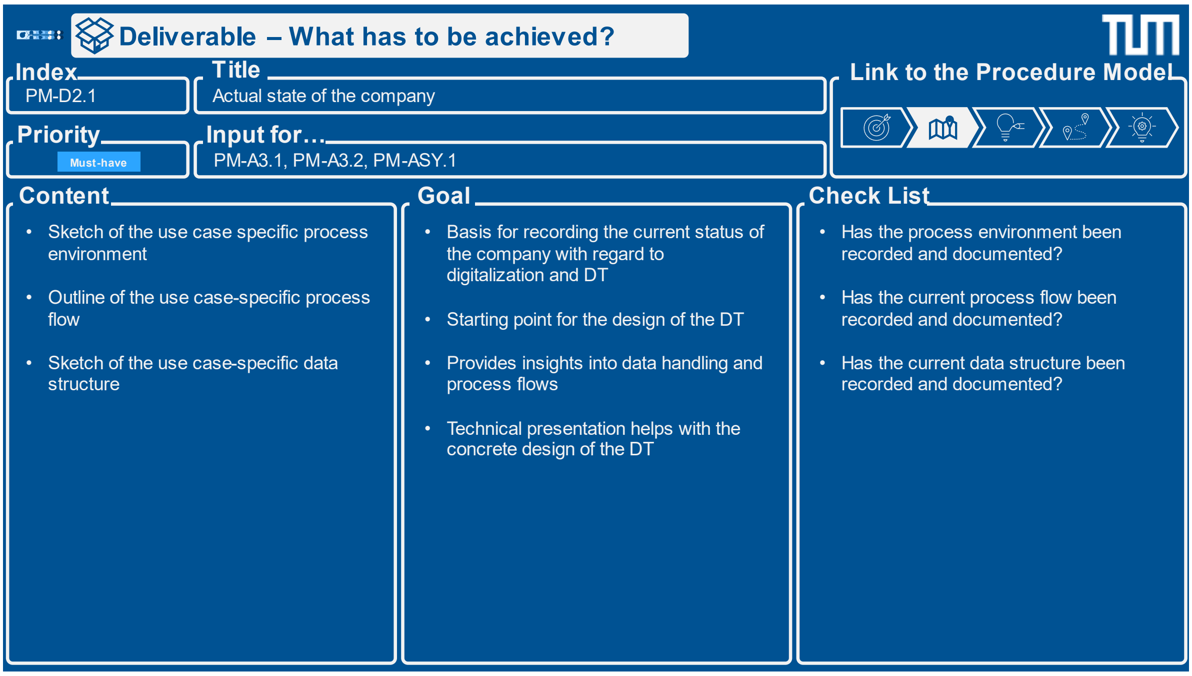


Figure A 115: Deliverable PM-D2.1 of the Digital Twin Procedure Model.

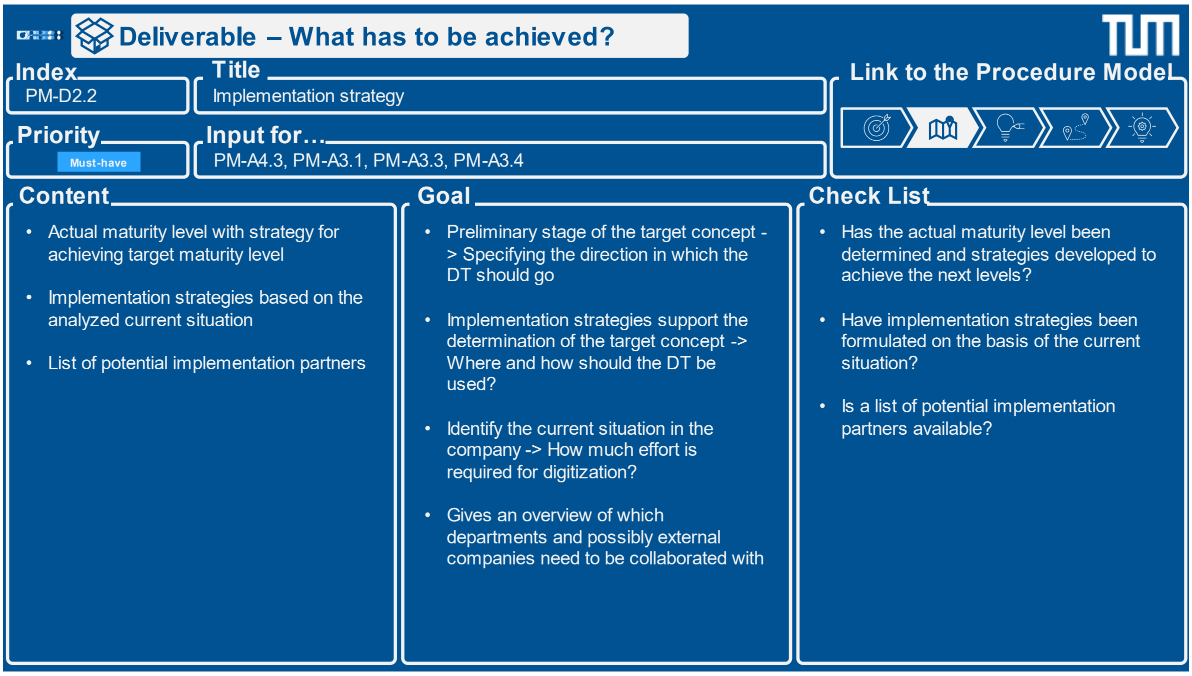


Figure A 116: Deliverable PM-D2.2 of the Digital Twin Procedure Model.

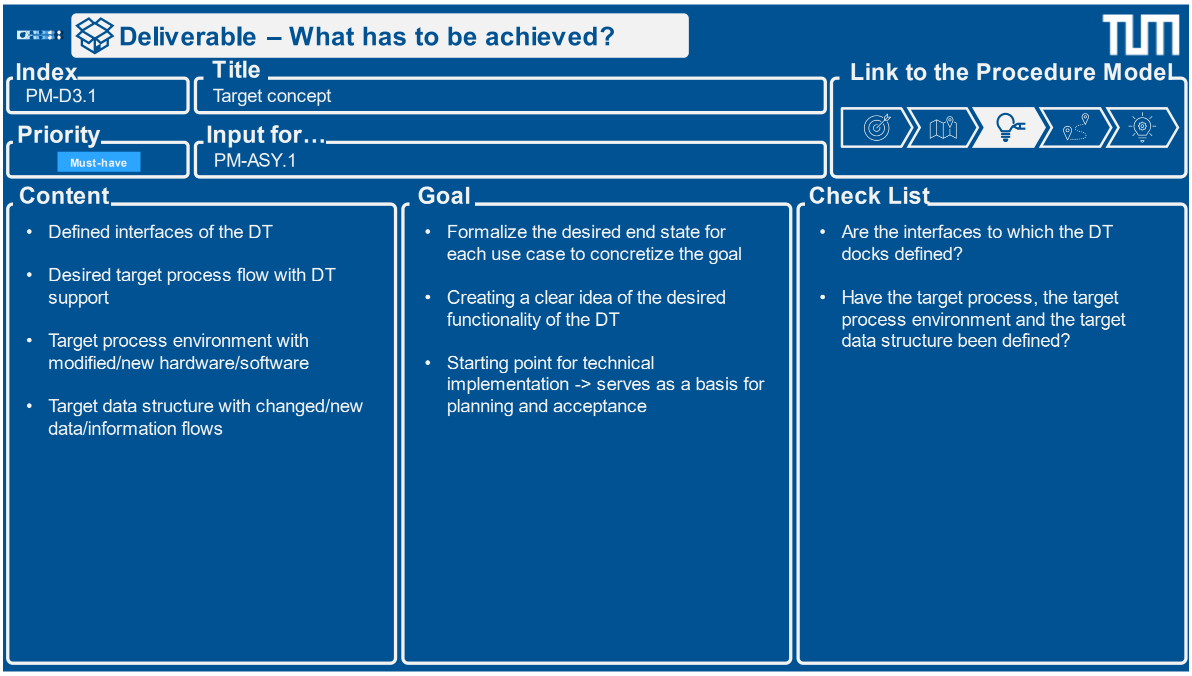


Figure A 117: Deliverable PM-D3.1 of the Digital Twin Procedure Model.

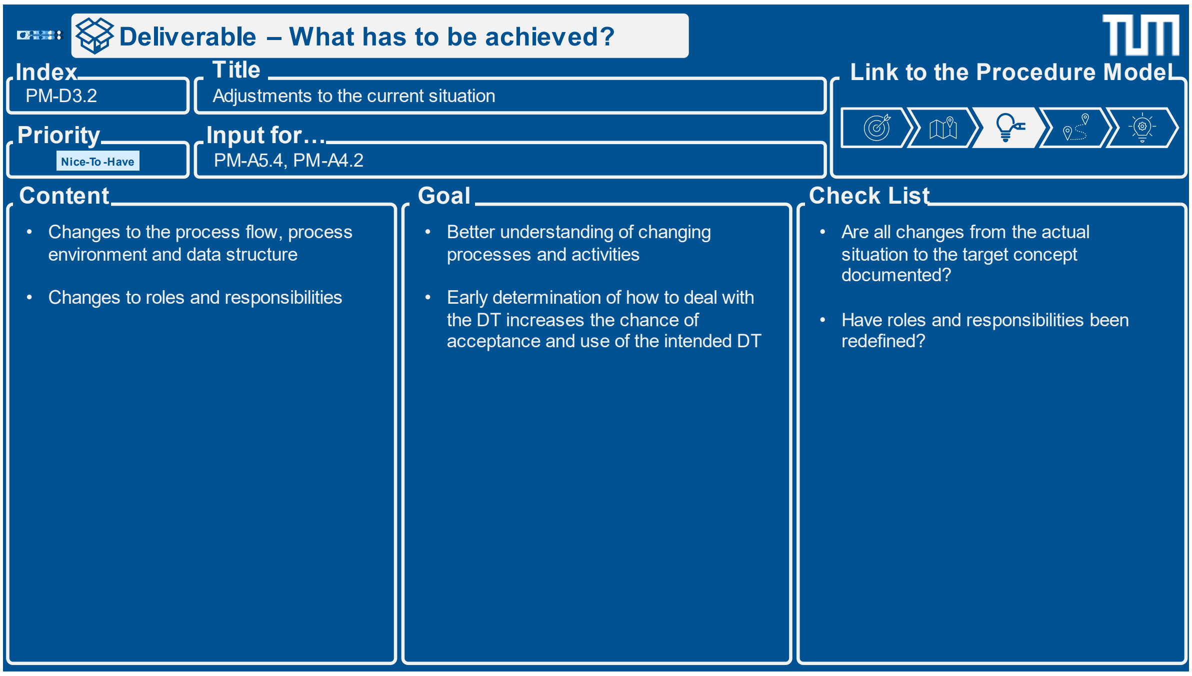


Figure A 118: Deliverable PM-D3.2 of the Digital Twin Procedure Model.

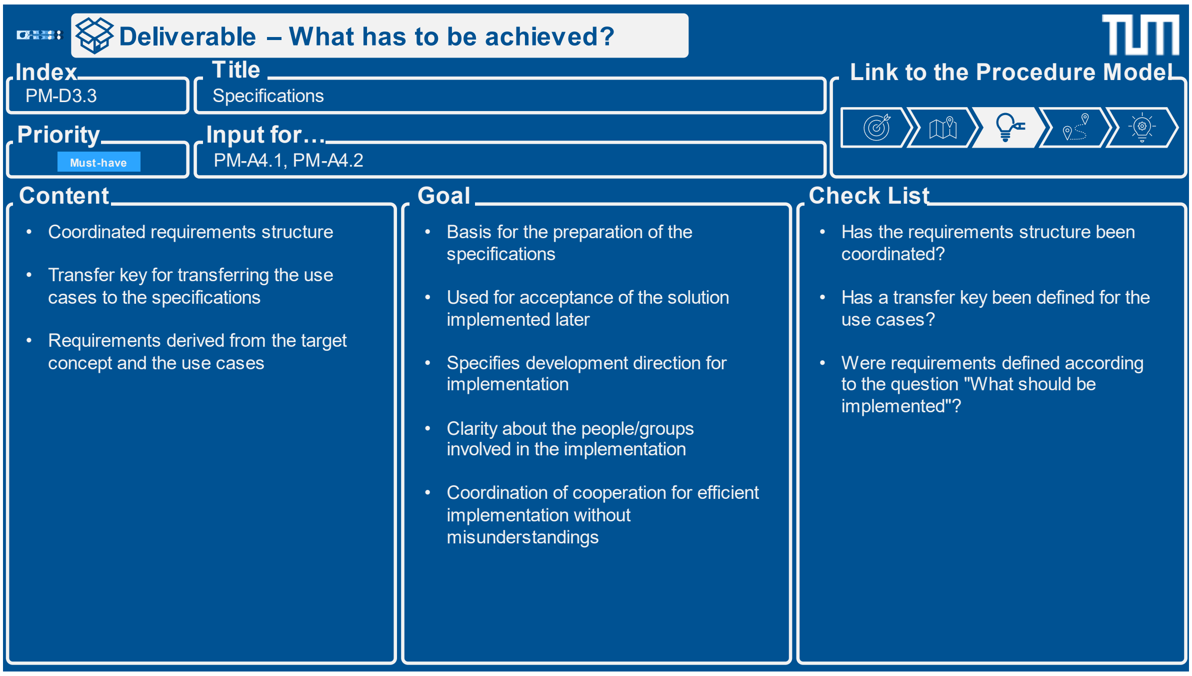


Figure A 119: Deliverable PM-D3.3 of the Digital Twin Procedure Model.

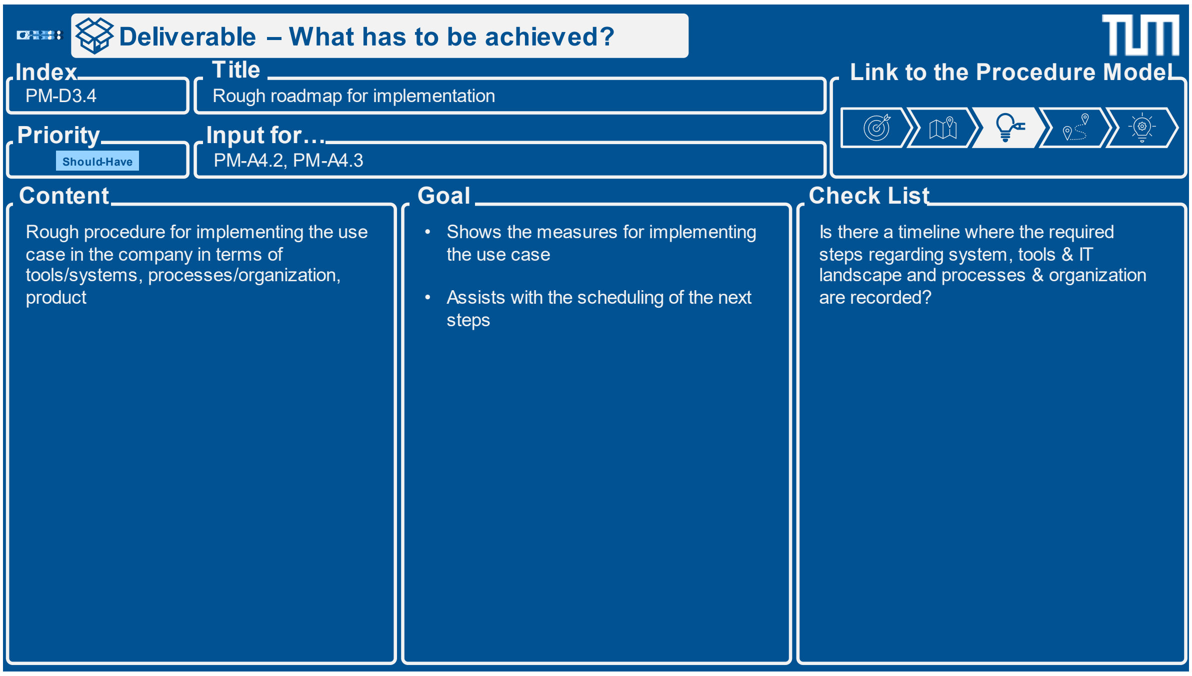


Figure A 120: Deliverable PM-D3.4 of the Digital Twin Procedure Model.

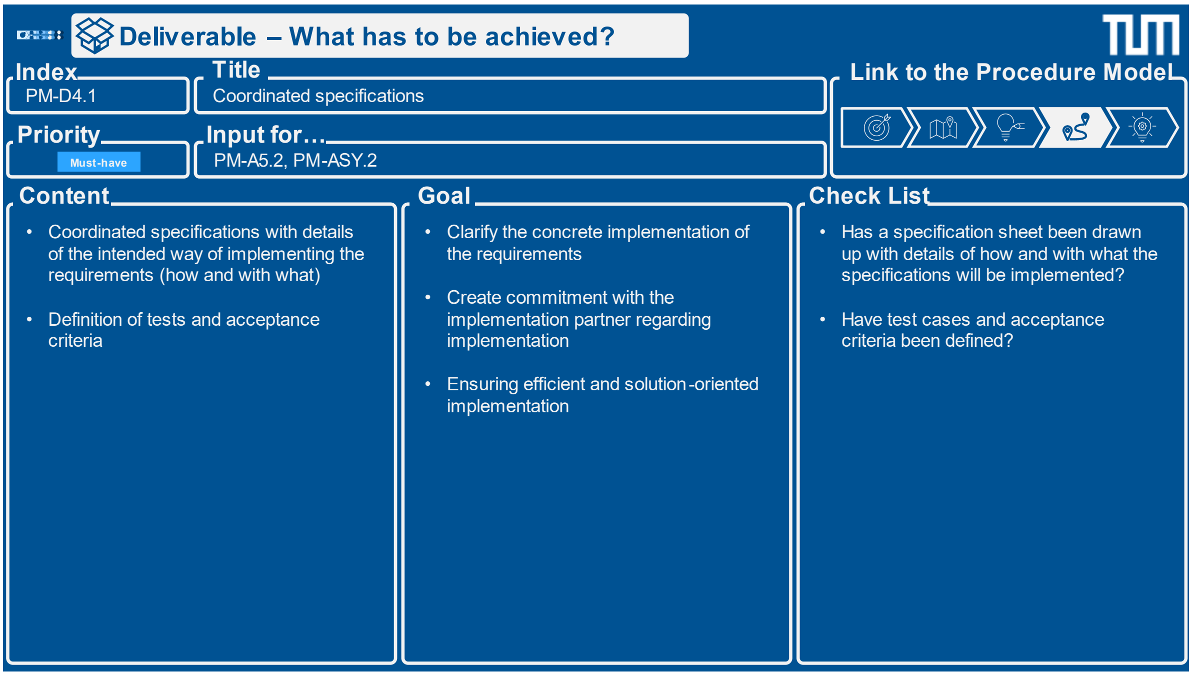


Figure A 121: Deliverable PM-D4.1 of the Digital Twin Procedure Model.

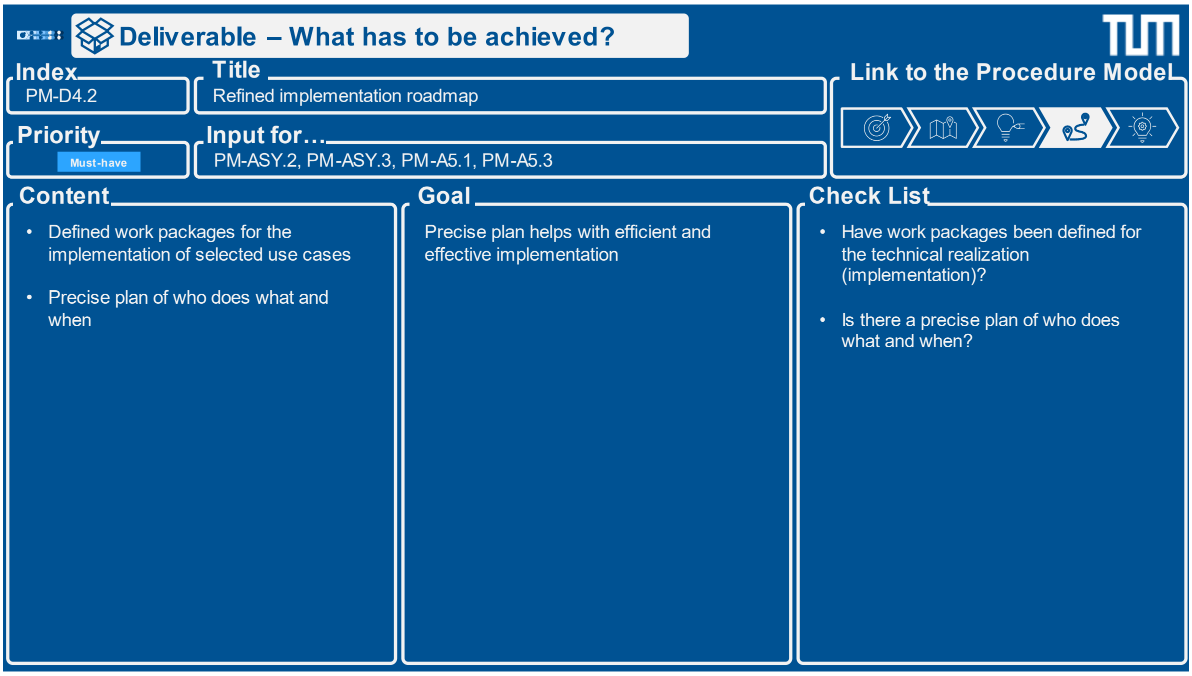


Figure A 122: Deliverable PM-D4.2 of the Digital Twin Procedure Model.

