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Cross-industry Digital Twin framework for deriving, designing, and describing Digital Twin applications

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To everyone who believed in me and supported me along the way, thank you.

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Abstract

The Digital Twin is a rather young concept within the digitalization trend, promising cross-industry benefits such as usage-centric design, real-time optimization, and predictive and preventive analysis. In recent years, research on the Digital Twin concept has seen exponential growth, with applications from more and more fields. With this cross-industry growth emerge challenges of confusing terminologies, unclear development strategies, and a variety of different architectures. This uncertainty discourages Digital Twin developers and companies and hampers the potential of the Digital Twin concept. This dissertation aims to consolidate the Digital Twin development cycle by proposing a Digital Twin framework for deriving, designing, and describing Digital Twin applications across industries. The framework consists of three publications that address one step each. A stakeholder-centric methodology is proposed that supports developers in deriving promising Digital Twin use cases and evaluating their value, effort, and scalability. A reference architecture model guides developers in designing Digital Twin applications considering functionality, dependability, and life cycle aspects. The description of Digital Twin applications is advised by a Digital Twin application description model. The applicability of this dissertation's framework is demonstrated through the example of a medical mechatronic product development case from the Siemens Healthineers Innovation Think Tank. Within this dissertation, the framework is allocated within Digital Twin development cycles, discussed with related literature, and its limitations and next steps are elaborated.

List of Included Scientific Papers

I. **S. R. Newrzella**, D. W. Franklin, and S. Haider, “5-Dimension Cross-Industry Digital Twin Applications Model and Analysis of Digital Twin Classification Terms and Models,” IEEE Access, vol. 9, pp. 131306–131321, 2021, doi: 10.1109/ACCESS.2021.3115055.
Impact Factor: 3.367

II. **S. R. Newrzella**, D. W. Franklin, and S. Haider, “Methodology for Digital Twin Use Cases: Definition, Prioritization, and Implementation,” IEEE Access, vol. 10, pp. 75444–75457, 2022, doi: 10.1109/ACCESS.2022.3191427.
Impact Factor: 3.367

III. **S. R. Newrzella**, D. W. Franklin, and S. Haider, “Three-dimension Digital Twin Reference Architecture Model for Functionality, Dependability, and Life Cycle Development across Industries,” IEEE Access, vol. 10, pp. 95390-95410, 2022, doi: 10.1109/ACCESS.2022.3202941.
Impact Factor: 3.367

1 Introduction

The following dissertation describes the development of the Digital Twin concept, how its loose definition and broad applicability result in confusion, mismanaged expectations, and unmet potential, and how universally applicable definitions, descriptions, development methodologies, and architectures can alleviate these challenges. The first subsection (1.1) introduces the Digital Twin concept with its history, definitions, application fields, application use cases, and potential business values. The second subsection (1.1.4) showcases the recent explosive growth of research on the Digital Twin concept, its spread to different industries, and its expected development. This development entails challenges to the success of the Digital Twin concept, which are introduced in subsection 1.2. These challenges build the foundation for this dissertation's Digital Twin framework and its three constituting scientific publications, whose aims are presented in subsection 1.3. Digital Twin development cycles are described in subsection 1.4, and the allocation of this dissertation's Digital Twin framework is explained before setting out the methodical approach of the included scientific publications in subsection 1.5.

1.1 The Digital Twin concept

As a result of digitalization across industries, technology trends have emerged, such as the Internet of Things (IoT), Artificial Intelligence (AI), Augmented and Virtual Reality (AR/VR), Cloud computing, and the Digital Twin concept. The latter, the Digital Twin concept, is rather young and has recently received increased interest from academia and the corporate field. The Digital Twin concept can be defined as follows.

> *"The Digital Twin concept contains a physical entity and its virtual representation, which evolves with its physical counterpart through real-time connection and offers additional value."* (Newrzella et al., 2021) [1]

These physical-virtual interlinked entities can be, for example, a human being's internet consumer behavior being tracked by browser cookies, with a model that creates a personalized virtual model of the consumer and provides personalized adverts to the human; a production process tracking individual dimensions of parts, calculating optimal part allocations in a virtual model, and feeding back improved production orders to the real-world production line; or an athlete's fitness condition being tracked through wearable sensors, a virtual model estimating performance, and suggesting behavior modifications to the athlete for performance improvements.

The concept promises time to market reduction, operational optimization, maintenance cost reduction, and user engagement increase, among others [2], [3]. The Digital Twin market is expected to be worth USD 15.66 Billion in 2023 [4] and USD 155.84 Billion in 2030 [5]. The COVID-19 pandemic has further accelerated the adoption of the Digital Twin concept, while such an exponential development also comes with challenges such as mismanaged expectations. The framework proposed in this dissertation aims to alleviate the challenges and support and consolidate the positive trend of the Digital Twin concept.

