

1 Introduction

“Uniform standardization of semantic models. We are now [with the Digital Twin] where we were after the turn of the millennium, where we came from the LPT interface, then you had VGA, then it started with all the connectors for the displays, DVI, and all these standards. Then there was Firewire, USB-A, and USB-B, which are now all USB-C. We have to ensure that we develop the Digital Twin in the direction of USB-C.”

One of the industrial experts on the primary challenges of Digital Twins.

1.1 Motivation

In recent years, researchers and practitioners have been keen to investigate and develop virtual replicas of physical systems. Enabled through the rapid advances in contexts of the Internet of Things (IoT), Cyber-Physical Systems (CPS), and generally the digitization of industrial systems, more precise and powerful virtual entities emerged. In this context, Digital Twins are an often-used concept. A Digital Twin typically is a digital picture of a physical asset (van der Valk et al., 2022a, p. 375). They can be used in many different domains, for several applications, and leverage vital business processes (Attaran and Celik, 2023, pp. 3–7).

In 2018, the course-setting mentioning of Digital Twins took place in the Gartner Hype Cycle. There, Gartner (2018, n. pag.) sees the concept of Digital Twins aiming for the peak of interest within five to ten years towards the so-called *Plateau of Productivity*. In fact, the research interest in Digital Twins started to grow exponentially in the same period (cf. Figure 13, Grieves, 2023, p. 103, Scopus, 2023a, n. pag.). Simultaneously, the topic gained interest in practice as well. For instance, DHL included the Digital Twin in their Logistics Trend Radar, positioned today as an impacting technology (DHL Trend Research, 2024, n. pag.). Similarly, BMW or Deutsche Bahn place the Digital Twin in their resp. trend radars (BMW, 2024, n. pag., Kolarsch et al., 2023, p. 5).

Thus, the *Center of Excellence Logistics and IT*, which anchors this research study, took up the topic. The excellence center is a collaboration between the TU Dortmund University, the Fraunhofer Gesellschaft, and the Leibniz Association (cf. Center of Excellence Logistics and IT, 2024). During the project work, it became apparent that there are many different perceptions of the concept (Cimino et al., 2019, p. 1). Besides the varying understanding of the Digital Twin notion in research originating from various disciplines, e.g., simulation (Boschert and Rosen, 2016) or product lifecycle management (Grieves, 2005), several related concepts emerged: Digital Shadows, Digital Threads, or Digital Models (Helu et al., 2017, Schacht et al., 2021, Urbina Coronado et al., 2018). Although differently defined, these notions were often used synonymously, thereby diluting the concept of a Digital Twin even further. Additionally, confusion about the definition of a Digital Twin and its delimitation became obvious when talking with other researchers and practitioners. Their individual background heavily influenced their perception of Digital Twins.

From these challenges, the motivation arose to structure the field of Digital Twins. Structuring and, moreover, standardizing a field of knowledge poses many advantages. Most importantly, standards typically bring high financial benefits. For example, the DIN reviewed savings due to the continuous application of their standards and accumulated yearly economic benefits of more than 16 billion Euros (Blind et al., 2012, p. 18). Thereby, the Encyclopedia Britannica (2015, n. pag.) defines a standard as “that which has been selected as a model to which objects or actions may be compared.” Indeed, reference models are a prime example of standardized models (Fettke and Loos, 2004, p. 334). Joining the descriptive and prescriptive nature of reference models, they allow not only representing the vast number of different approaches to Digital Twins but also the derivation and illustration of a standardizing new definition for the concept. Yet, a standard framework, e.g., a reference model, alone is insufficient. The users of such a framework also need to know how to implement it to fully leverage its potential (cf. Esswein, 2016, p. 58). Therefore, a standardizing framework shall come together with a process model of the framework’s implementation.