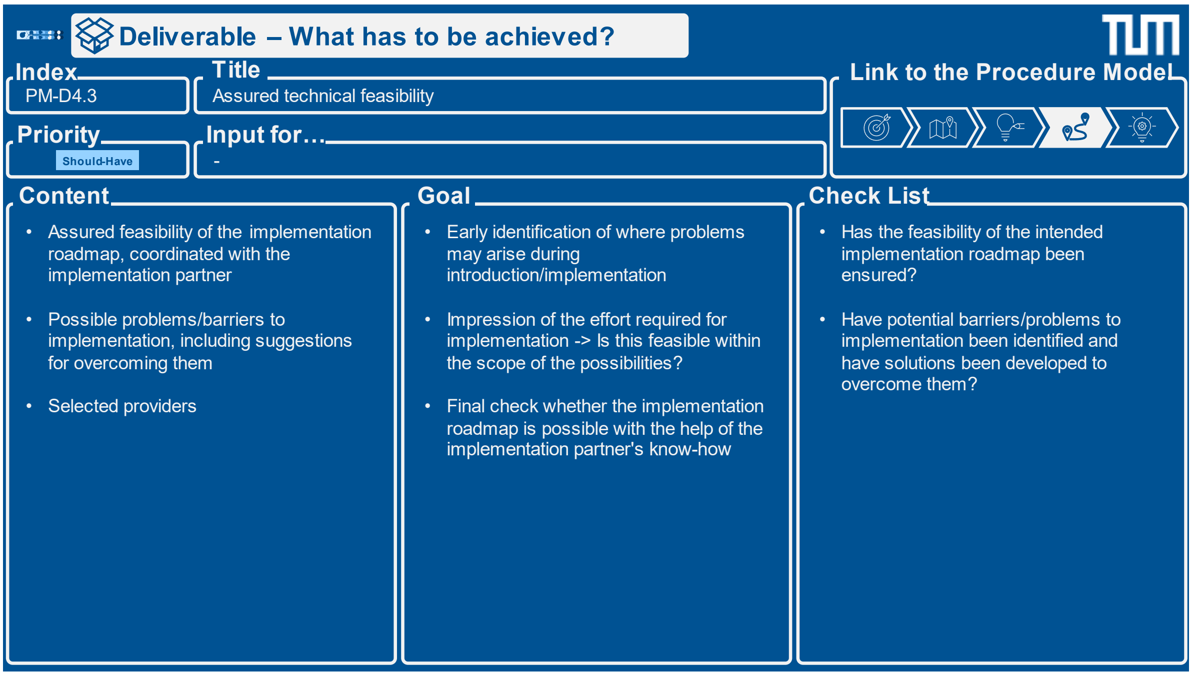


Figure A 123: Deliverable PM-D4.3 of the Digital Twin Procedure Model.

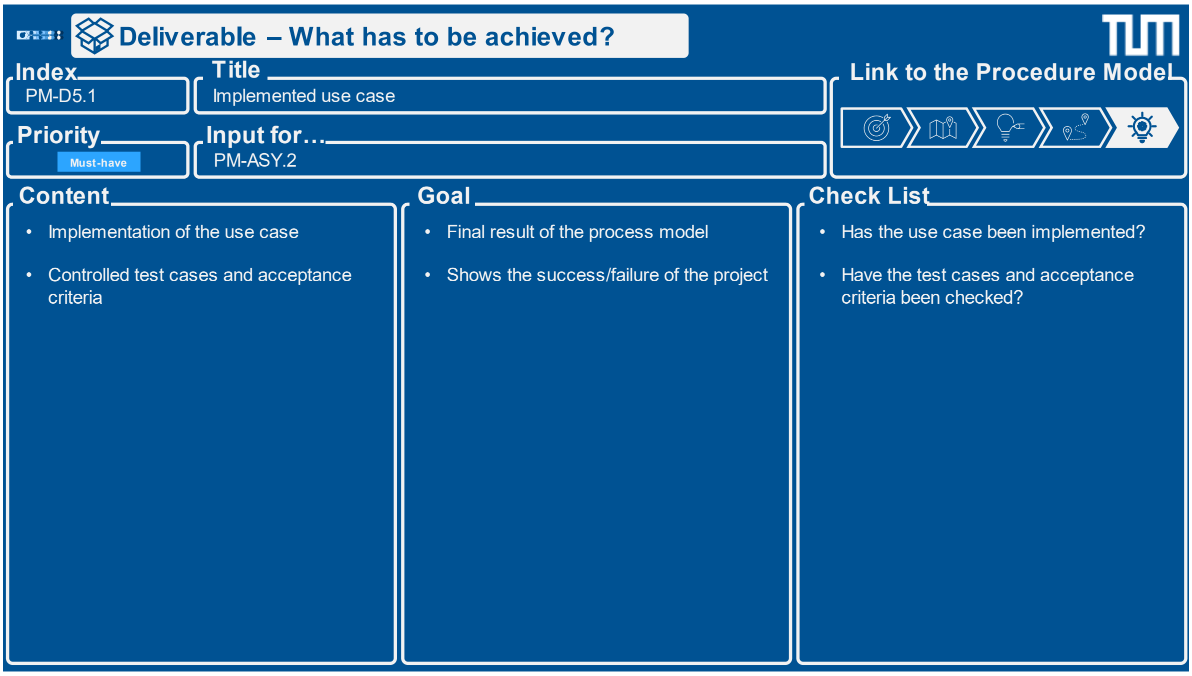


Figure A 124: Deliverable PM-D5.1 of the Digital Twin Procedure Model.

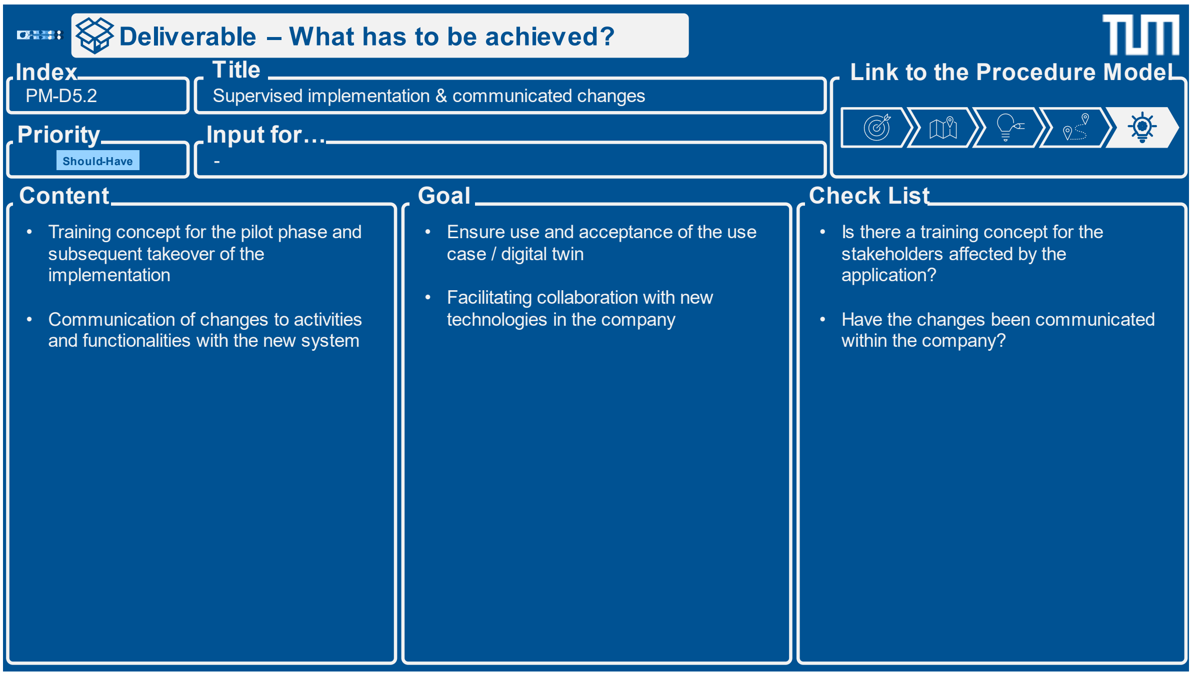


Figure A 125: Deliverable PM-D5.2 of the Digital Twin Procedure Model.

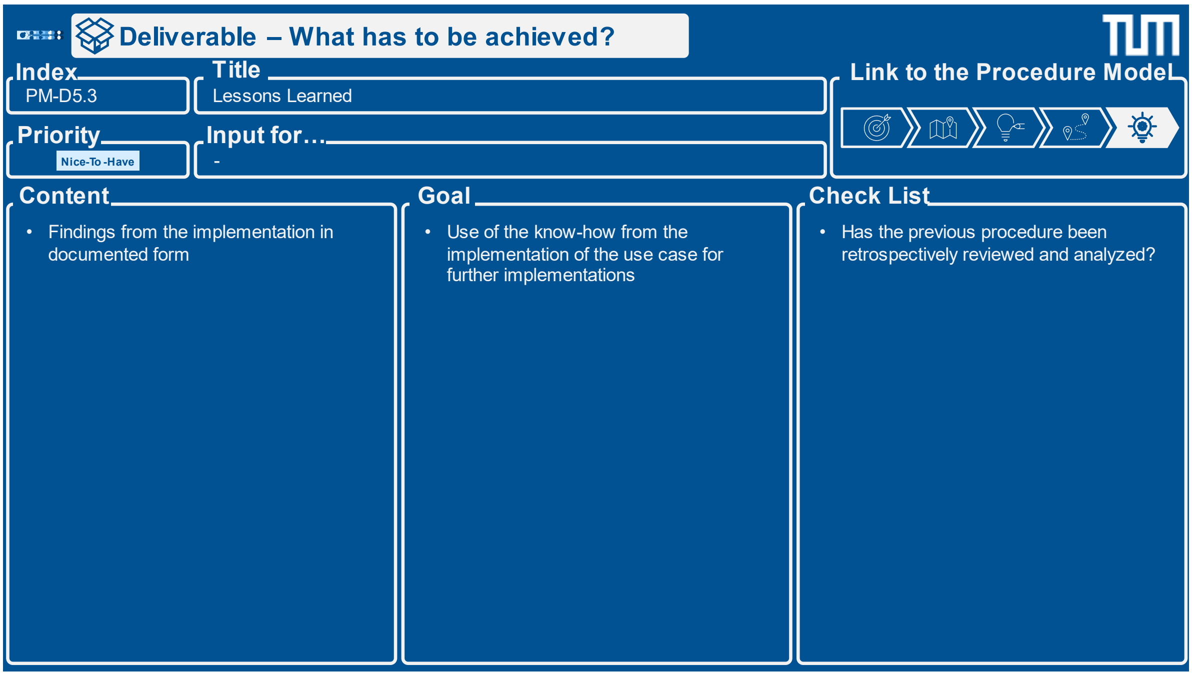


Figure A 126: Deliverable PM-D5.3 of the Digital Twin Procedure Model.

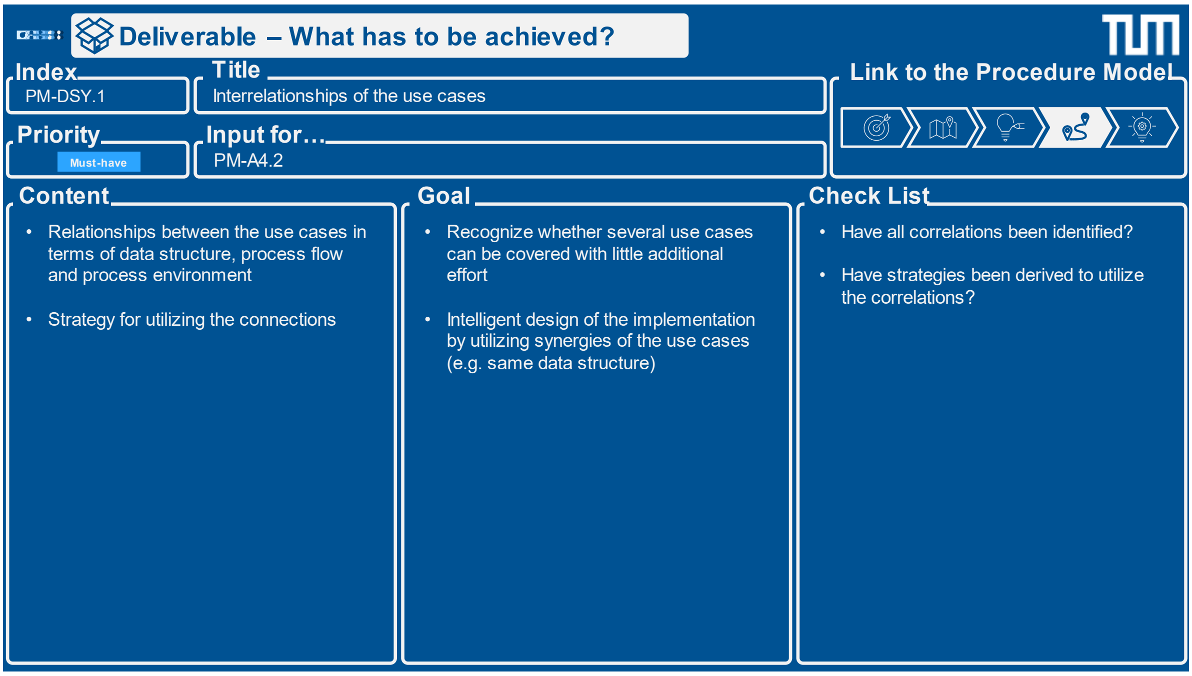


Figure A 127: Deliverable PM-DSY.1 of the Digital Twin Procedure Model.

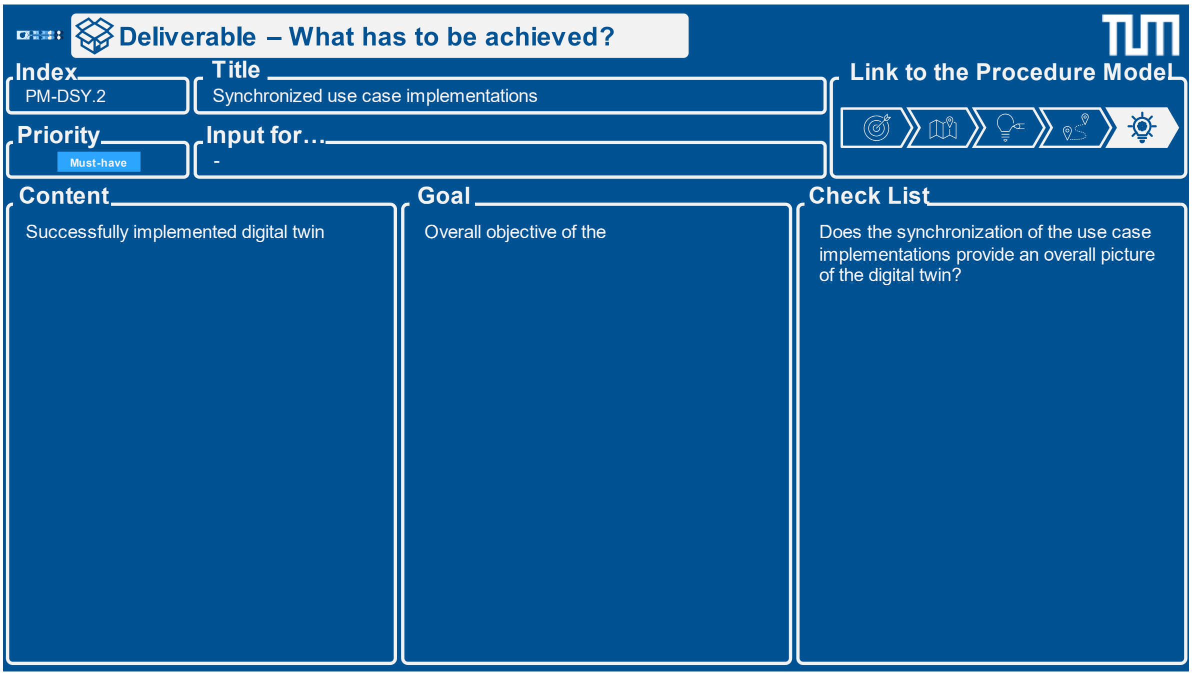


Figure A 128: Deliverable PM-DSY.2 of the Digital Twin Procedure Model.

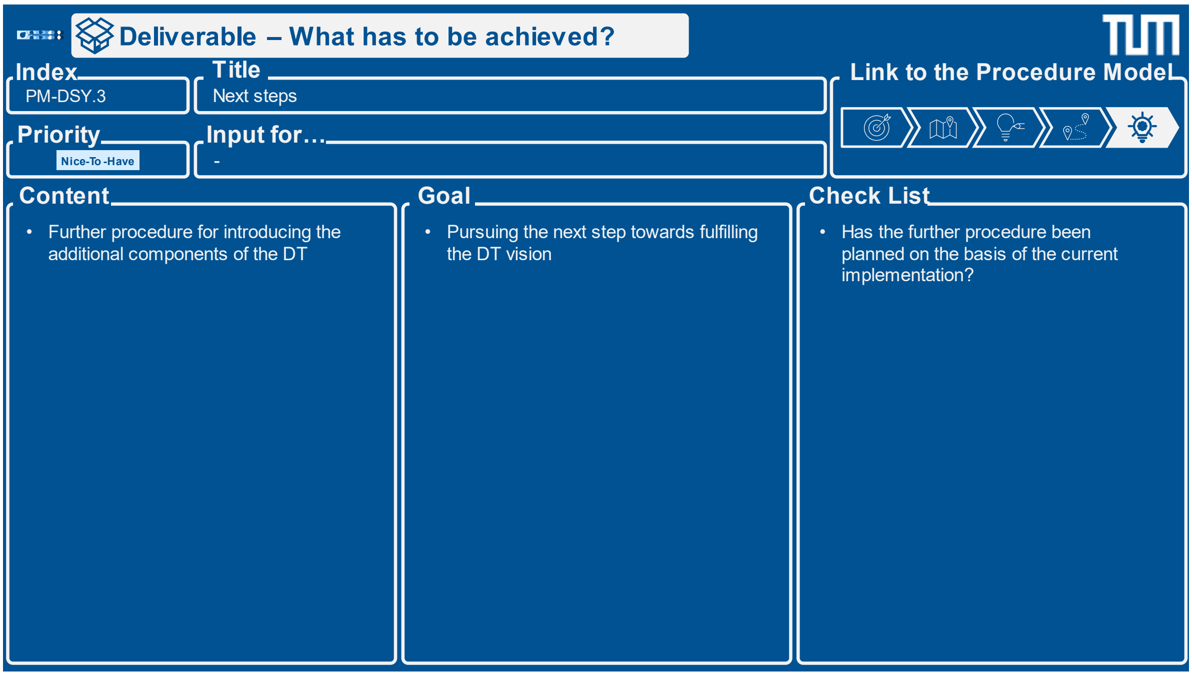


Figure A 129: Deliverable PM-DSY.3 of the Digital Twin Procedure Model.

A8.2 Additional Material of the Business Modelling Approach

Literature Review on Basic Business Model Elements

Table A 11: Overview of Basic Elements of Business Modelling Approaches (adapted from Trauer et al., 2023).

	Osterwalder and Pigneur (2010)	***Gassmann et al. (2014)***	***Jodlbauer (2020)***	***Schneider (2012)***	***Laudon and Traver (2014)***	***Voelpel et al. (2004)***	***Lindgardt et al. (2013)***	***Johnson and Lafley (2010)***	***Bieger and Reinhold (2011)***	***De Kluyver (2012)***	***Chesbrough (2010)***	***Alt and Zimmermann (2001)***	***Hamel (2002)***	***Wirtz (2020)***	**Total**
Customer Segments	x	x	x	x		x	x	x	x	x	x	x	x	x	**14**
Value Proposition	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**14**
Channels	x	x	x					x	x	x			x	x	**8**
Customer Relationship	x	x	x	x									x	x	**6**
Revenue Streams	x	x	x	x	x		x	x	x		x	x	x	x	**12**
Key Resources	x	x	x	x		x	x	x	x	x	x	x	x	x	**13**
Key Activities	x	x	x	x		x	x	x	x	x	x	x	x	x	**13**
Key Partners	x	x	x	x		x	x	x	x	x	x	x	x	x	**13**
Cost Structures / Budget	x	x	x				x	x			x			x	**7**
Market opportunity					x										**1**
Competitive environment					x									x	**2**
Market strategy					x										**2**
Organizational development					x		x			x					**3**
Competitive advantage					x						x		x		**3**
Development Concept									x						**1**
Legal Issues												x			**1**
Information & Insights (key resources)													x		**1**
Management team / Leader-ship & governance					x	x									**2**
Organization							x								**1**

The Steps of the Digital Twin Business Modelling Approach

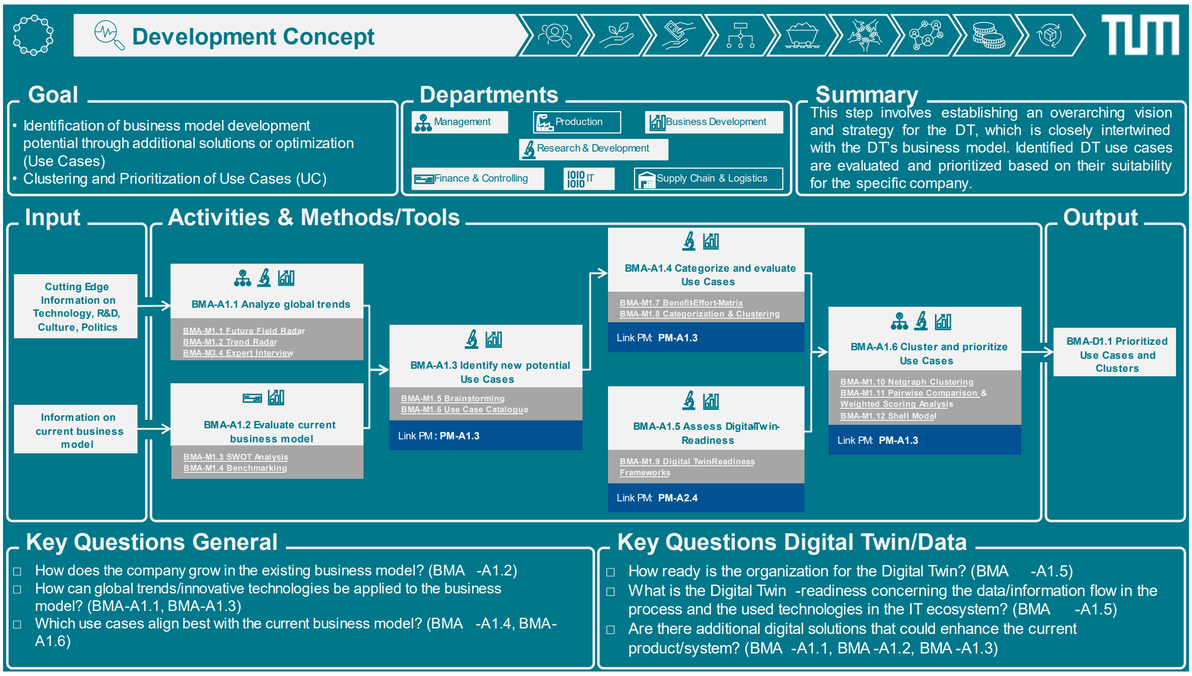


Figure A 130: Overview of "Step 1 - Development Concept" of the Digital Twin Business Modelling Approach.