1.1.1. History

The idea of creating a copy of a physical entity and using it for safe simulation and testing without interfering with the original entity can be dated back to 1970, when NASA built two space shuttles in its Apollo program [6], [7]. This concept proved helpful when the oxygen tanks of the Apollo 13 mission exploded in space. With the help of the grounded counterpart, an air purifier was developed that could be built with just the material and tools available to the astronauts in space. This solution got the astronauts safely back to earth. This example shows the potential of twinning an object. David Gelernter first described the idea of creating virtual twins of the real world in his book “Mirror Worlds” in 1992 [8]. In the book, he describes a potential future in which every detail in the real world has a real-time software twin connected to its physical twin. This concept enables the analysis and planning of every aspect of daily life and business. The informal introduction of the Digital Twin concept is credited to Michael Grieves in late 2002. In his lecture at the University of Michigan, he presented his product life cycle management (PLM) presentation about the “Conceptual Ideal for PLM” [9], [10], which he referred to as “Mirrored Spaces Model” in 2005 [11]. The concept visualized in Figure 1 consists of three main parts, a physical entity in real space, a virtual entity in virtual space, and connections of data and information tying virtual and real entity together. A more detailed depiction can be found in Figure 3.

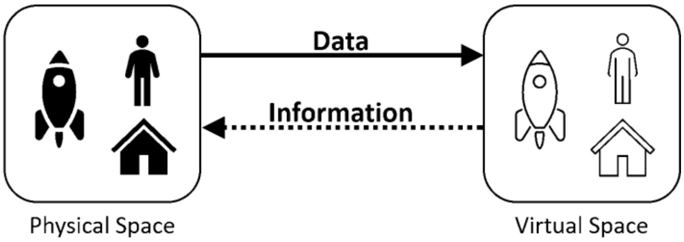


Figure 1: Illustration from Newrzella et al. (2021) [1]*: The Digital Twin concept, based on Grieves (2015)* [10]

In 2003, Främling et al. [12] proposed a similar concept, “an agent-based architecture where each product item has a corresponding ‘virtual counterpart’ or agent associated with it,” for handling product information along the entire life cycle of a product item. In 2006, Grieves called the concept “Information Mirror Model” [13] and highlighted the bidirectional communication between physical and virtual space and the possibility to create multiple virtual spaces for alternate option exploration [3]. In 2010, Grieves’ former NASA colleague John Vickers gave the concept its name “Digital Twin” in the NASA roadmap [14], [15]. An overview of the name development is visualized in Figure 2. Soon after the NASA implemented the concept in its roadmap, the US Air Force started using the Digital Twin concept for the design, maintenance, and scenario prediction of their aircraft [16]–[18]. The “Airframe Digital Twin” was described as monitoring the structural integrity of aircrafts for the remaining life calculation, while the Digital Twin concept was also proposed for sustainable space exploration and future aerospace vehicles [3], [6].

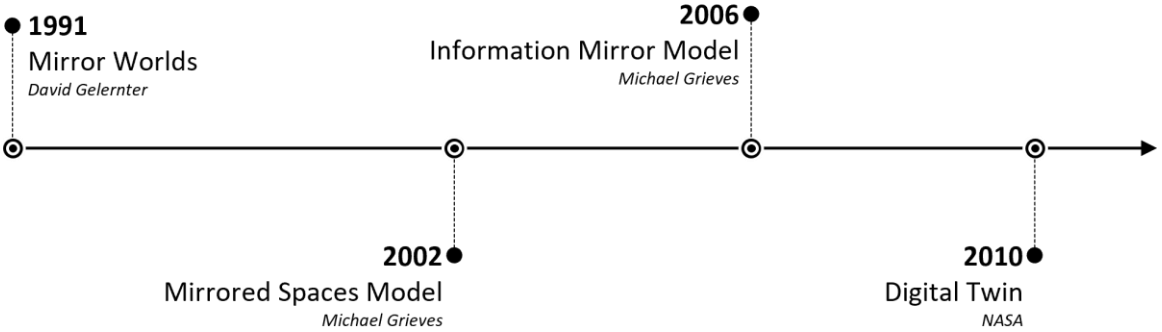


Figure 2: Timeline of the Digital Twin concept, based on Singh et al. (2021) [3].

1.1.2. Definition

Since its introduction, the term “Digital Twin” was not always, and its definition still is not commonly agreed on. Similar concepts with the same or partially identical characteristics as the Digital Twin concept have been introduced. The Digital Twin concept is also often described by different terms. Exemplary terms of the Digital Twin and similar concepts are device shadow [19], [20], mirrored system [20], [21], synchronized virtual prototype [20], virtual twin [22], virtual object [23], digital counterpart [24]–[27], digital surrogate [28], digital or virtual model [16], [25], [37], [29]–[36], hyper-computational model [20], layout [38], doppelganger [39], clone [40], footprint [41], representation [42]–[45], software analogue [46], information constructs [47], [48], simulation [6], [49]–[53], product agent [12], [54], product avatar [24], [55], and avatar [56]. Some of these terms are commonly used in certain technology fields, but these terms have not caught wider public attention [57].