In the course of this research study, the need for a standardized Digital Twin definition became more and more critical. In the interviews conducted for this study, several interlocutors discussed this aspect of their own Digital Twin initiative. The above excerpt

originates from the last evaluation interview at the end of the study. Yet, as the interlocutor stated, the necessity of standardization in practice is still not satisfied. Nevertheless, the interest in Digital Twins is still high. The newest Gartner Hype Cycle includes two Digital Twin sub-technologies for Supply Chain Strategies, i.e., Digital Twins of Supply Chains and Digital Twins of a Customer (Tohamy, 2023, n. pag.). Furthermore, the Digital Twin is an emerging technology that will soon be fully implemented in business processes (Perri, 2024, n. pag.).

At the beginning of 2024, one of the big worldwide IT companies acquired the Digital Twin professional services division of a US company providing a market-leading real-time visualization software that is, amongst others, able to implement customer-specific Digital Twins (cf. Capgemini, 2024). Thereby, the IT service provider wants to strengthen its footprint in the areas of Intelligent Industries and Business Transformation. Also, this example demonstrates the high actuality and the unbroken or even increasing relevance of Digital Twins.

In conclusion, this research study covers a relevant topic that is the focus of research and high on today's agenda of many companies. Thereby, the study aims to close the research gap to support the future evolvement of the concept in theory and practice.

1.2 Research Questions and Study Objective

As the motivation for this research project shows, there is no uniform understanding of Digital Twins. Therefore, this research project's main task is to structure Digital Twins. The focus will be on the domain of their origin, namely industrial systems. Since the Digital Twin has its roots in product life cycle management and thus in an inherent core task of process planning and production design in mechanical engineering, it is assumed that within this domain, both the necessity and, at the same time, the database for such a structuring project is very significant. The primary research objective (RO) is therefore:

RO 1: Structuring Digital Twins in Industrial Systems

Fundamental classic structuring mechanisms, such as a taxonomy, archetypes, and a reference model, will be used for this purpose. According to a scientifically sound procedure for structuring and developing the three artifacts, intermediate and sub-goals arise for the research project.

These primarily come from the overall research procedure. Yet, a division into more prescriptive and descriptive ROs is possible. This research starts with the latter. The descriptive ROs address the recording of the as-is state. In detail, the theoretical and practical knowledge about the Digital Twin should first be sorted and classified:

RO 2: Sorting and classifying central features and properties of Digital Twins

This sorting and classification is a necessary prerequisite to capture the current status of Digital Twins. From there, all subsequent steps of the research procedure originate. To achieve this RO, a taxonomy and archetypes of Digital Twins are created, thereby following the overarching goal of structuring the Digital Twin. Moreover, these artifacts also lay the foundation for the most critical artifact of this research, i.e., the reference model. Therefore, implementing RO 2 additionally categorizes the various types of Digital Twins and a pattern of common descriptions.

At this point, the more descriptive study transforms into a more prescriptive one. Yet, a framework shall result from the previous findings:

RO 3: Design of a reference model and an implementation guideline for Digital Twins

This RO allows for the development of a precise architecture that uses the input from the previous RO and delivers the main prescriptive artifact that serves the primary purpose of this study. Nevertheless, the study should also enable readers to use the framework practically. Thus, an accompanying guideline is necessary to guide the implementation of the reference model.

More fine-granular ROs originate from the overarching research method in the particular chapters. These are explained in more detail, where they are defined. Yet, the following Table 1 already displays an overview:

Table 1: Fine-Granular Research Objectives of this Study

#	Research Objective
4.1	Sort the theoretical knowledge about Digital Twins
4.2	Classify central features and properties of Digital Twins and order them into corresponding dimensions
5.1	Enhance the taxonomy with the industrial community's knowledge