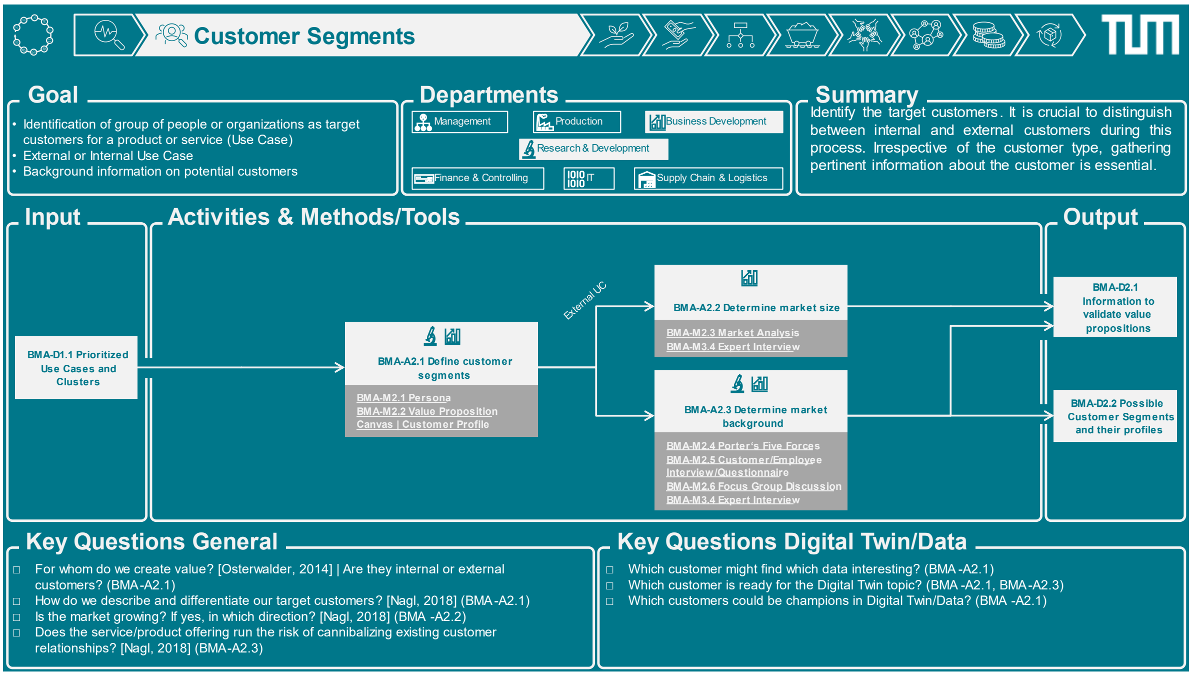


Figure A 131: Overview of "Step 2 – Customer Segments" of the Digital Twin Business Modelling Approach.

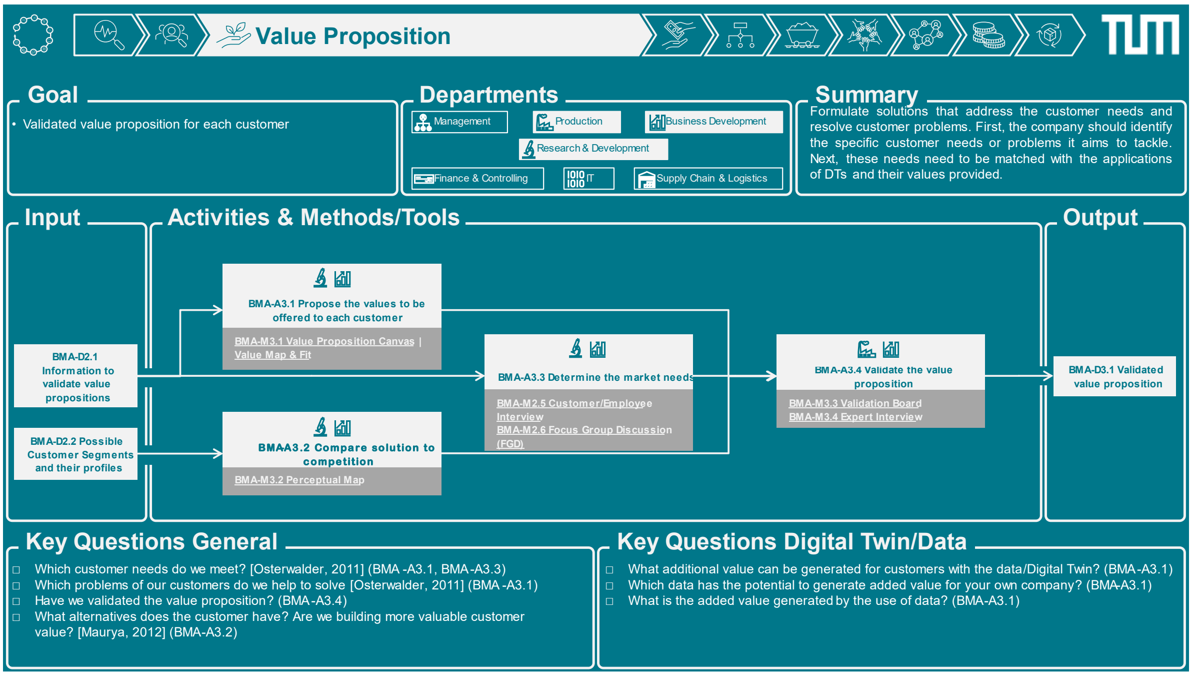


Figure A 132: Overview of "Step 3 – Value Proposition" of the Digital Twin Business Modelling Approach.

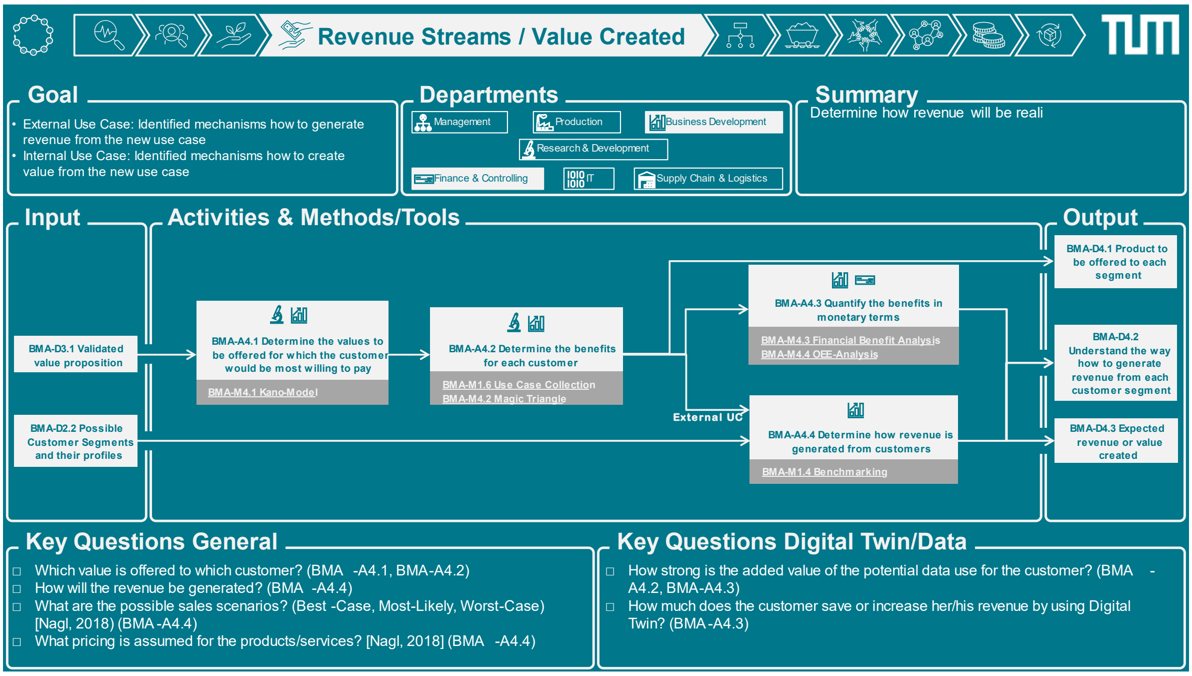


Figure A 133: Overview of "Step 4 – Revenue Streams / Value Created" of the Digital Twin Business Modelling Approach.

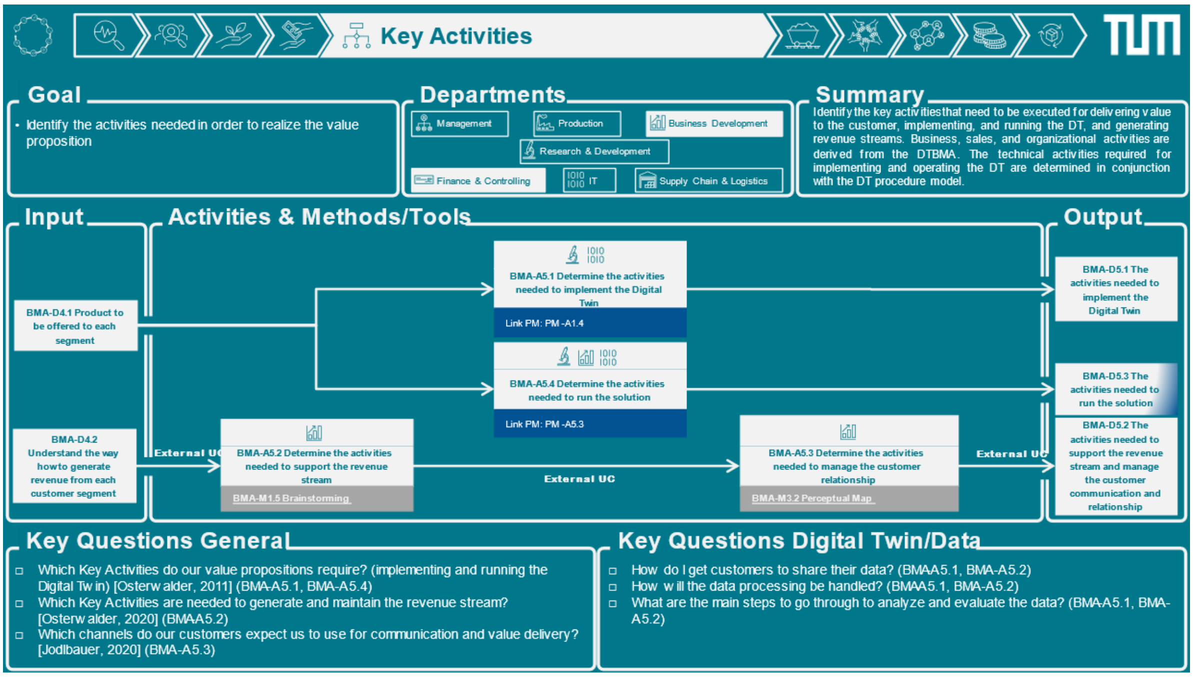


Figure A 134: Overview of "Step 5 – Key Activities" of the Digital Twin Business Modelling Approach.

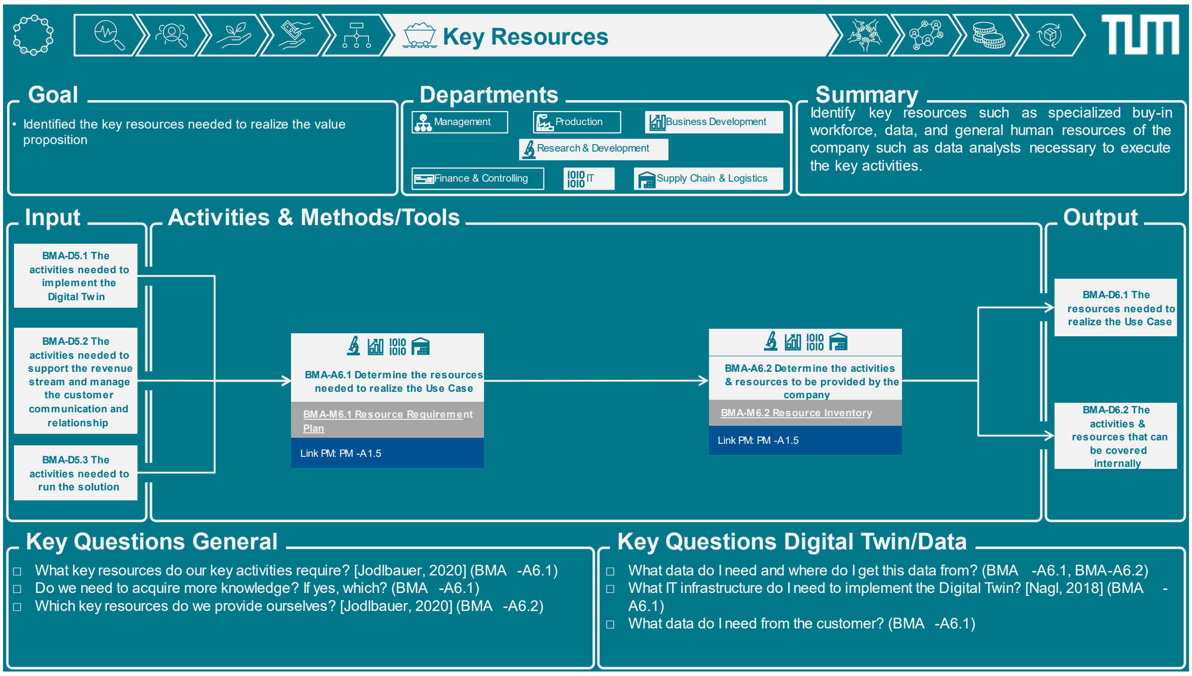


Figure A 135: Overview of "Step 6 – Key Resources" of the Digital Twin Business Modelling Approach.

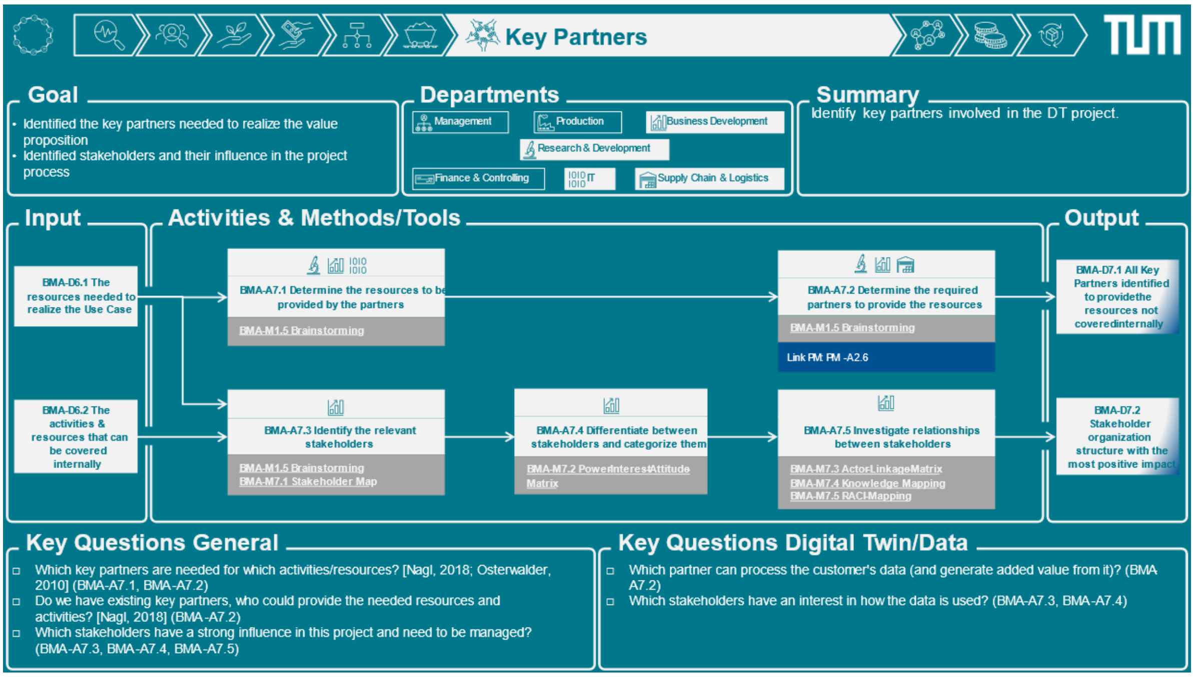


Figure A 136: Overview of “Step 7 – Key Partners” of the Digital Twin Business Modelling Approach.

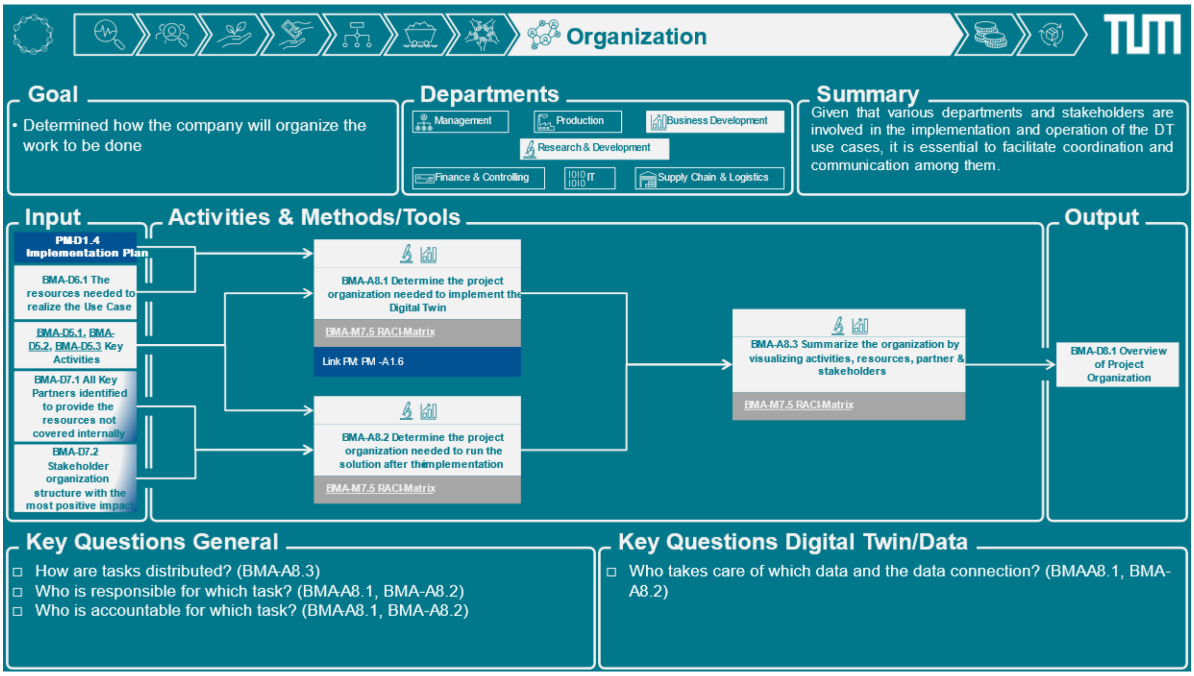


Figure A 137: Overview of “Step 8 - Organization” of the Digital Twin Business Modelling Approach.

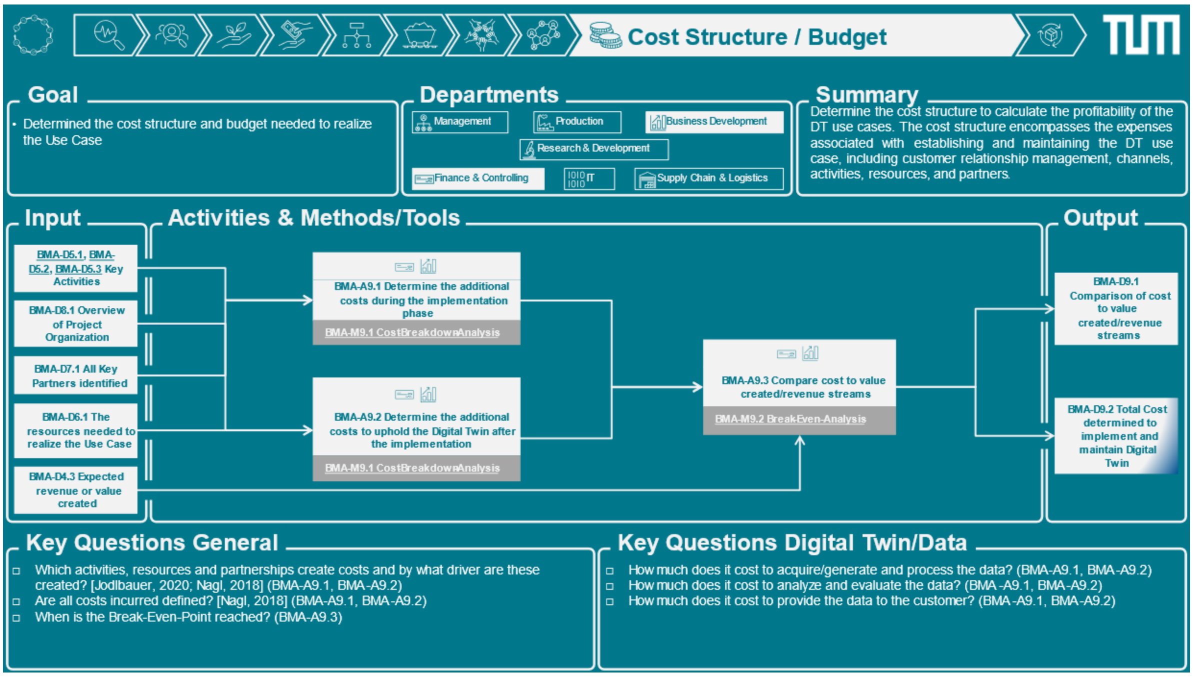


Figure A 138: Overview of "Step 9 – Cost Structure / Budget" of the Digital Twin Business Modelling Approach.

Structure of the One Pagers for Activities, Methods, and Tools

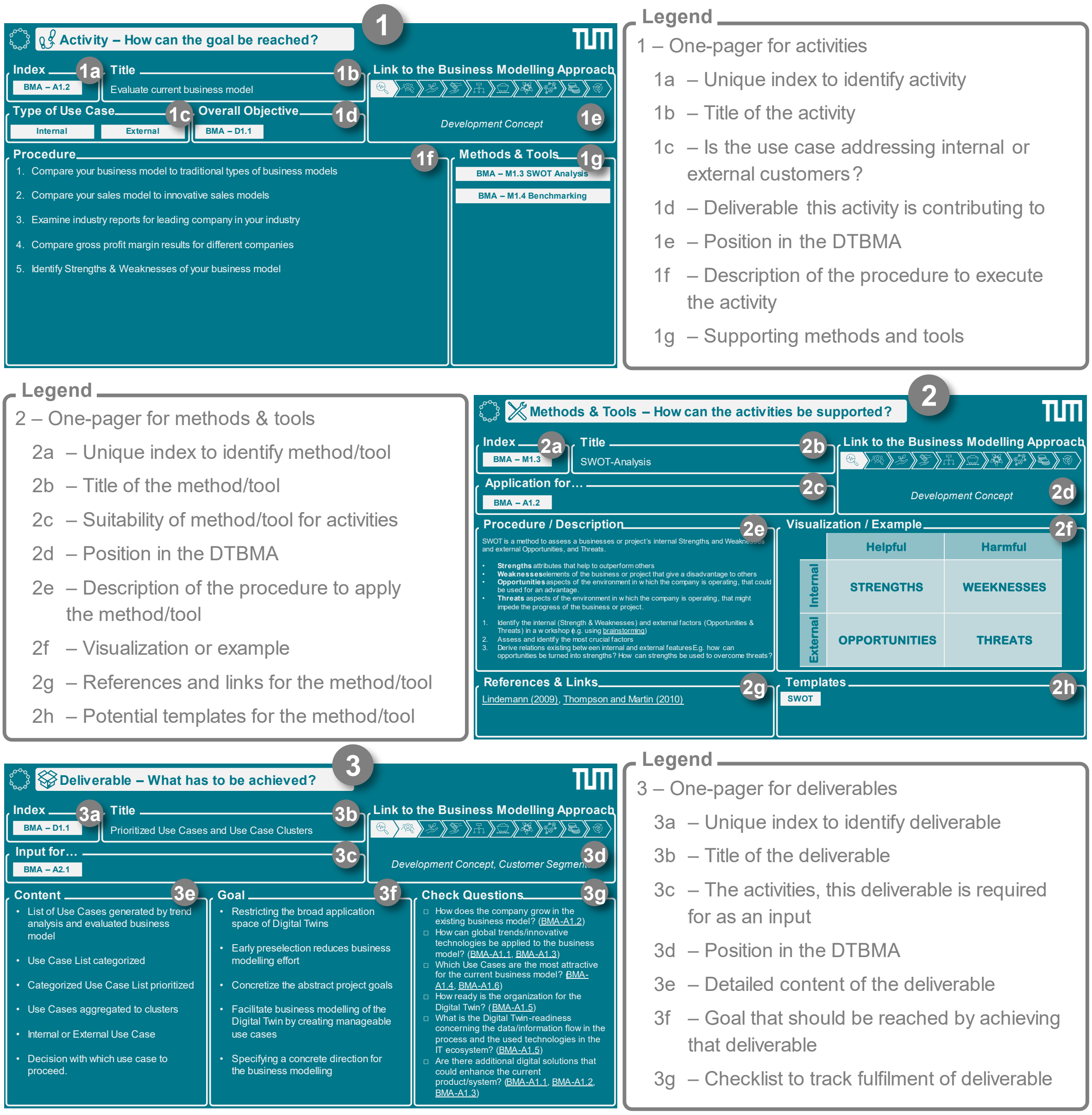


Figure A 139: Overview of the One-Pagers for Activities (Top), Methods 6 Tools (Middle), and Deliverables (Bottom). Exemplarily Shown for Elements of Step 1 – Development Concept.

A8.3 Additional Material of the Digital Twin Value Map

The Digital Twin Value Map

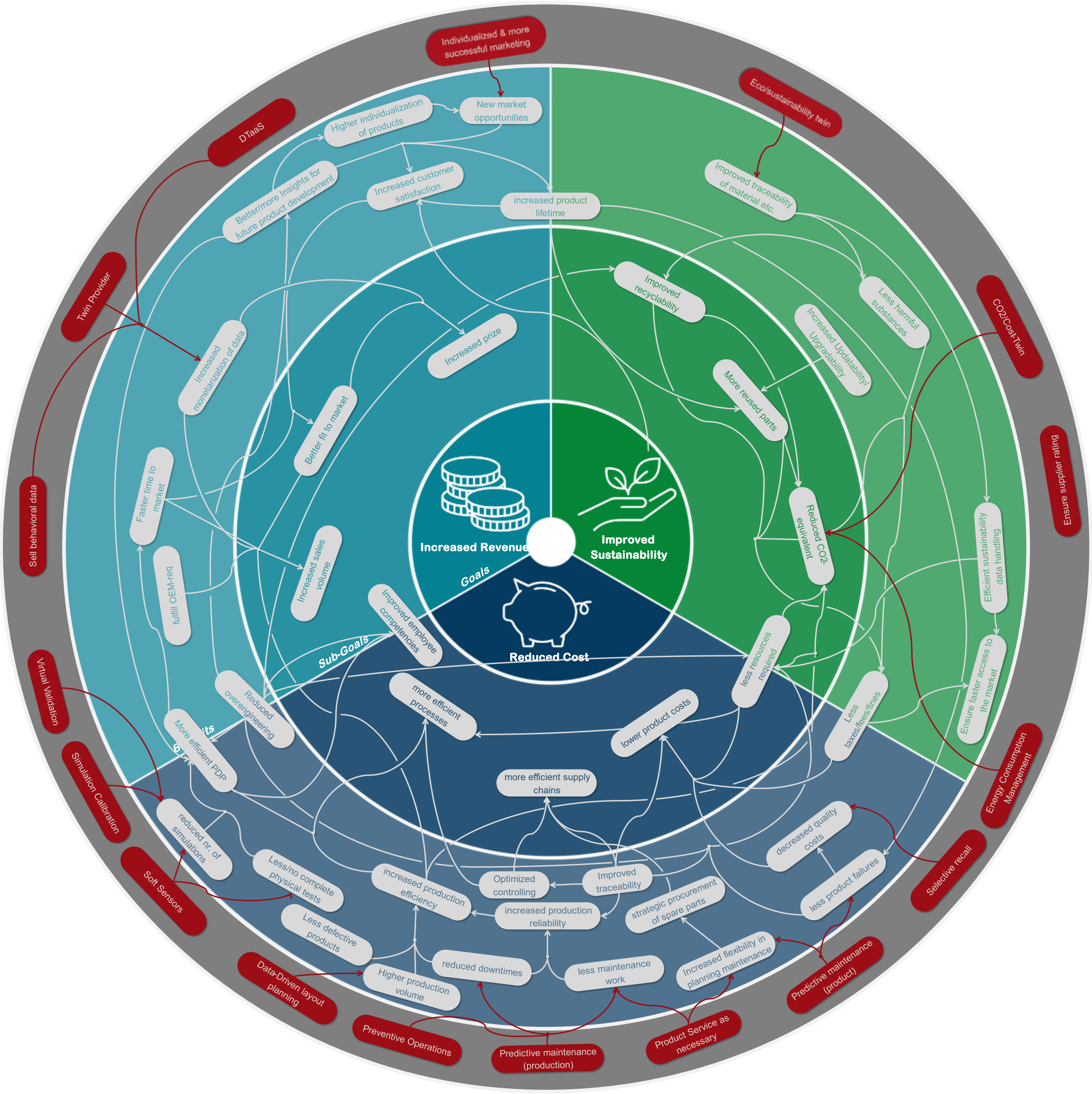


Figure A 140: The Digital Twin Value Map.

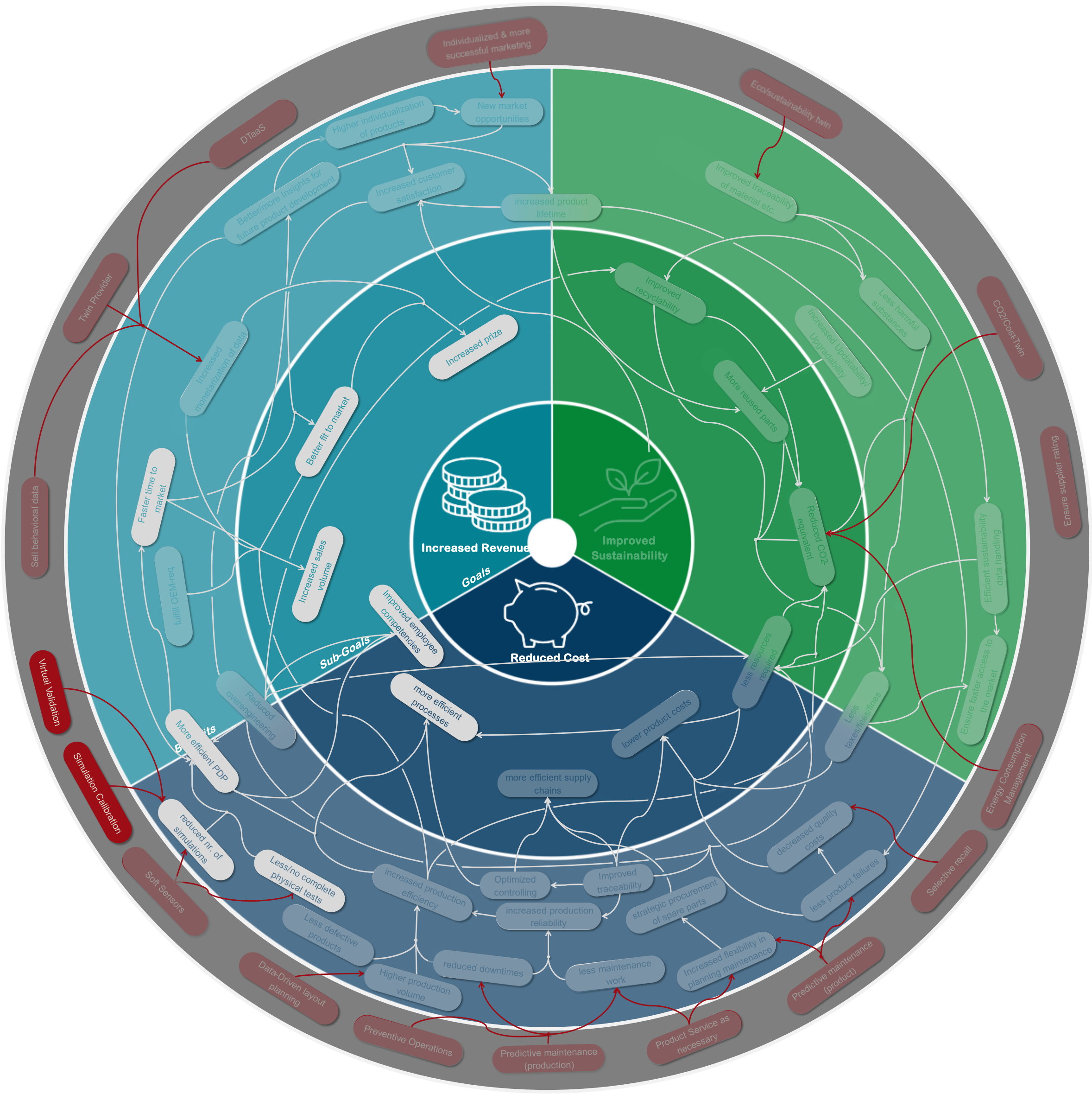


Figure A 141: The Digital Twin Value Map Applied to the Case Study on Engineering Twins Described in Section 4.2.

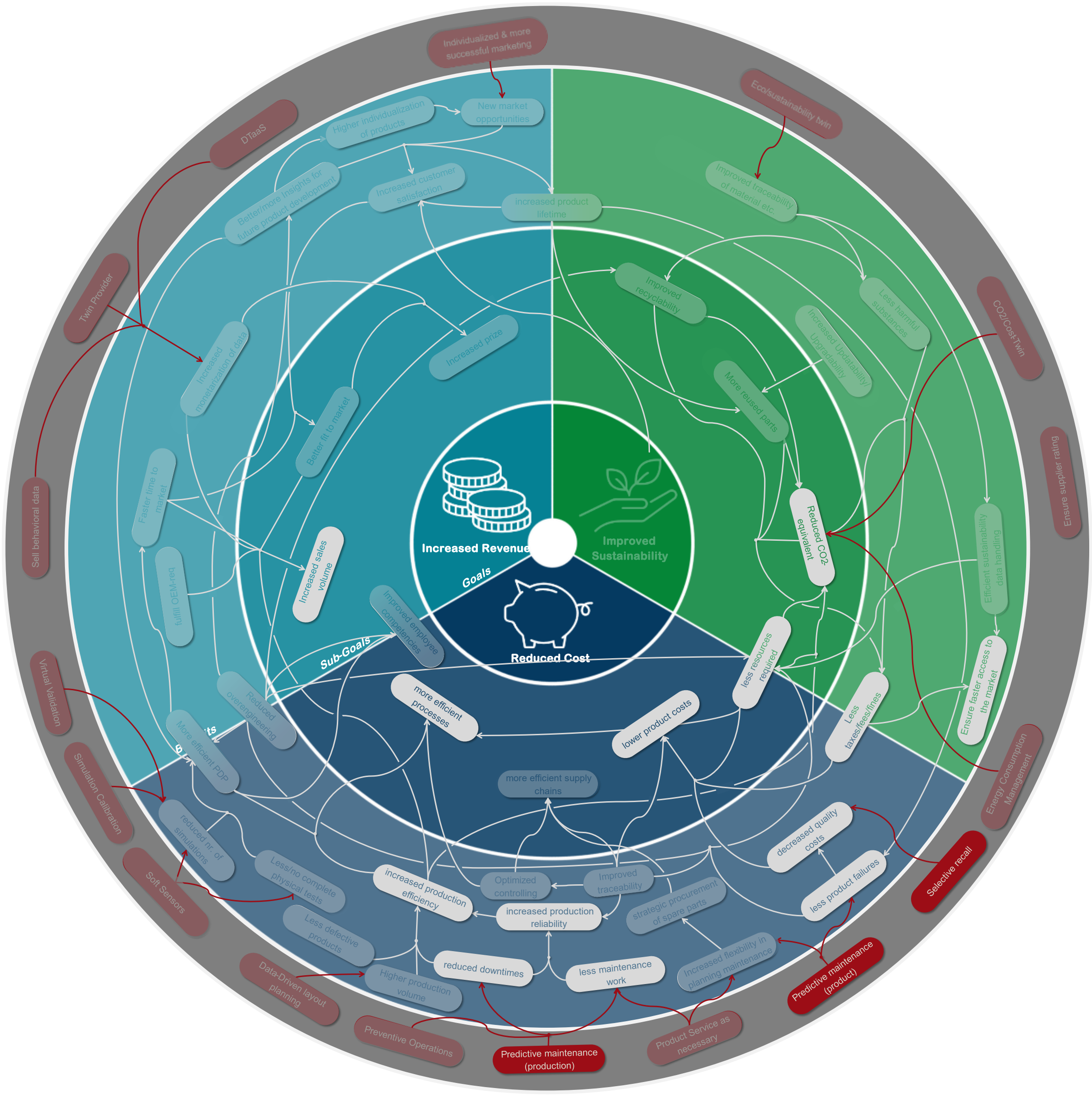


Figure A 142: The Digital Twin Value Map Applied to the Case Study on Production Twins Described in Section 4.3.

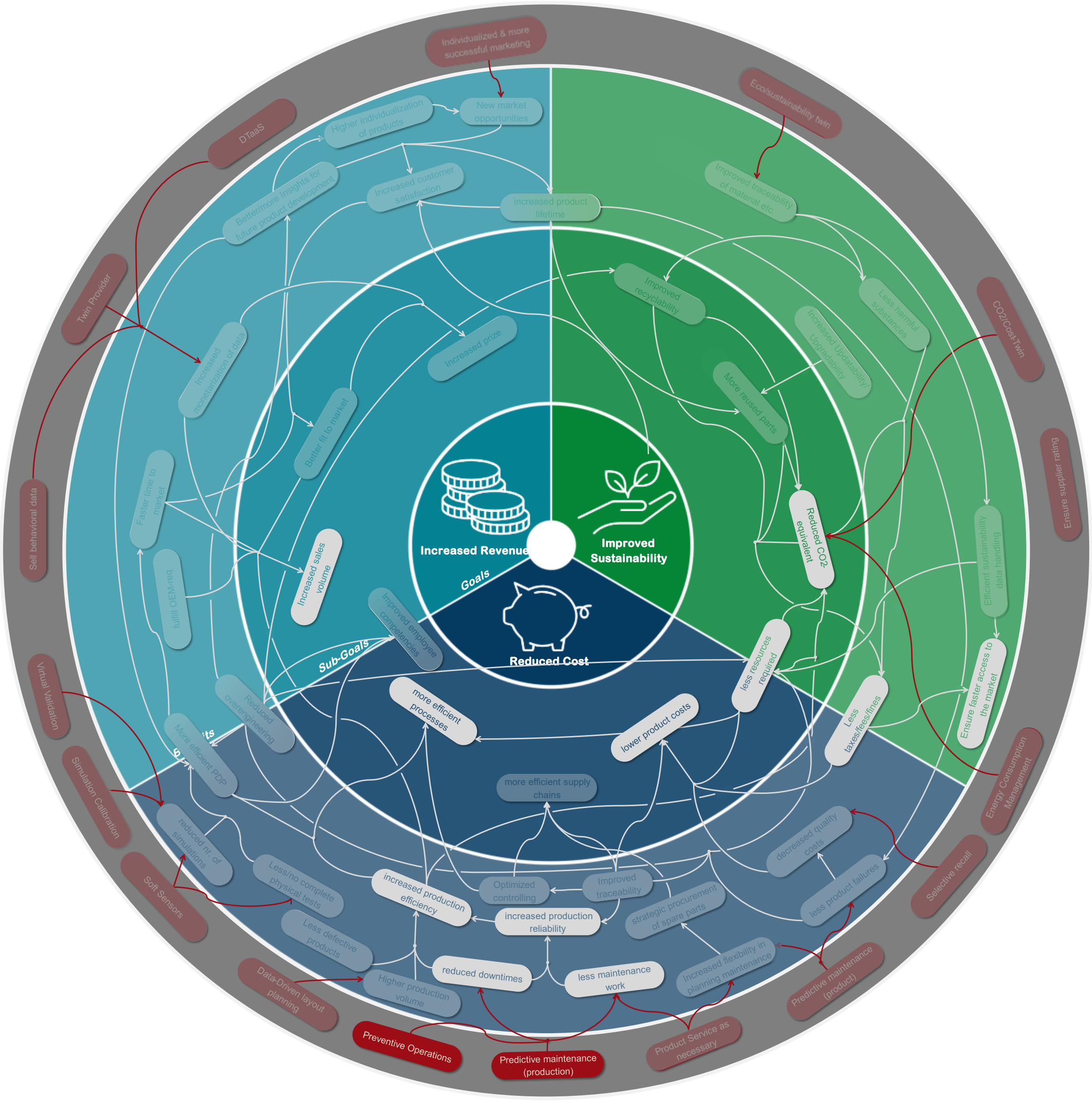


Figure A 143: The Digital Twin Value Map Applied to the Case Study on Operation Twins Described in Section 4.4.

Table A 12: Matrix Showing the Interdependencies Between the Elements of the Digital Twin Value Map. The Numbers Represent the Amount of Indirect and Direct Links Between the Elements.