Continuation of Table 1

5.2	Evaluate the taxonomy through expert interviews
6.1	Define meaningful clusters of a Digital Twin
6.2	Derive archetypical descriptions to group configuration possibilities
7.1	Identify empirical requirements for Digital Twins
7.2	Enhance the empirical requirements with literature-based ones to get an exhaustive picture
8.1	Design a partial reference model for each archetype
8.2	Synthesize partial models into generic reference model of Digital Twins
8.3	Develop an application instruction for Digital Twins
8.4	Implement exemplarily the reference model to prove its applicability
8.5	Evaluate the reference model

1.3 Structure and Research Design of the Thesis

The thesis' underlying research design follows a combination of different activities. The interface between information systems (IS) research and the engineering discipline marks this research's position. Thus, the particular research activities blend IS-focused ones, e.g., the literature search, with more engineering-rooted ones, e.g., developing a process model. The structure of this study reflects this combination and guides the reader through the research process. Figure 1 illustrates the actual structure of this research.

This research study contains five parts. The first part contains Chapters 1 to 3 and comprises the introduction, the research methodology, and the conceptual foundations. The second part consists of Chapters 4 to 6 and illustrates the categorization of Digital Twins. The third part deals with the reference model comprising the Chapters 7 and 8. Part IV displays the concluding statements, and Part V of this research study provides all directories and the appendix.

In Part I, Chapter 1 outlines the underlying motivation and research gap for this research. It specifies the study's objectives and explains the overall structure of the thesis.

The second chapter illustrates the research methodology. It clarifies the benefits and foundations of reference modeling in software development. Several reference modeling

methods are juxtaposed to find the most suitable one for modeling the reference model. The chapter elaborates on the tailored approach and the adaption of the chosen reference modeling method. Further auxiliary methods help to gather the data, structure it, and derive the requirements for the reference model. Lastly, the research methods for object classification, i.e., the taxonomy and archetype design methods, close the second chapter.