		Reduced Cost/Time	Improved Revenue	Improved Sustainability	More Efficient Processes	More Efficient Supply Chains	Lower Product Costs	Improved Employee Competencies	Increased Prize	Better Fit To Market	Increased Sales Volume	Less Resources Required	Reduce Co2-equivalent	More Reused Parts	Improved Recyclability	Reduced Nr. Of Simulations	Less/No Physical Tests	More Efficient PDP	Less Defective Products	Higher Production Volume	Increased Production Efficiency	Increased Production Reliability	Optimized Controlling	Improved Traceability	Reduced Downtimes	Less Maintenance Work	Increased Flexibility In Planning Maintenance	Strategic Procurement Of Spare Parts	Decreased Quality Cost	Less Product Failures	Increased Customer Statisfaction	Higher Individualization Of Products	New Market Opportunities	Reduced Overengineering	Better/More Insights For Future PDP	Increased Monetarization Of Data	Faster Time To Market	Fulfill Oem-req	Less Taxes/Fees/Fines	Less Harmful Substances	Increased Product Lifetime	Increased Updatability/Upgradability	Efficient Sustainability Data Handling	Improved Traceability Of Material
Goals	Reduced Cost/Time		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Improved Revenue	0		0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Improved Sustainability	2	4		0	0	1	0	0	4	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
Sub-Goals	More Efficient Processes	4	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	More Efficient Supply Chains	4	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Lower Product Costs	4	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Improved Employee Competencies	4	0	0	0	0	0		0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0
	Increased Prize	0	4	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Better Fit To Market	0	4	0	0	0	0	0	3		3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0
	Increased Sales Volume	0	4	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Less Resources Required	0	0	4	0	0	3	0	0	1	0		3	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	2	0	2	0	0	0	0	0	1	0	1	1	0	0	0	0
	Reduce Co2-equivalent	0	0	4	0	0	0	0	0	1	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	2	0	0	0	0	0
	More Reused Parts	0	0	4	0	0	0	0	0	1	0	0	3		0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	1	1	0	0	0	0
	Improved Recyclability	0	0	4	0	0	0	0	0	1	0	0	3	0		0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	2	1	0	0	1	0
Benefits	Reduced Nr. Of Simulations	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Less/No Physical Tests	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	More Efficient PDP	2	0	0	4	0	0	4	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
	Less Defective Products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Higher Production Volume	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Increased Production Efficiency	2	1	3	4	0	0	0	0	0	4	4	4	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Increased Production Reliability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Optimized Controlling	2	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Improved Traceability	3	0	2	0	4	4	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4	4		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Reduced Downtimes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Less Maintenance Work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Increased Flexibility In Planning Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Strategic Procurement Of Spare Parts	1	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Decreased Quality Cost	1	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Less Product Failures	1	0	2	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Increased Customer Statisfaction	0	3	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0
	Higher Individualization Of Products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		4	0	0	0	0	0	0	0	0	0	0	0
	New Market Opportunities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0		0	0	0	0	0	0	0	0	0	0	0
	Reduced Overengineering	2	0	4	0	0	0	4	0	0	0	4	0	0	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0
	Better/More Insights For Future PDP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	4		0	0	0	0	0	4	0	0	0
	Increased Monetarization Of Data	0	2	0	0	0	0	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
	Faster Time To Market	0	4	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
	Fulfill Oem-req	0	1	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
	Less Taxes/Fees/Fines	1	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0		0	0	0	0	0
	Less Harmful Substances	0	0	5	0	0	0	0	0	0	0	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4		0	0	0	0
	Increased Product Lifetime	0	0	2	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0		0	0	0
	Increased Updatability/Upgradability	0	0	2	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
	Efficient Sustainability Data Handling	1	0	2	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0		0
	Improved Traceability Of Material	0	0	2	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	
Use Cases	Eco/Sustainability Twin	0	0	64	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	CO2/Cost-Twin	192	64	0	16	16	16	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
	Ensure Supplier Rating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Energy Consumption Management	64	192	0	0	0	16	0	0	32	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
	Selective Recall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Predictive Maintenance (product)	128	0	0	0	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Product Service as Necessary	64	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Predictive Maintenance (Production)	64	64	128	16	0	0	0	0	0	16	16	16	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Preventive Operations	64	64	128	16	0	0	0	0	0	16	16	16	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	Data-Driven Layout Planning	64	64	128	16	0	0	0	0	0	16	16	16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Soft Sensors	256	0	0	32	0	0	32	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Simulation Calibration	128	0	0	16	0	0	16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Virtual Validation	256	0	0	32	0	0	32	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Behavioral Data	128	0	0	16	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0
	Twin Provider	0	128	0	0	0	0	0	0	16	16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
	Digital Twin as a Service	128	0	0	16	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0
	Individualized & More Successful Marketing	0	64	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Metrics	Cost Benefit Analysis	128	256	64	16	0	0	16	0	32	32	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1
	Number of Simulations	128	0	0	16	0	0	16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	PHM Damage Index	64	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Customer Satisfaction Score (CSAT)	192	128	256	16	0	0	32	0	32	0	32	0	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0
	Net Promoter Score (NPS)	192	128	256	16	0	0	32	0	32	0	32	0	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0
	Time to Market	128	128	0	16	0	0	16	0	16	16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0
	Overall Equipment Efficiency	256	192	384	48	0	16	0	0	0	48	48	48	0	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Energy Consumption	64	64	64	0	0	16	0	0	16	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
	CO2-Equivalent	128	256	128	0	0	32	0	0	48	16	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	0	1
	Revenue	192	128	128	32	0	0	16	0	16	16	16	16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0
	Mean Time to Repair (MTTR)	128	0	0	0	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mean Time to Failure (MTTF)	64	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mean Time between Failure (MTBF)	64	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Storage Costs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance Cost	64	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Development Lead Time	576	320	192	64	16	0	64	0	48	32	16	0	16	16	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0
	Number of Tests	128	0	0	16	0	0	16	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Inventory Reduction	64	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

A8.4 Additional Material of the Digital Twin Use Case Catalogue

Entry Tickets of the Digital Twin Use Case Catalogue

1. Industry/ Sector

- ❑ Production & Manufacturing
- ❑ Industrial Equipment
- ❑ Automotive
- ❑ Aerospace
- ❑ Energy Production
- ❑ Healthcare
- ❑ Smart Cities
- ❑ Retail
- ❑ Agriculture
- ❑ Education
- ❑ Construction
- ❑ E-Commerce

2. Product Lifecycle Phase

- ❑ Product Planning
- ❑ Development/ Design
- ❑ Work Preparation
- ❑ Product Manufacturing
- ❑ Product Sales
- ❑ Product Use/ Maintenance
- ❑ Product Recycling
- ❑ *Entire Lifecycle*

3. Application Area

- ❑ Design
- ❑ System Integration
- ❑ Diagnostics
- ❑ Prediction
- ❑ Advanced Services
- ❑ Adaptive Field Service
- ❑ Predictive Monitoring Service
- ❑ Maintenance

4. Benefit

- ❑ Increased Efficiency
- ❑ Improved Transparency
- ❑ Reduced Risk
- ❑ Increased Quality
- ❑ More Flexibility
- ❑ Increased Growth/ Revenue

5. Enabling Data

- ❑ Location
- ❑ Condition
- ❑ Availability
- ❑ Usage

Figure A 144: The Digital Twin Quick Check.

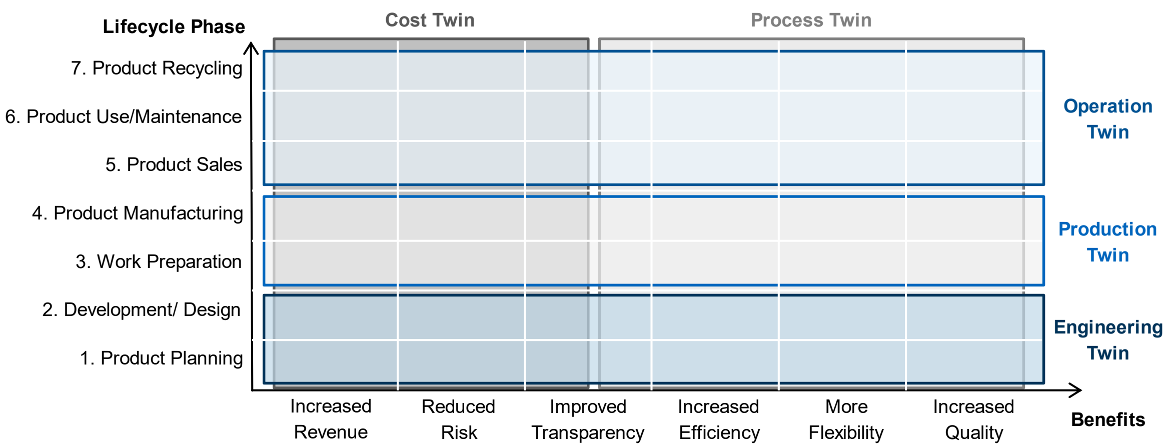


Figure A 145: The Digital Twin Typology Matrix.

Digital Model	Digital Thread	Digital Shadow	Digital Twin	
Descriptive	*Diagnostic*	*Predictive*	*Prescriptive*	Data Analytics Level
Manual	*Manual & Automated*	*Unidirectionally Automated*	*Bidirectionally Automated*	Data Connection Requirement
Monitoring	*Control*	*Optimization*	*Autonomy*	Level of Decision Making
Medium	*Medium - High*	*High*	*Very High*	Effort

Figure A 146: The Digital Twin Maturity Assessment.

Exemplary Selection of Use Cases Using the Entry Tickets

DT Quick Check Characteristics	Select	Specification	Use Cases 1: Image monitoring for illness detection	2: Proactive maintenance based on tracked conditions in Aviation	3: "Real" Environment data for ongoing quality improvements	4: Realtime process-monitoring in Manufacturing	5: Anomaly detection and warning in medical devices	6: Real time information to optimize the engine	7: Realtime performance monitoring of light illumination in Cities	8: Optimize utilization of car-sharing fleet	9: Monitoring of product quality	10: Optimized sales-planning
Industry		Production & Manufacturing	0	0	1	9	9	1	0	0	9	0
		Industrial Equipment	0	0	0	3	0	3	0	3	3	3
	x	Automotive	0	3	9	3	0	9	0	9	9	3
	x	Aerospace	0	9	3	1	0	3	0	3	1	3
		Energy Production	0	0	0	0	0	1	0	1	3	3
		Healthcare	9	0	3	0	0	3	0	0	3	3
		Smart Cities	0	0	0	0	0	1	9	3	0	0
		Retail	0	0	1	3	1	0	0	1	3	3
		Agriculture	0	1	3	0	0	0	1	3	3	0
		Education	0	0	0	0	0	0	1	0	0	0
		Construction	1	0	0	1	0	0	1	1	3	0
		E-Commerce	0	0	0	0	0	0	0	1	3	9
		Industry Score	0	6	6	2	0	6	0	6	5	3
Lifecycle Phase		Product Planning	0	1	1	1	0	3	1	0	1	1
		Development/ Design	0	0	3	3	0	9	3	0	3	3
		Work Preparation	0	0	1	3	0	3	0	0	1	0
	x	Product Manufacturing	0	0	3	9	0	1	0	0	3	0
		Product Sales	3	3	3	0	3	3	0	3	3	9
	x	Product Use/ Maintenance	9	9	3	0	9	3	9	9	3	3
		Product Recycling	0	0	1	0	0	0	3	0	3	0
		Entire Lifecycle	0	0	9	0	0	0	0	0	9	0
		Product Lifecycle Phase Score	4,5	4,5	3	4,5	4,5	2	4,5	4,5	3	1,5
Application Area		Design	0	0	3	0	0	9	0	0	3	0
		System Integration	1	0	1	3	3	3	3	0	3	0
		Diagnostics	9	3	3	3	3	3	9	3	0	0
	x	Prediction	3	3	3	3	3	1	1	0	0	9
		Advanced Services	3	1	0	0	0	0	0	3	9	0
		Adaptive Field Service	0	3	0	0	0	0	3	9	0	3
		Predictive Monitoring Service	0	3	3	9	9	3	3	1	3	3
		Maintenance	0	9	0	3	0	1	0	0	3	0
		Application Area Score	3	3	3	3	3	1	1	0	0	9
Benefit		Increased Efficiency	3	3	3	0	0	9	3	0	3	3
		Improved Transparency	0	0	3	9	3	0	9	3	3	0
	x	Reduced Risk	9	0	0	3	9	3	0	3	1	0
		Increased Quality	3	9	9	0	3	3	0	0	9	0
		More Flexibility	0	0	0	0	0	0	3	9	0	3
		Increased Growth/ Revenue	3	3	3	0	3	0	0	3	3	9
		Benefit Score	9	0	0	3	9	3	0	3	1	0
Enabling Data		Location	3	0	0	3	0	0	3	3	0	0
	x	Condition	9	9	9	9	0	9	9	0	3	9
	x	Availability	0	0	3	3	9	3	3	9	3	0
		Usage	0	3	3	3	3	3	0	3	0	0
		Transmitted Data Score	4,5	4,5	6	6	4,5	6	6	4,5	3	4,5
		Total Score	21	18	18	18,5	21	18	11,5	18	12	18

Most applicable ↑↓ Least Applicable

ID	Name of use-case	Total Score	Relevance
1	Image monitoring for illness detection	21	a: highly relevant
1	Anomaly detection and warning in medical devices (Witlings)	21	b: relevant
3	Realtime process-monitoring in Manufacturing (GE)	18,5	b: relevant
4	Real time information to optimize the engine (Mercedes AMG)	18	b: relevant
4	"Real" Environment data for ongoing quality improvements (Tesla Motors)	18	b: relevant
4	Optimize utilization of car-sharing fleet (BMW)	18	c: applicable
4	Proactive maintenance based on tracked conditions in Aviation	18	c: applicable
4	Optimized sales-planning	18	c: applicable
9	Monitoring of product quality	12	c: applicable
10	Realtime performance monitoring of light illumination in Cities (Philips)	11,5	c: applicable

Update

Press the button to sort the use cases according to their score

Figure A 147: Assessment and Exemplary Selection of the Ten Exemplary Use Cases According to the Entry Ticket "Digital Twin Quick Check".

DT Matrix Typology Characteristics	Select	Specification	Use Cases 1: Image monitoring for illness detection	2: Proactive maintenance based on tracked conditions in Aviation	3: "Real" Environment data for ongoing quality improvements	4: Realtime process-monitoring in Manufacturing	5: Anomaly detection and warning in medical devices	6: Real time information to optimize the engine	7: Realtime performance monitoring of light illumination in Cities	8: Optimize utilization of car-sharing fleet	9: Monitoring of product quality	10: Optimized sales-planning
Product Lifecycle Phase		Product Planning	0	1	1	1	0	3	1	0	1	1
		Development/ Design	0	0	3	3	0	9	3	0	3	3
		Work Preparation	0	0	1	3	0	3	0	0	1	0
	x	Product Manufacturing	0	0	3	9	0	1	0	0	3	0
		Product Sales	3	3	3	0	3	3	0	3	3	9
	x	Product Use/ Maintenance	9	9	3	0	9	3	9	9	3	3
		Product Recycling	0	0	1	0	0	0	3	0	3	0
		Entire Lifecycle	0	0	9	0	0	0	0	0	9	0
		Product Lifecycle Phase Score	4,5	4,5	3	4,5	4,5	2	4,5	4,5	3	1,5
Benefit		Increased Efficiency	3	3	3	0	0	9	3	0	3	3
		Improved Transparency	0	0	3	9	3	0	9	3	3	0
	x	Reduced Risk	9	0	0	3	9	3	0	3	1	0
		Increased Quality	3	9	9	0	3	3	0	0	9	0
		More Flexibility	0	0	0	0	0	0	3	9	0	3
	x	Increased Growth/ Revenue	3	3	3	0	3	0	0	3	3	9
		Benefit Score	6	1,5	1,5	1,5	6	1,5	0	3	2	4,5
		Total Score	10,5	6	4,5	6	10,5	3,5	4,5	7,5	5	6

Most applicable ↑↓ Least Applicable

ID	Name of use-case	Total Score	Relevance
1	Image monitoring for illness detection	10,5	b: relevant
1	Anomaly detection and warning in medical devices (Witlings)	10,5	b: relevant
3	Optimize utilization of car-sharing fleet (BMW)	7,5	b: relevant
4	Proactive maintenance based on tracked conditions in Aviation	6	b: relevant
4	Realtime process-monitoring in Manufacturing (GE)	6	c: applicable
4	Optimized sales-planning	6	c: applicable
7	Monitoring of product quality	5	c: applicable
8	"Real" Environment data for ongoing quality improvements (Tesla Motors)	4,5	c: applicable
8	Realtime performance monitoring of light illumination in Cities (Philips)	4,5	c: applicable
10	Real time information to optimize the engine (Mercedes AMG)	3,5	c: applicable

Update

Press the button to sort the use cases according to their score

Figure A 148: Assessment and Exemplary Selection of the Ten Exemplary Use Cases According to the Entry Ticket "Digital Twin Typology Matrix".

DT Maturity Assessment Characteristics	Select	Specification	Use Cases 1: Image monitoring for illness detection	2: Proactive maintenance based on tracked conditions in Aviation	3: "Real" Environment data for ongoing quality improvements	4: Realtime process-monitoring in Manufacturing	5: Anomaly detection and warning in medical devices	6: Real time information to optimize the engine	7: Realtime performance monitoring of light illumination in Cities	8: Optimize utilization of car-sharing fleet	9: Monitoring of product quality	10: Optimized sales-planning
Data Analytics Level	x	Descriptive	0	0	1	0	0	1	0	1	1	0
		Diagnostic	0	0	3	0	0	3	0	3	3	0
		Predictive	3	3	0	3	3	0	3	0	0	0
		Prescriptive	0	0	0	0	0	0	0	0	0	3
		Data Analytics Level Score	0	0	1	0	0	1	0	1	1	0
Data Connection Requirement		Manual	0	0	0	3	0	0	3	0	3	3
		Manual & Automated	0	0	0	9	0	0	9	0	9	9
		Unidirectional & Automated	9	1	1	0	9	9	0	9	0	0
	x	Bidirectional & Automated	0	9	9	0	1	1	0	1	0	0
		Data Connection Requirement Score	0	9	9	0	1	1	0	1	0	0
Level of Decision Making		Monitoring	3	0	0	0	0	3	1	1	3	0
		Control	0	1	1	0	1	0	3	3	0	0
	x	Optimization	0	3	3	0	3	0	0	0	0	3
		Autonomy	0	0	0	3	0	0	0	0	0	0
		Level of Decision Making Score	0	3	3	0	3	0	0	0	0	3
Transformational Effort		Medium	0	0	0	3	0	0	3	0	3	3
		Medium-High	0	0	0	9	0	0	9	0	9	9
	x	High	9	1	1	1	9	9	3	9	0	0
		Very High	0	9	9	0	1	1	0	1	0	0
		Transformational Effort Score	9	1	1	1	9	9	3	9	0	0
		Total Score	9	13	14	1	13	11	3	11	1	3

	ID	Name of use-case	Total Score	Relevance
Most applicable	1	"Real" Environment data for ongoing quality improvements (Tesla)	14	a: highly relevant
	2	Proactive maintenance based on tracked conditions in Aviation	13	b: relevant
	2	Anomaly detection and warning in medical devices (Witlings)	13	b: relevant
	4	Real time information to optimize the engine (AMG)	11	b: relevant
	4	Optimize utilization of car-sharing fleet (BMW)	11	b: relevant
	6	Image monitoring for illness detection	9	c: applicable
	7	Optimized sales-planning	3	c: applicable
	7	Realtime performance monitoring of light illumination in Cities (Philips)	3	c: applicable
	9	Realtime process-monitoring in Manufacturing (GE)	1	c: applicable
Least Applicable	9	Monitoring of product quality	1	c: applicable

Update

Press the button to sort the use cases according to their score

Figure A 149: Assessment and Exemplary Selection of the Ten Exemplary Use Cases According to the Entry Ticket "Digital Twin Maturity Assessment".

A8.5 Additional Material of the Digital Twin Use Case Template

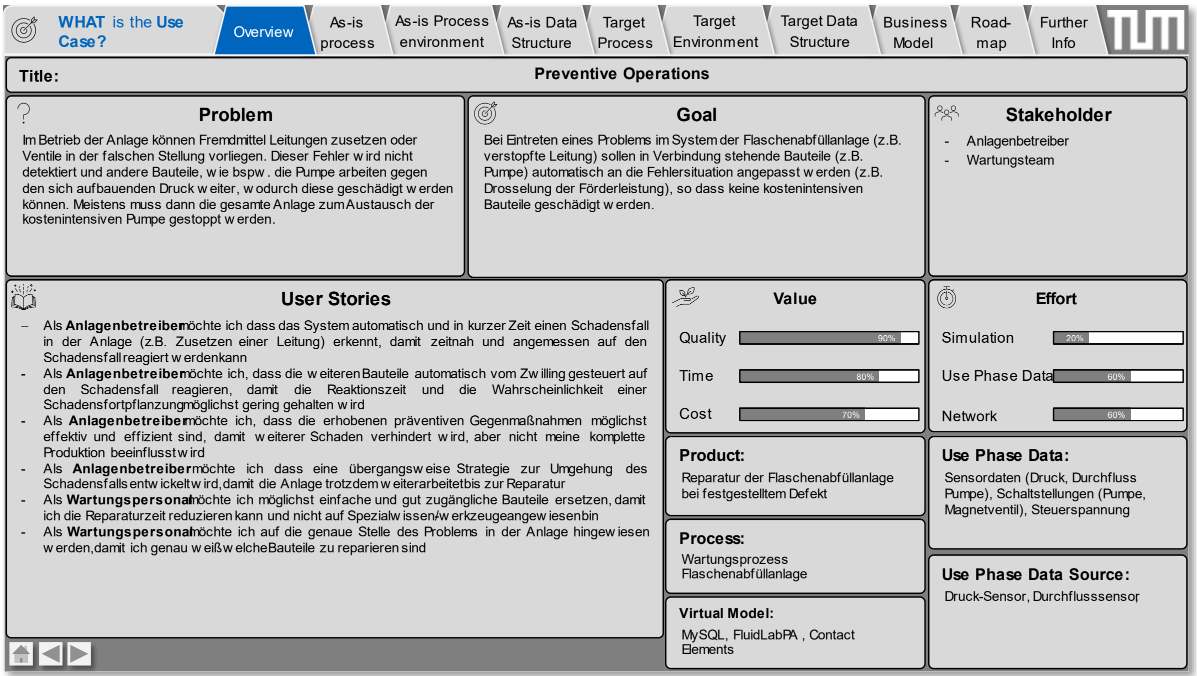


Figure A 150: "Overview"-Page of the Digital Twin Use Case Template. This Page is Relevant to all Subtypes of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

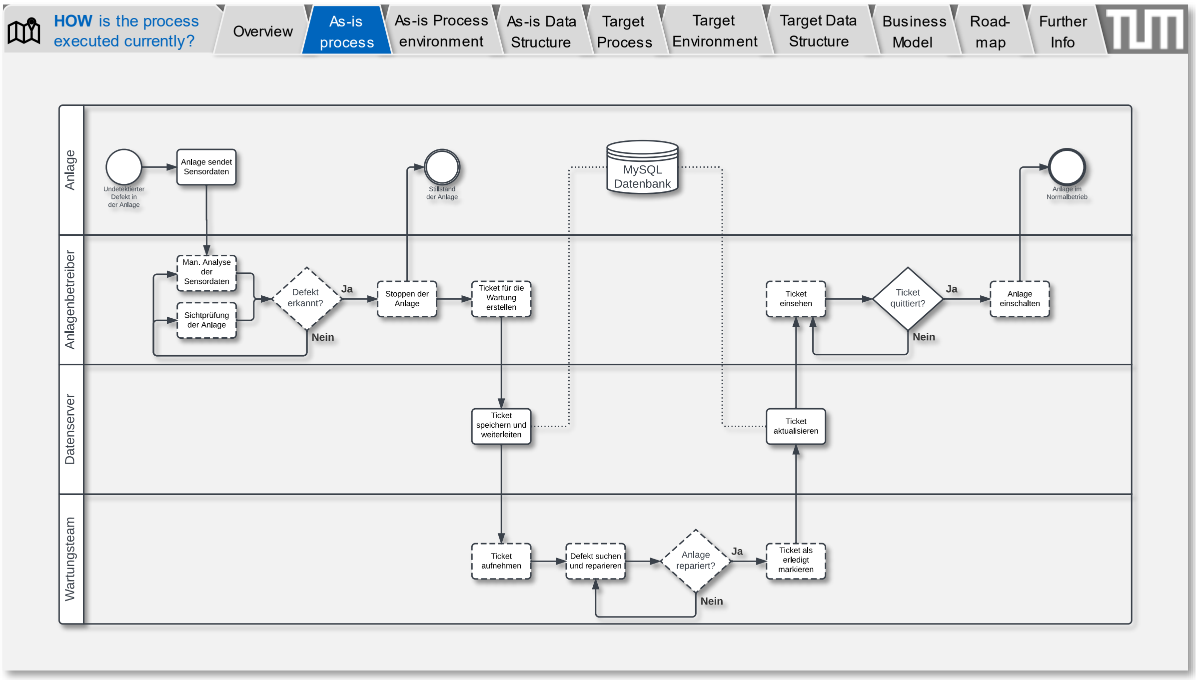


Figure A 151: "As-Is Process"-Page of the Digital Twin Use Case Template. This Page is Relevant to all Sub-types of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

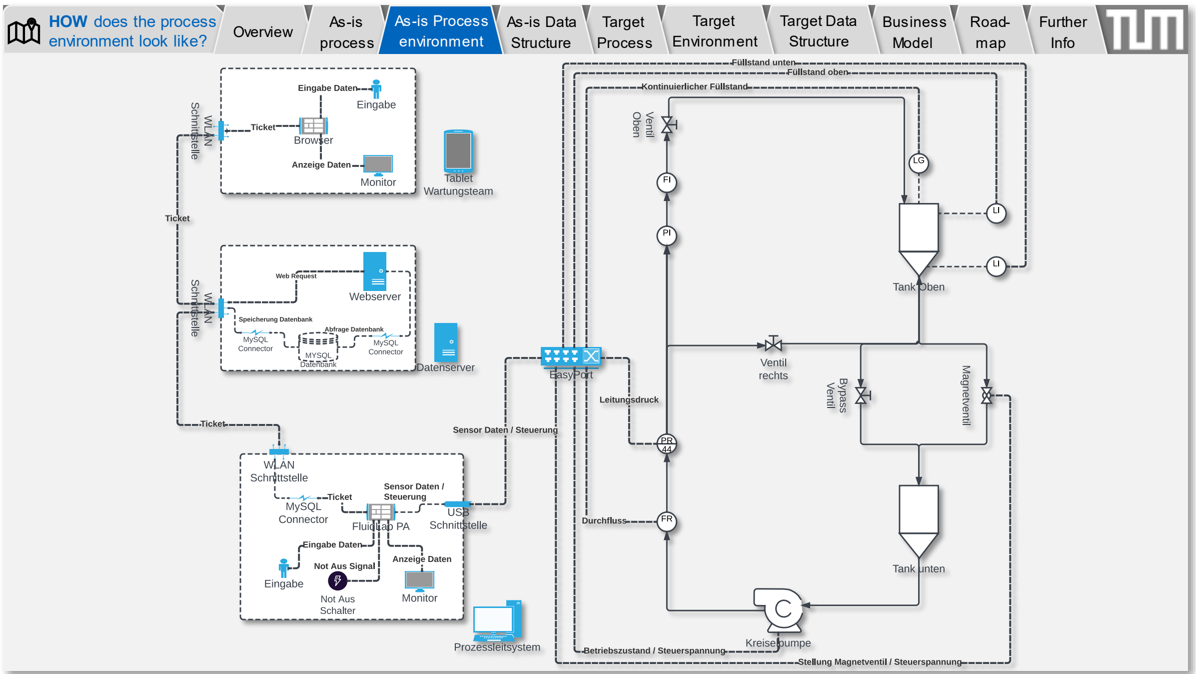


Figure A 152: "As-Is Process Environment"-Page of the Digital Twin Use Case Template. This Page is only Relevant for Production and Operation Twins – not for Engineering Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

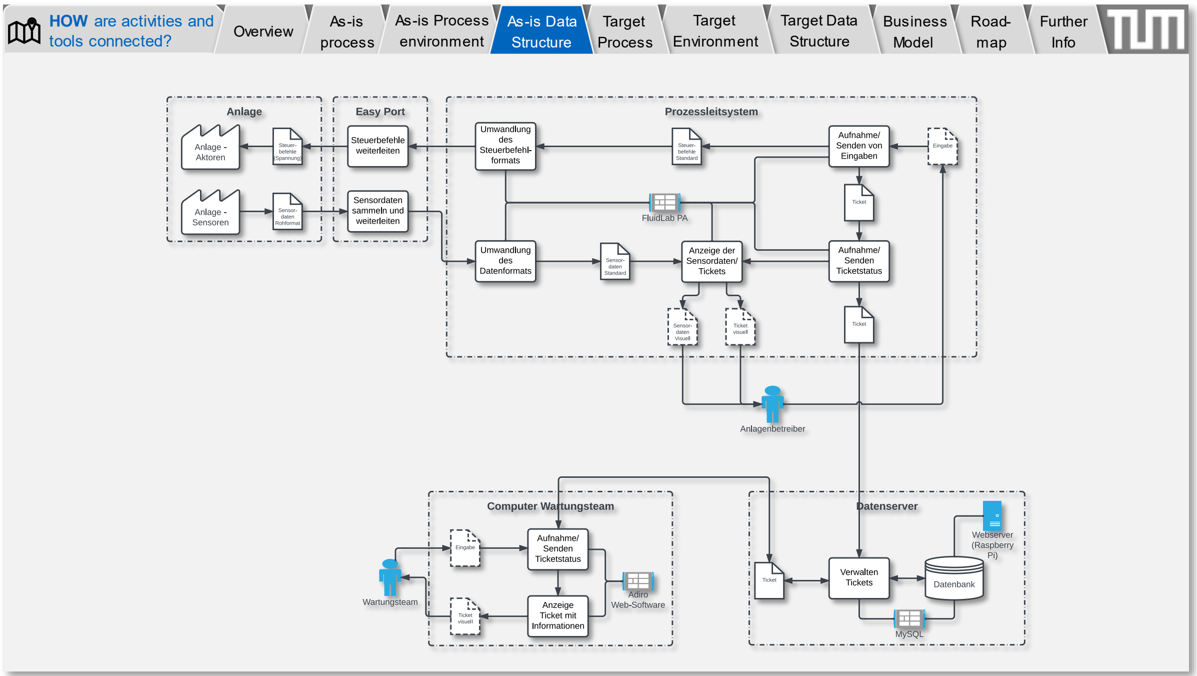


Figure A 153: "As-Is Data Structure"-Page of the Digital Twin Use Case Template. This Page is Relevant to all Subtypes of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

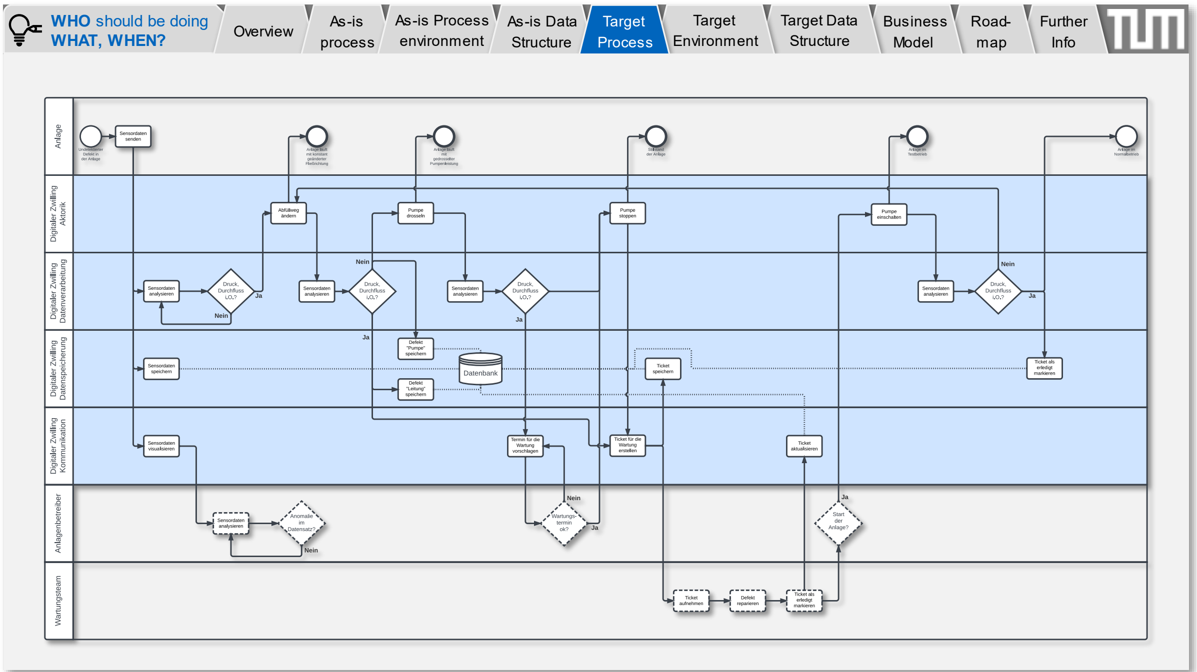


Figure A 154: "Target Process"-Page of the Digital Twin Use Case Template. This Page is Relevant to all Subtypes of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

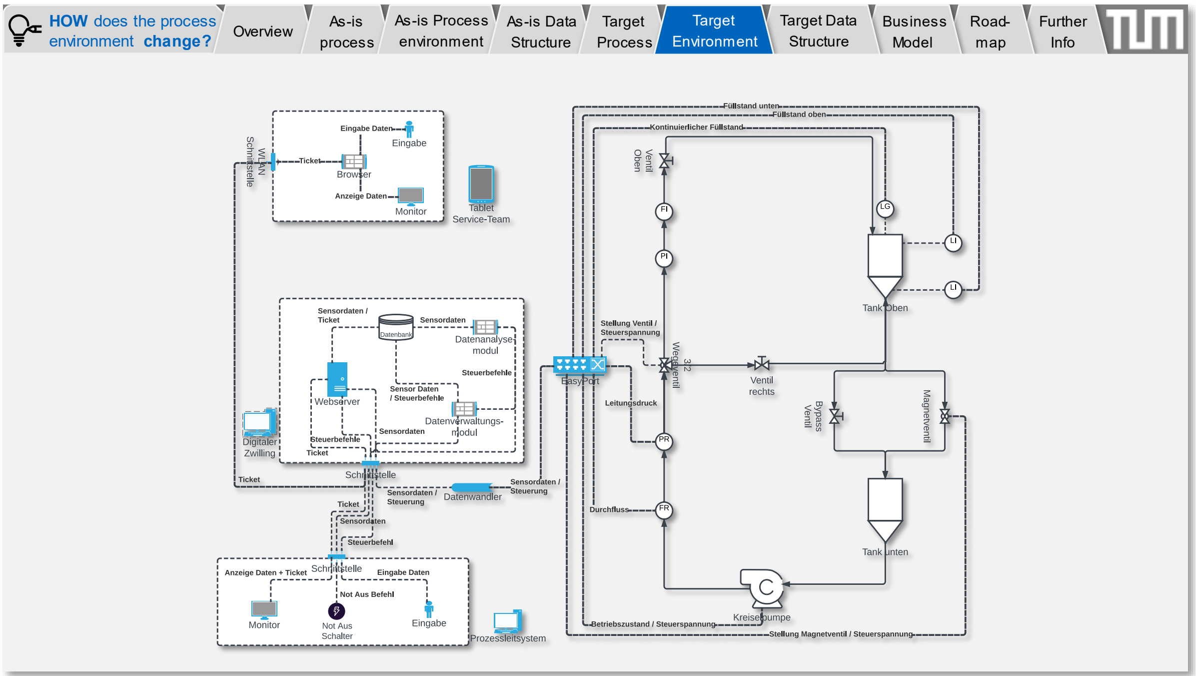


Figure A 155: *"Target Process Environment"-Page of the Digital Twin Use Case Template. This Page is only Relevant for Production and Operation Twins – not for Engineering Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.*

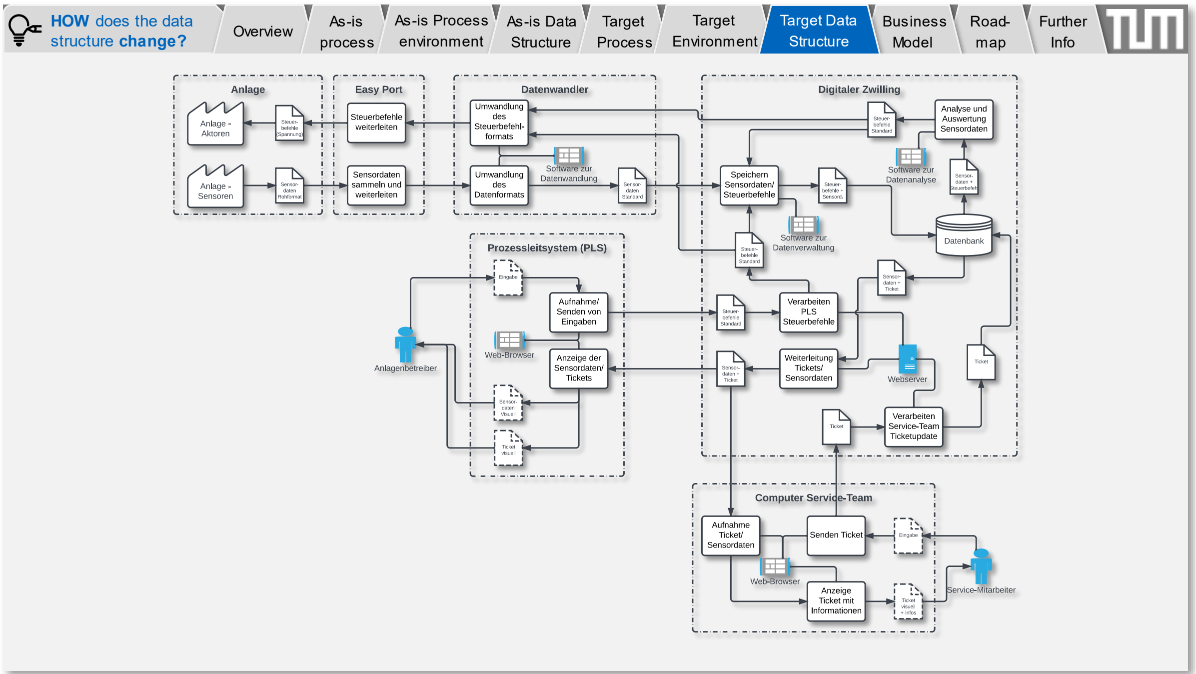


Figure A 156: *"Target Data Structure"-Page of the Digital Twin Use Case Template. This Page is Relevant to all Subtypes of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.*

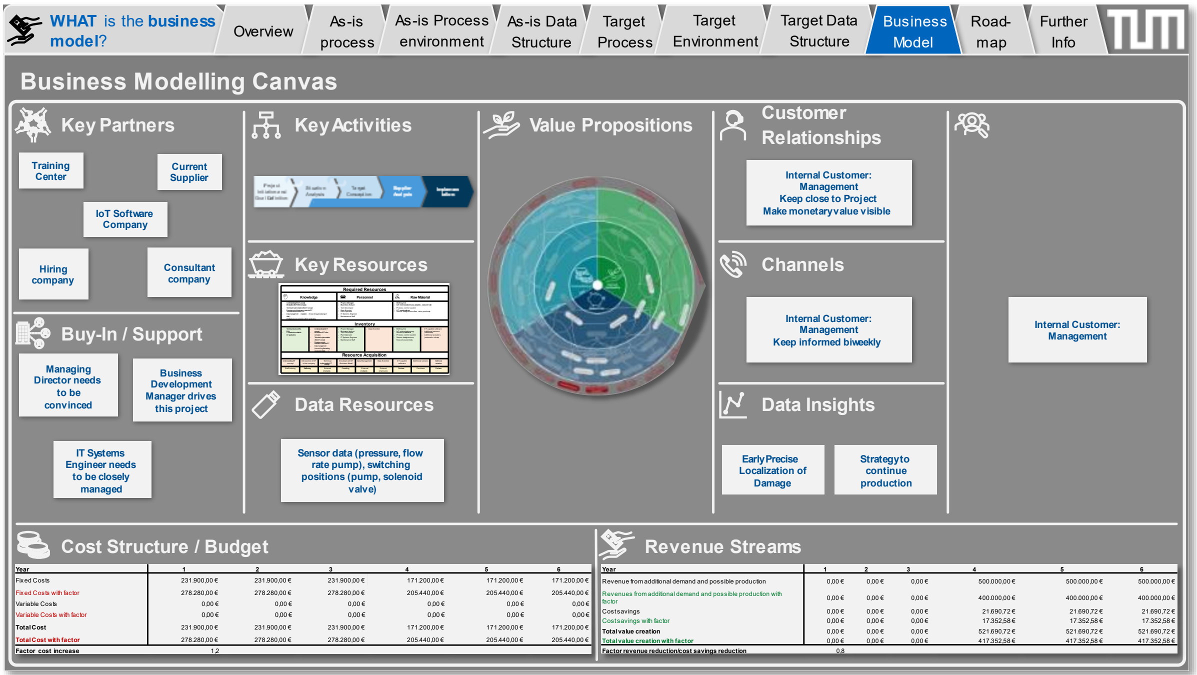


Figure A 157: "Business Model"-Page of the Digital Twin Use Case Template. This Page is Relevant to all Subtypes of Digital Twins. Instructions on How to Fill it can be Found in the Digital Twin Business Modelling Approach (cf. Section 6.2.2). Instantiated for the Academic Case Study on the Bottle Filling Machine.