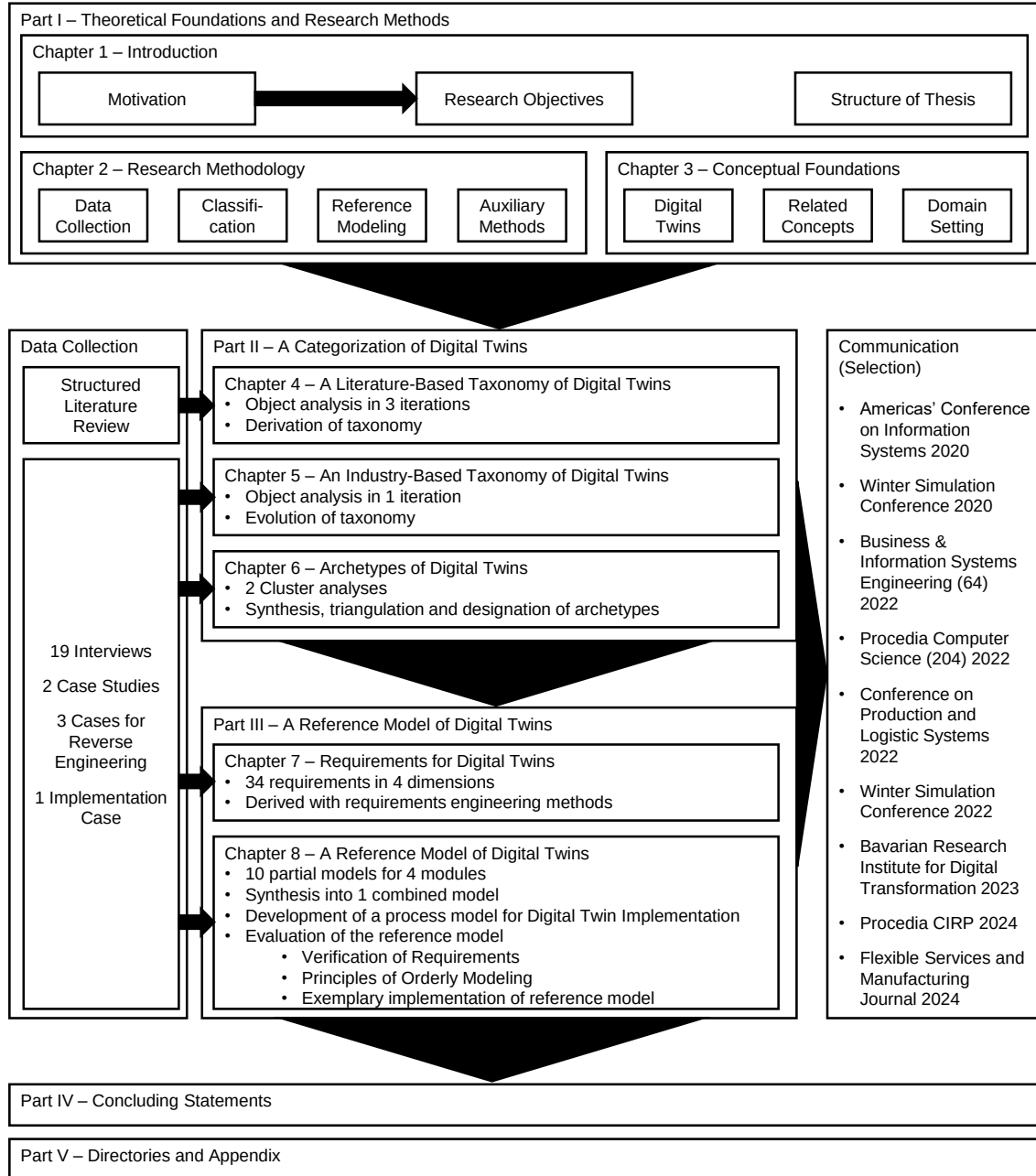


Figure 1: Structure of the Thesis

Chapter 3 presents the conceptual foundations necessary for the objects portrayed in this study. In particular, these are Digital Twins with their history, conceptual background,

existing architectural approaches and reference models, and present applications. The further related concepts, i.e., Digital Models, Digital Shadows, Digital Threads, and the Industrial Metaverse, follow suit and are delineated against the Digital Twins. The chapter closes by explaining the domains relevant to this research: production, logistics, and CPS.

Chapter 4 commences the second part of the study. It reports on a structured literature review (SLR) about Digital Twins. This review is the foundation for the initial taxonomy developed in this chapter. In three iterations, a literature-based taxonomy of Digital Twins emerges.

The 5th chapter enhances this taxonomy with input from two case studies and an interview series where 15 industrial experts presented their views on Digital Twins. The chapter reports on the interview series, highlights the characteristics of Digital Twins and further aspects mentioned by the experts, and explains the two case studies. These case studies are of high relevance to the development of the final taxonomy. Furthermore, they directly influence the derivation of the archetypes and pose as one option for evaluation. Finally, the case studies appear again during the development of the reference model. The case studies a) affect the partial models and impose design inspirations and b) support the evaluation of the overall synthesized reference model.

Chapter six takes up the taxonomy from the previous chapter. It presents the synthesis and the triangulation of archetypes of Digital Twins based on a cluster analysis. A second interview series to evaluate these archetypes closes this chapter.

With the 7th chapter, the third part of this study starts, and the requirements for Digital Twins are explained and divided into dimensions. The requirements originate from the previously executed interviews and SLR. The chapter further details the evaluation of the requirements.

The eighth chapter reports on the design of the reference model. First, partial models building up on the archetypes emerge. Through synthesis, these partial models join into one reference model. The remainder of this chapter shows the design of a process model for Digital Twin implementation and clarifies the overall evaluation of the reference and process models.

Part four of the study only includes the 9th chapter, which concludes the research and presents the study's limitations and the outlook for further investigation.

Finally, part five closes the study with the directories and the appendix.

Comprehensive parts of the study have already been pre-published during the work. Specifically, this concerns the Chapters 4 to 8. Figure 1 partly references the corresponding communications.