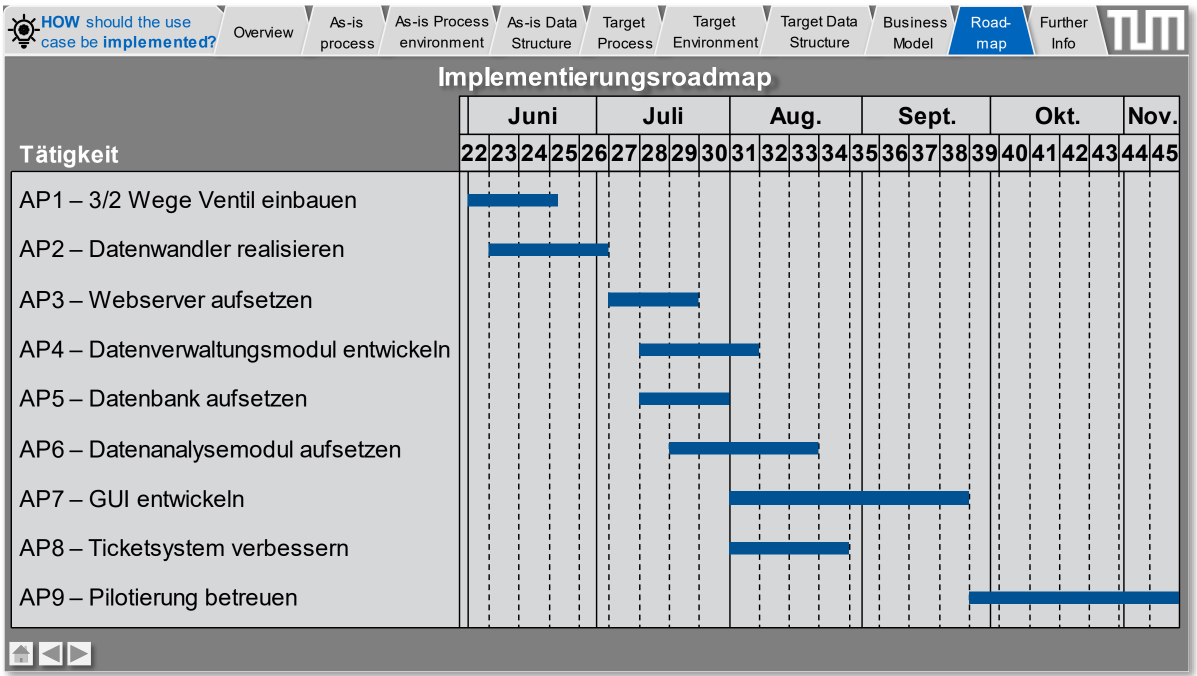


Figure A 158: Template for the Implementation Roadmap. This Page is Relevant to all Subtypes of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

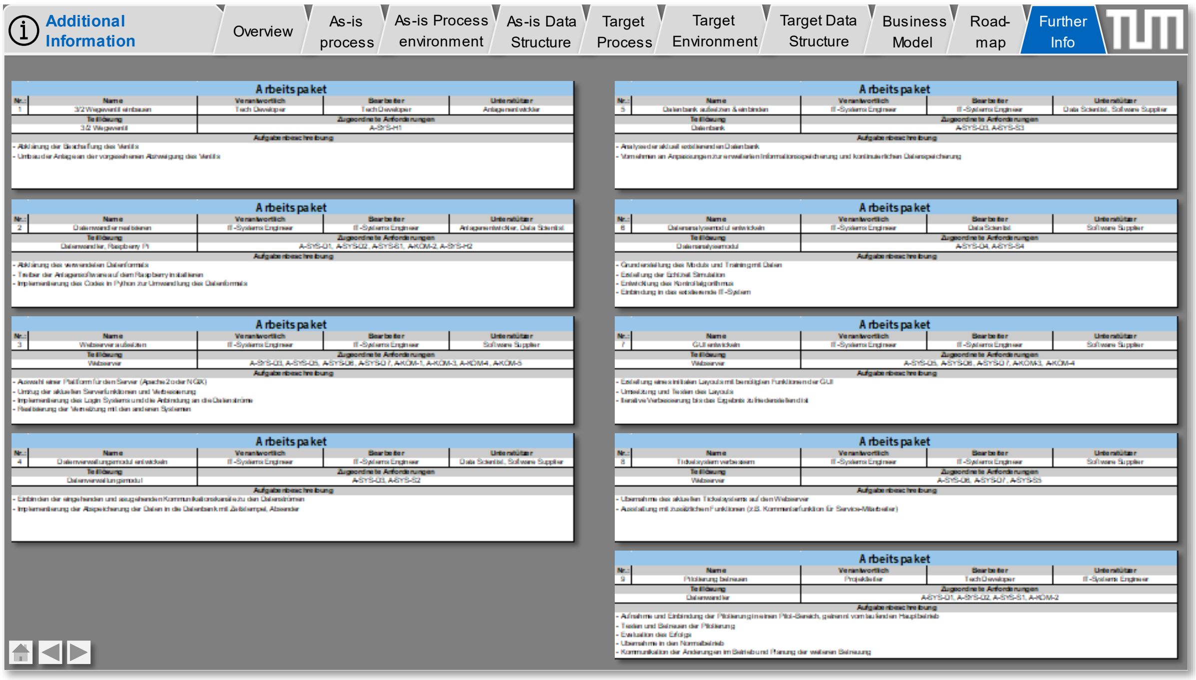


Figure A 159: Additional Information to be Collected for the Digital Twin Use Case Template. This Page is Relevant to all Subtypes of Digital Twins. Instantiated for the Academic Case Study on the Bottle Filling Machine.

A8.6 Additional Material of the Digital Twin Trust Framework

Legend of the Digital Twin Trust Framework Handbook

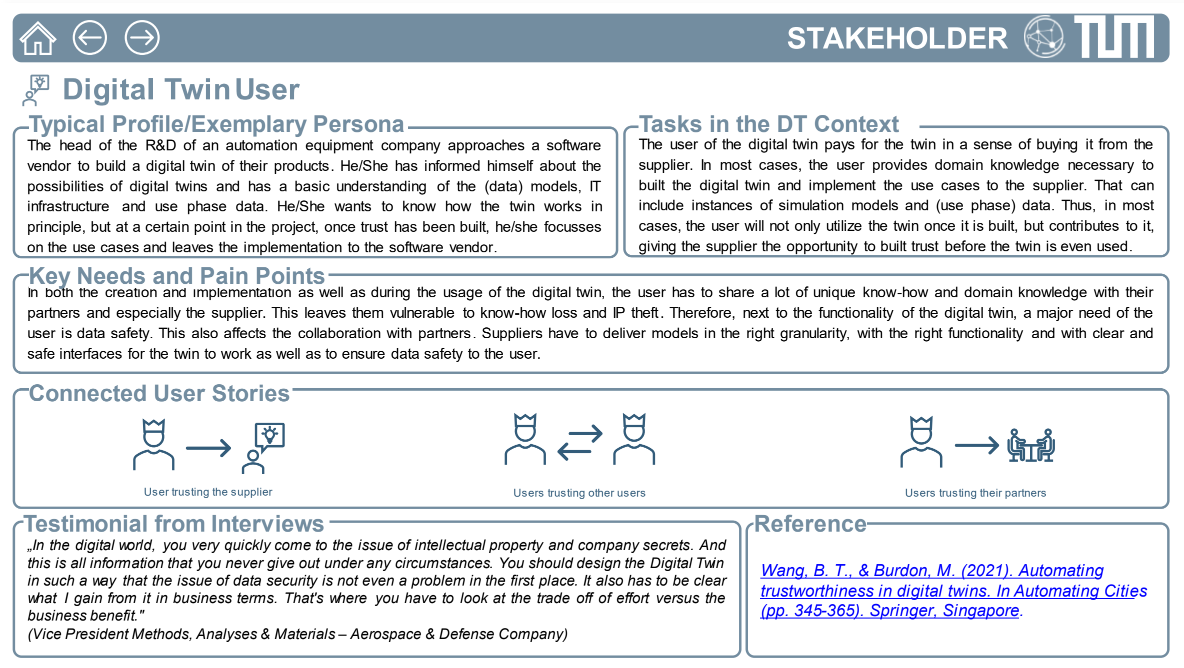


Figure A 160: The Description of the Stakeholder “Digital Twin User”.

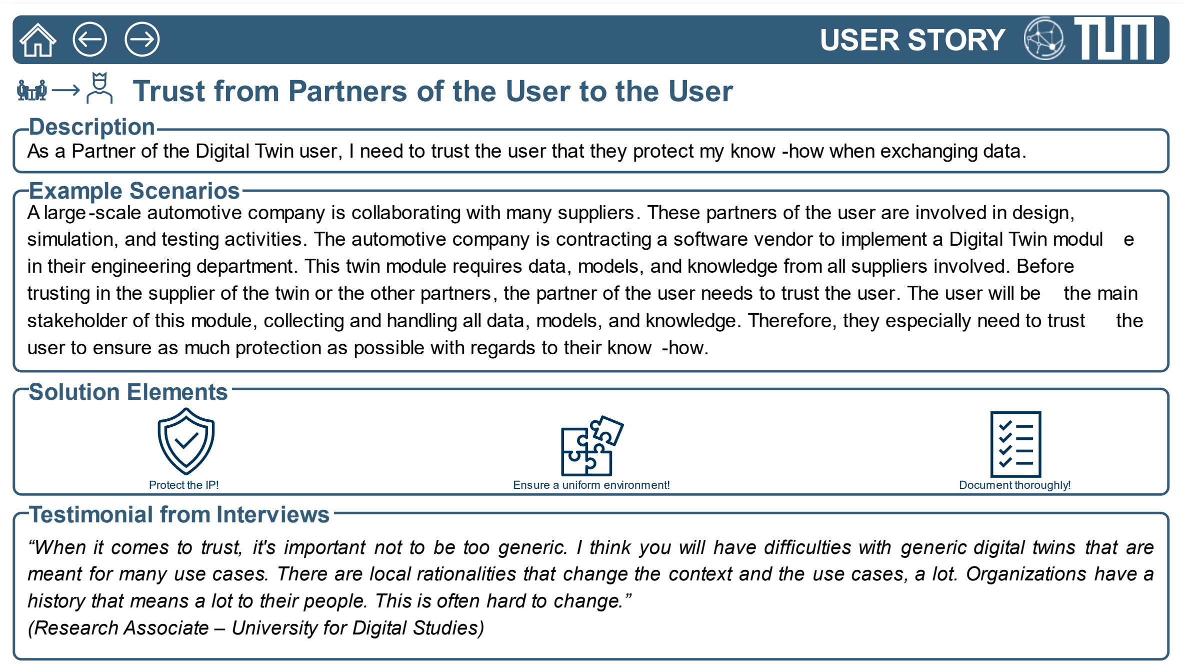


Figure A 161: The Description of the User Story “Trust from Partners of the User to the User”.

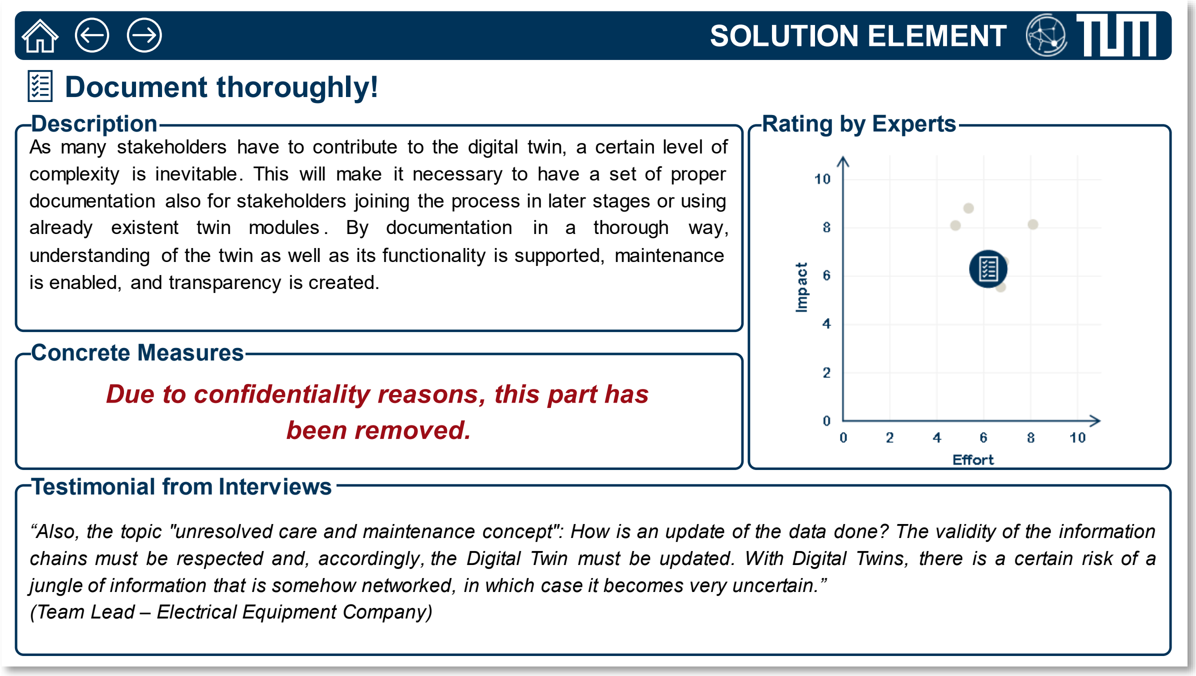


Figure A 162: The Description of the Solution Element "Document Thoroughly". Concrete Measures have been Removed Due to Confidentiality Reasons.

Pairwise Comparison of the Solution Elements with Respect to User Stories

DT suppliers trusting their users

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		-1	1	0	1	1	-1	1	3	58%	3	4
	1		1	1	1	1	0	5	1	92%	4	8
	-1	-1		1	1	1	-1	0	4	50%	2	2
	0	-1	-1		1	1	-1	-1	5	42%	2	2
	-1	-1	-1	-1		-1	-1	-6	7	0%	1	1
	-1	-1	-1	-1	1		-1	-4	6	17%	1	1
	1	0	1	1	1	1		5	1	92%	4	8

DT suppliers trusting other suppliers

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		1	1	-1	-1	-1	0	-1	4	42%	2	2
	-1		-1	-1	-1	-1	-1	-6	7	0%	1	1
	-1	1		-1	-1	-1	-1	-4	6	17%	1	1
	1	1	1		1	1	1	6	1	100%	4	8
	1	1	1	-1		-1	1	2	3	67%	3	4
	1	1	1	-1	1		1	4	2	83%	3	4
	0	1	1	-1	-1	-1		-1	4	42%	2	2

DT suppliers trusting partners of the user

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		1	1	-1	-1	-1	-1	-2	5	33%	2	2
	-1		0	-1	-1	-1	-1	-5	7	8%	1	1
	-1	0		-1	-1	-1	0	-4	6	17%	1	1
	1	1	1		0	0	1	4	1	83%	4	8
	1	1	1	0		0	1	4	1	83%	4	8
	1	1	1	0	0		1	4	1	83%	4	8
	1	1	0	-1	-1	-1		-1	4	42%	2	2

Figure A 163: Pairwise Comparison of the Suitability of Solution Elements with Respect to DT Supplier Induced User Stories.

Users trusting their DT suppliers

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		-1	0	0	1	1	0	1	3	58%	3	4
	1		1	1	0	1	1	5	1	92%	4	8
	0	-1		0	-1	1	1	0	5	50%	2	2
	0	-1	0		0	1	1	1	3	58%	3	4
	-1	0	1	0		1	1	2	2	67%	3	4
	-1	-1	-1	-1	-1		-1	-6	7	0%	1	1
	0	-1	-1	-1	-1	1		-3	6	25%	1	1

Users trusting other users

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		1	1	1	1	0	-1	3	2	75%	3	4
	-1		0	1	1	0	-1	0	5	50%	2	2
	-1	0		1	1	0	0	1	4	58%	2	2
	-1	-1	-1		0	-1	-1	-5	6	8%	1	1
	-1	-1	-1	0		-1	-1	-5	6	8%	1	1
	0	0	0	1	1		0	2	3	67%	3	4
	1	1	0	1	1	0		4	1	83%	4	8

Users trusting their partners

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		-1	-1	1	-1	-1	0	-3	6	25%	1	1
	1		1	0	1	1	1	5	1	92%	4	8
	1	-1		0	1	1	0	2	2	67%	3	4
	-1	0	0		-1	1	1	0	4	50%	2	2
	1	-1	-1	1		1	0	1	3	58%	3	4
	1	-1	-1	-1	-1		0	-3	6	25%	1	1
	0	-1	0	-1	0	0		-2	5	33%	2	2

Figure A 164: Pairwise Comparison of the Suitability of Solution Elements with Respect to DT User Induced User Stories.

Partners of the users trusting the suppliers

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		1	-1	-1	-1	-1	1	-2	4	33%	2	2
	-1		1	-1	-1	-1	1	-2	4	33%	2	2
	1	-1		-1	-1	-1	1	-2	4	33%	2	2
	1	1	1		1	0	1	5	1	92%	4	8
	1	1	1	-1		0	1	3	3	75%	3	4
	1	1	1	0	0		1	4	2	83%	3	4
	-1	-1	-1	-1	-1	-1		-6	7	0%	1	1

partners of the user trusting other partners

-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		1	1	0	1	-1	-1	1	4	58%	2	2
	-1		-1	-1	0	-1	-1	-5	7	8%	1	1
	-1	1		-1	-1	-1	-1	-4	6	17%	1	1
	0	1	1		1	0	1	4	2	83%	3	4
	-1	0	1	-1		-1	-1	-3	5	25%	2	2
	1	1	1	0	1		1	5	1	92%	4	8
	1	1	1	-1	1	-1		2	3	67%	3	4

Partners of the user trusting the user

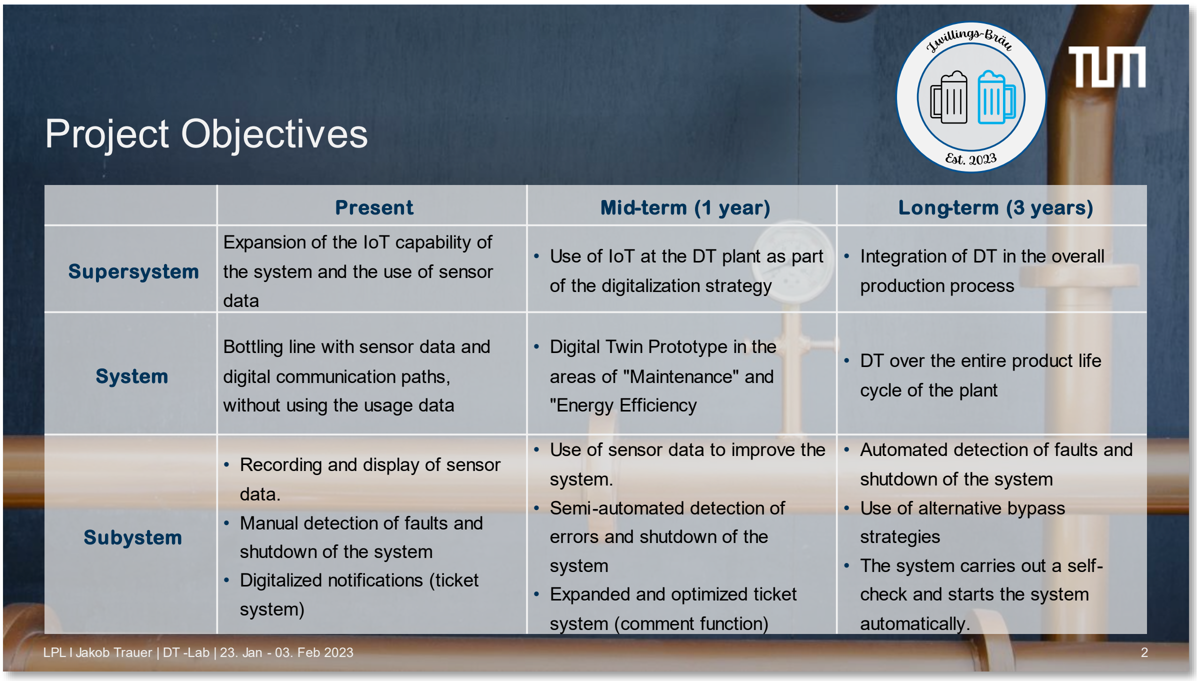
-1: schlechter 0: gleich 1: besser								Sum	Rank	Score	Points - lin	Points - prog
		0	1	-1	1	1	0	2	2	67%	3	4
	0		1	-1	1	0	1	2	2	67%	3	4
	-1	-1		-1	1	1	1	0	4	50%	2	2
	1	1	1		1	1	0	5	1	92%	4	8
	-1	-1	-1	-1		1	0	-3	6	25%	1	1
	-1	0	-1	-1	-1		-1	-5	7	8%	1	1
	0	-1	-1	0	0	1		-1	5	42%	2	2

Figure A 165: Pairwise Comparison of the Suitability of Solution Elements with Respect to User Stories Induced by the Partners of the User.

A9 Additional Material on the Initial Evaluation of the Solution Approach

A9.1 Task Description

Figure A 166: General Description of the Company “Zwillingsbräu GmbH”.



	Present	Mid-term (1 year)	Long-term (3 years)
Supersystem	Expansion of the IoT capability of the system and the use of sensor data	• Use of IoT at the DT plant as part of the digitalization strategy	• Integration of DT in the overall production process
System	Bottling line with sensor data and digital communication paths, without using the usage data	• Digital Twin Prototype in the areas of "Maintenance" and "Energy Efficiency	• DT over the entire product life cycle of the plant
Subystem	• Recording and display of sensor data. • Manual detection of faults and shutdown of the system • Digitalized notifications (ticket system)	• Use of sensor data to improve the system. • Semi-automated detection of errors and shutdown of the system • Expanded and optimized ticket system (comment function)	• Automated detection of faults and shutdown of the system • Use of alternative bypass strategies • The system carries out a self-check and starts the system automatically.

Figure A 167: Fictional Project Objectives of the Company.

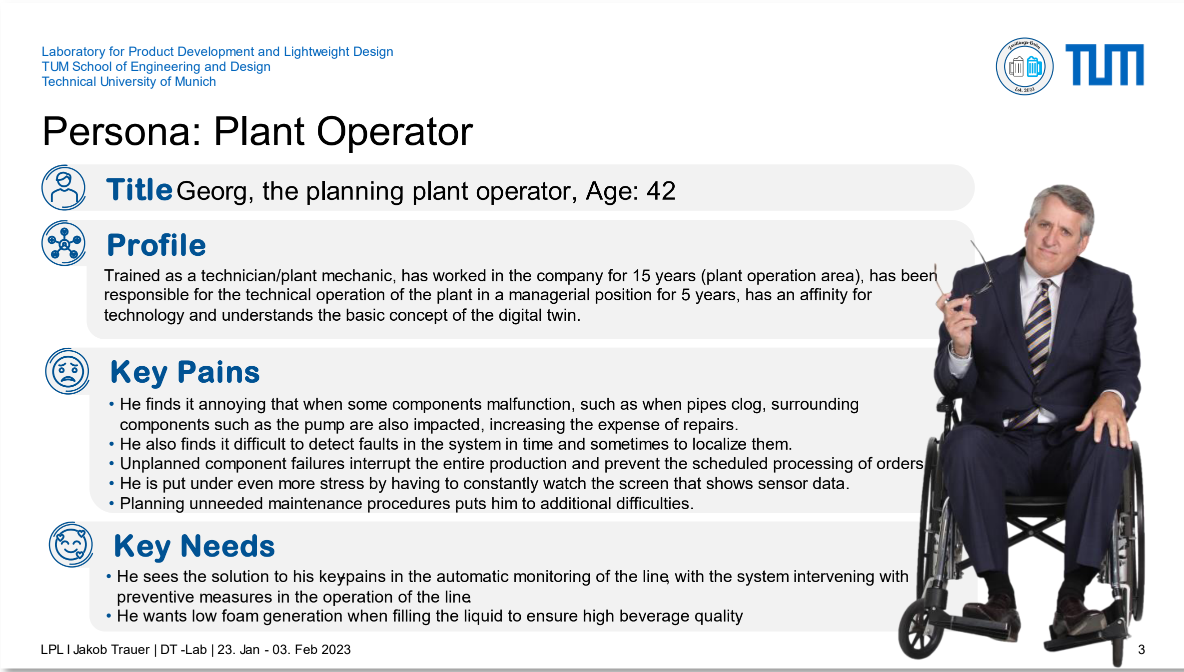


Figure A 168: Persona of the "Plant Operator".

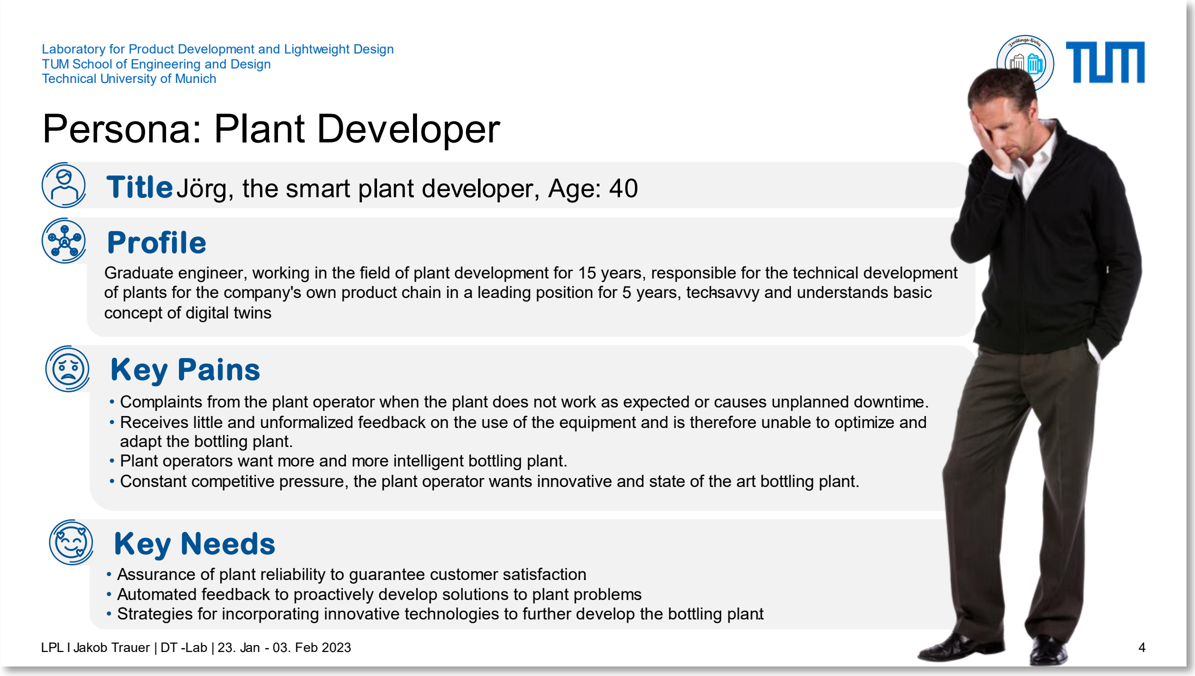


Figure A 169: Persona of the "Plant Developer".

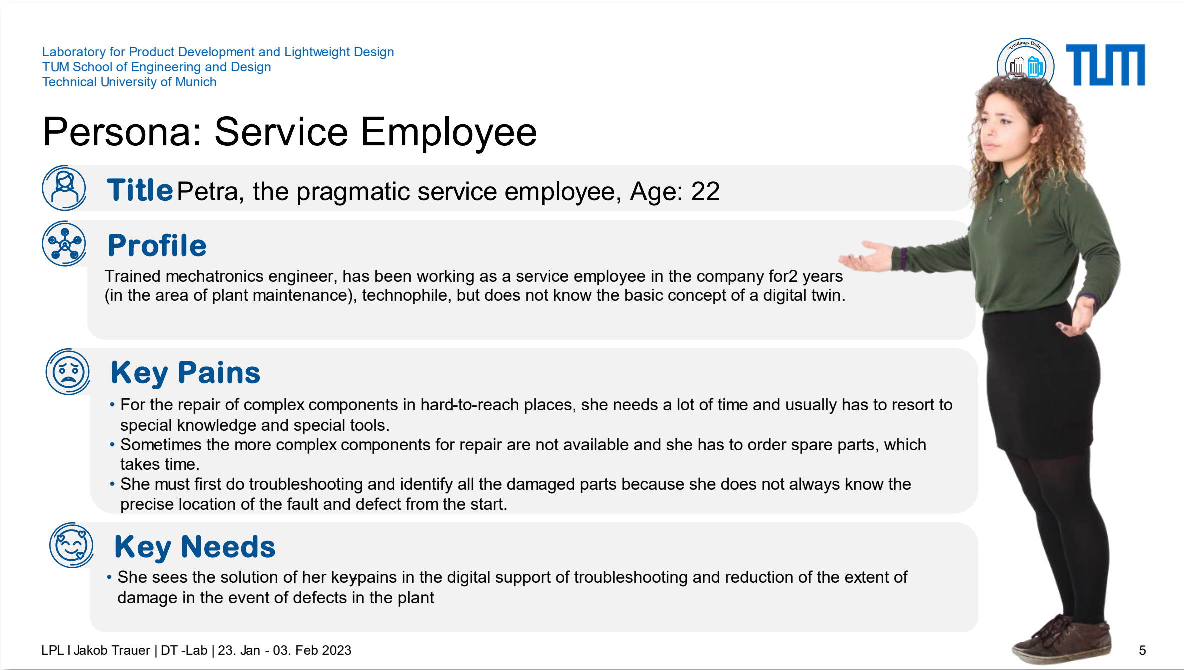


Figure A 170: Persona of the "Service Employee".

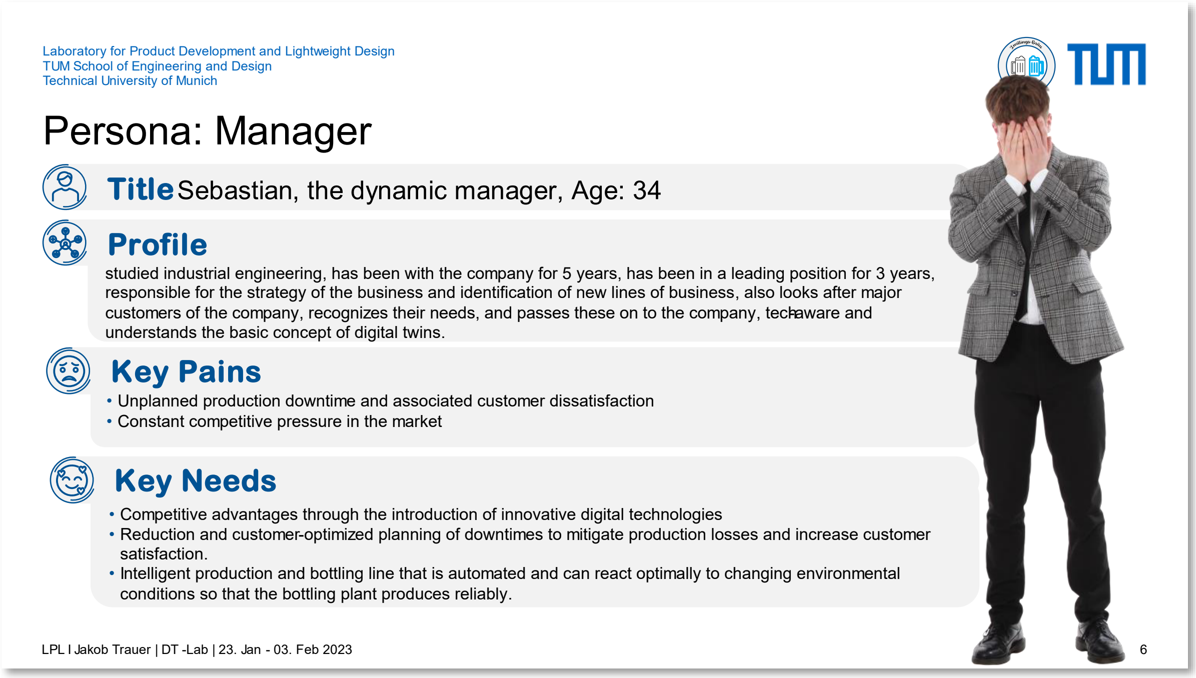


Figure A 171: Persona of the "Manager".

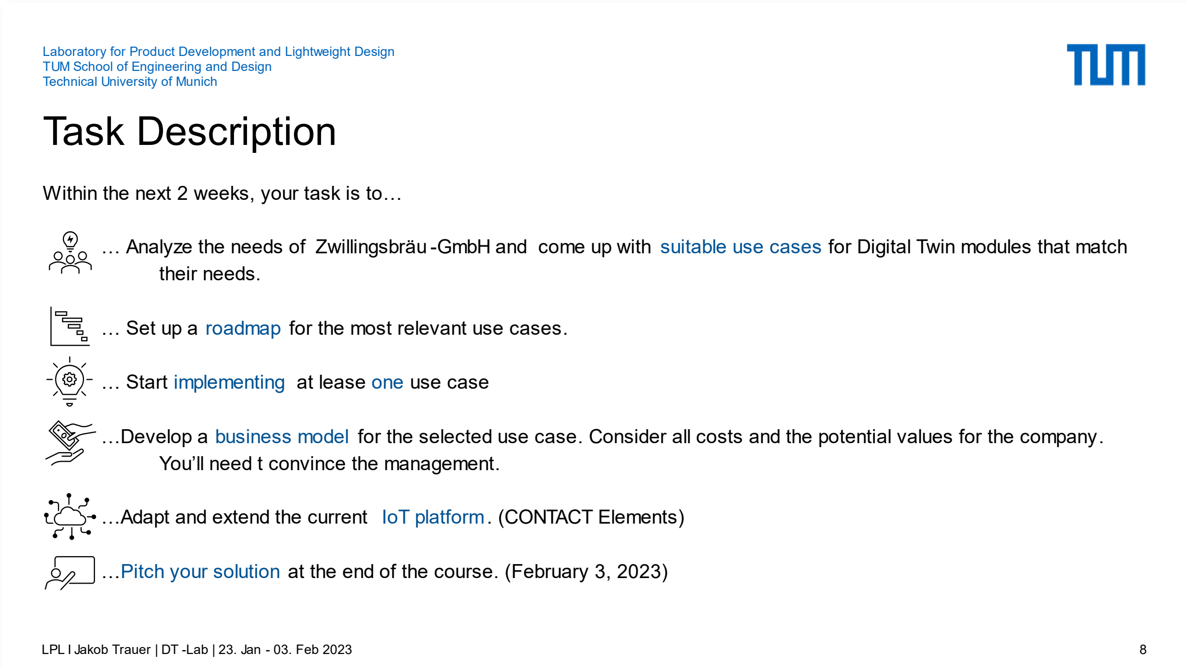


Figure A 172: Task Description for the Student Teams.

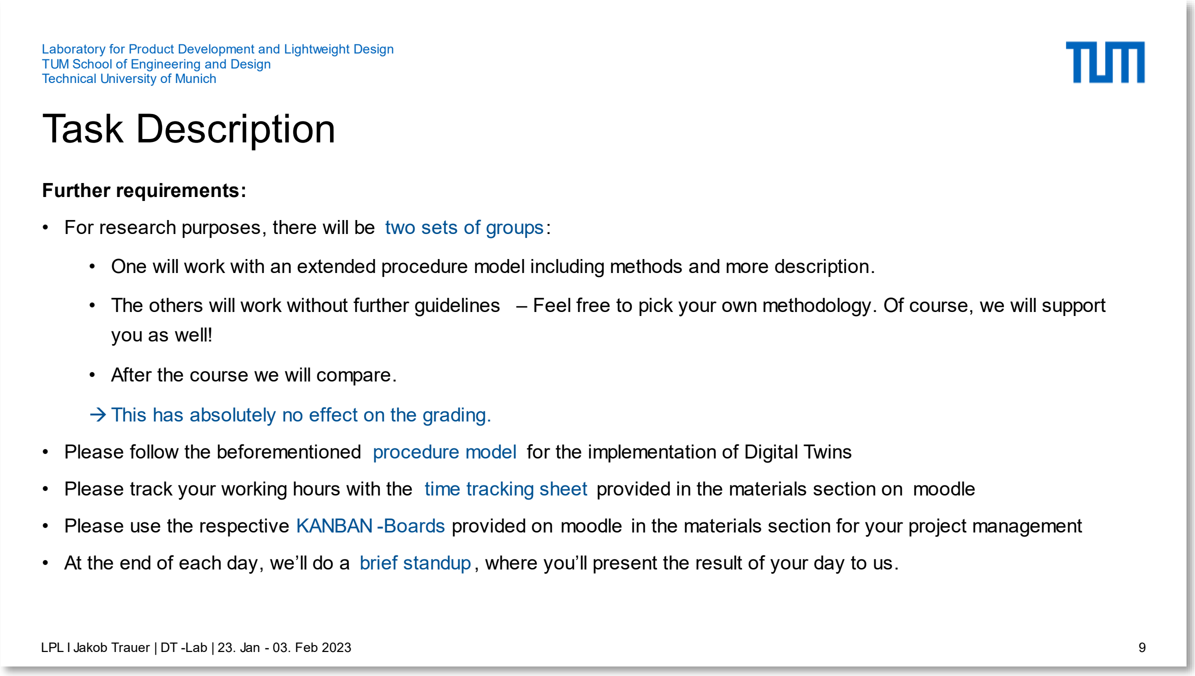


Figure A 173: Further Requirements for the Student Teams.

A9.2 Pre-Test

In this section, the question design and wording are outlined in detail. Therefore, the questions (Q) are numbered. The type of question and the given answers, if existing, are written cursive behind the question. In addition to that, the aim of the questions as well as evaluation methods for the specific questions are described. The survey was introduced with the following statement:

> *Dear students,*
>
> *Thank you for participating in our practical course on the design and development of Digital Twins (DTs).*
>
> *Why participating is important:*
>
> *With your help you will help us to improve the format. As the course is going to take place for the first time, we want to evaluate the effectiveness of this new teaching element.*
>
> *Confidentiality:*
>
> *Your participation in this study is entirely confidential. Any fidings of the study will only be published as non-identifiable data, ensuring your anonymity will be preserved.*
>
> *Your answers will not affect the grading at the end of the course!*
>
> *Thank you very much,*
>
> *Jakob Trauer, M.Sc.*

After this editorial part, the pre-test begins.

Q1: First Name

Text

Q2: Last Name

Text

Q3: Age

Text

Q4: TUM Department

Multiple Choice

- *Chemistry*
- *Electrical and Computer Engineering*
- *Informatics*
- *Mathematics*
- *Medicine*
- *Physics*
- *Sport and Health Sciences*
- *TUM School of Engineering and Design*
- *TUM School of Life Sciences*
- *TUM School of Management*
- *TUM School of Social Sciences and Technology*
- *Sonstiges*

Q5: Study Program

Text

Q6: Bachelor or Master?

Single Choice

Q7: Semester

Text

Q8: Please select 3 characteristics that would describe you the most

Multiple choice, max. 3

- *creative*
- *innovative*
- *team player*
- *leader*
- *organized*

- *technophile*
- *analytical*
- *big picture*
- *self organized*

Q9: How familiar are you with "Digital Twins"?

Single Choice, from 1 to 10

Q10: To what extend do you think, you would know what must be done to develop a Digital Twin?

Single Choice, from 1 to 5

Q11: Have you learned about Digital Twins in your studies before?

Single Choice, yes or no

Q12: Have you worked on Digital Twins before?

Single Choice, yes or no

Q13: In which context did you work on Digital Twins?

Text

Q14: Rate your Level of Familiarity according to your experiences on the following topics.

Likert-Scale from 1 to 5

- *Hardware Development*
- *Software Development*
- *Project Management*
- *Systems Engineering*
- *Business Development*
- *Innovation*
- *Digitalization*
- *Internet of things*
- *Industry 4.0*
- *Databases*
- *Data Analysis*
- *Artificial Inteligence*
- *Machine Learning*

Q15: Which of these terms have you heard before?

Multiple Choice

- *Digital Model*
- *Digital Thread*
- *Digital Shadow*

- *Device Shadow*
- *Device Twin*
- *Digital Twin*

Q16: In general, what are your expecations on the course?

Text

Q17: What would you like to learn?

Text

Q18:Are you worried about something? If yes, what?

Text

A9.3 Post-Test

In this section, the question design and wording are outlined in detail. Therefore, the questions (Q) are numbered. The type of question and the given answers, if existing, are written cursive behind the question. In addition to that, the aim of the questions as well as evaluation methods for the specific questions are described. The survey was introduced with the following statement:

Dear students,

Thank you for participating in our practical course on the design and development of Digital Twins (DTs).

Why participating is important:

With your help you will help us to improve the format. As the course is going to take place for the first

time, we want to evaluate the effectiveness of this new teaching element.

Confidentiality:

Your participation in this study is entirely confidential. Any fidings of the study will only be published as

non-identifiable data, ensuring your anonymity will be preserved.

Your answeres will not affect the grading at the end of the course!

Thank you very much

Jakob Trauer, M.Sc.

After this editorial part, the post-test begins.

Q1: How familiar are you with "Digital Twins"?

Single Choice, from 1 to 10

Q2: To what extend do you think, you would know what must be done to develop a

Digital Twin?

Single Choice, from 1 to 5

Q3: Name three things that you liked about the course!

Text

Q4: Name three things that you did not like about the course!

Text

Q5: How would you rate the collaboratin with your team partner?

Single Choice, from 1 to 5

Q6: Please tell us whether you agree with the following statements.

Likert-scale, from 1 to 6

- *The duration of the course was sufficient*
- *The theoretical input in the course was sufficient*
- *The project was fun*
- *The scenario setting of the project was suitable*
- *The scenario setting of the project was to complex*
- *My expectations were met*
- *The course format was suitable to learn sth on Digital Twins*

Q7: To which extent do you think the following challenges could cause issues in your digital twin project?

Likert-Scale from 1 (very unlikely to cause problems) to 6 (very likely to cause problems)

- *Integration of Digital Twin in legacy system*
- *Security and privacy*
- *Efficient storage, processing and analysis of large volumes of data*
- *Reliability and robustness*
- *Low latency communication, tracking and reporting*
- *Lack of expertise and specialists*
- *Bureaucracy, cultural inertia and knowledge assessment*
- *Setting realistic expectations and trust*
- *Identifying clear and valid value propositions associated with the Digital Twin solution*
- *Combining product lifecycle management, manufacturing execution systems and operations management systems*
- *No standardization of data, models and communication*
- *Ensuring real-time capability, data quality and usefulness*
- *IT infrastructure*
- *Development and deployment time and resources required*
- *Insufficient maintenance of the models across the life cycle of the physical twin*
- *No systematic approach for identifying promising use cases*

- *Difficulties in setting up a strategy for the implementation of Digital Twin use cases*
- *Lack of suitable procedures for an efficient implementation*

Q8: How often did you use the DITTID methods in your team (days/week)?

Text

Q9: Which of the following elements of DITTID would you rate the most useful to overcome challenges in implementing Digital Twins?

Likert-scale from 1 (not useful at all) to 6 (very useful)

- *Procedure Model*
- *Business Modelling Approach*
- *Value Map*
- *Use Case Catalogue*
- *Use Case Template*
- *Trust Framework*

Q9: Please tell us whether you agree to the following statements.

Likert-scale from 1 (not at all) to 6 (absolutely)

- *The methods are helpful*
- *The methods are useful to develop DTs more efficiently*
- *The methods are helpful to develop better business models*
- *The methods are hindering the development of DTs*
- *It would have been easier without the methods*
- *The methods are useful to develop better DT use cases*

Q10: Name three things that you liked about the toolbox (all support provided)?

Text

Q11: Name three things that you did not like about the toolbox (all support provided)?

Text

Q12: Do you think there is something missing in the toolbox?

Text

A9.4 General Feedback on DITTID

Table A 13: Positive Aspects of DITTID Named by the Students who Applied DITTID in the Practical Course.

ID	Positive Aspects of DITTID
1	• *“We had a better orientation about what we were supposed to do”* • *“They are interactive”* • *“We had some examples given which helped us how to proceed with our use case”*
2	• *„Paarweise Vergleich“* • *„Use Case Katalog“* • *„welche Daten werden benötigt und inwiefern sind sie vorhanden“*
3	• *„Man sollte es schon einmal durchgedacht haben bevor man es anfändet aber letztlich machen die Schritte und Methoden Sinn“* • *„Vorlagen für Methoden z.B. value map“* • *„man kann bei der Implementierung darauf zurückgreifen und vergisst nichts“*
4	• *“The clear illustration of the glide path.”* • *“The supporting documentation for each step.”* • *“The expected input and outputs of each step.”*

Table A 14: Negative Aspects of DITTID Named by the Students who Applied DITTID in the Practical Course.

ID	Negative Aspects of DITTID
1	• *“I had a feeling that we are repeating ourselves, just all the time in another templates.”* • *“Instead of focusing more on the implementation, we were more focused on the planning.”* • *“It was a bit too much information for such a short period”*
2	• *“I think it's hard to really evaluate the quality or usefulness of the toolbox in the context of this course as the duration was only two weeks while the planning was covering multiple years. So, what might seem extensive now might be way too little in the real world planning.”*
3	• *„Manche Schritte sind für kleine Projekte nicht zwangsläufig notwendig“* • *„praktische Fragestellungen wie z.B. it Architektur werden nicht erarbeitet“*
4	• *“Lack of examples. For the case of this practical, there were too many steps which were not relevant or were difficult to see the relevancy. Some steps had better documentation than others.”*