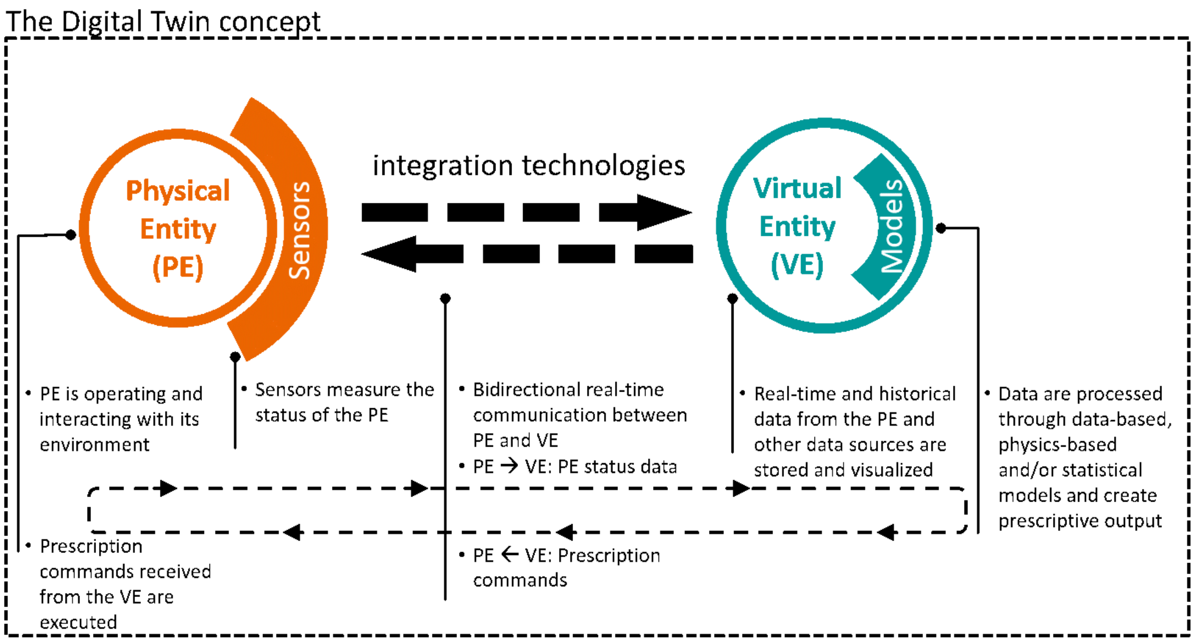


Figure 3: Illustration from Newrzella et al. (2021) [1]. *The Digital Twin concept.*

Coming from a PLM and aviation background, the Digital Twin concept has always had strong ties to the product-centric aviation domain. Early definitions of the Digital Twin concept contained terms like "aircraft" [16], [18], [33], "airframe" [18], [32], and "vehicle" [6], [49], [50]. NASA first defined the "Digital Twin" in its 2010 roadmap as a multi-physics, multi-scale simulation of the as-built vehicle or system, incorporating high-fidelity modeling and simulation and situational awareness into a real-time-mission-life virtual construct of the flying vehicle or system [15]. The concept quickly expanded to other application domains and the terms used in Digital Twin definitions shifted to "product" [7], [24], [35], [38], [44], [45], [48], [53], "object" [27], [38], [42], [43], [46], "entity" [27], [47], "asset" [34], [36], [40], [41], "device" [46], "machine" [31], [58], "system" [7], [25], [59], [26], [29], [37], [38], [41], [47], [52], [53], or "process" [27], [29], [35], [36], [38], [45], [58], [59]. Manufacturing is now a strong application domain for the Digital Twin concept, with the International Academy for Production Engineering CIRP defining the Digital Twin concept as follows.

> *"The Digital Twin is a digital representation of an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) 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."*
>
> (Stark and Damerau, 2019) [60]

Other definitions exist and have been summarized in review articles [26], [27], [60]–[63]. An exemplary table of such an analysis is given in Table 1.

Table 1: Table from Liu et al. (2021) [61]*: Digital Twin definitions in academic publications.*

No.	Refs.	Time	Definition of Digital Twin	key points
1	[13]	2010.11	A digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin.	integrated simulation
2	[25]	2014.4	Digital twin is a life management and certification paradigm whereby models and simulations consist of as-built vehicle state, as-experienced loads and environments, and other vehicle-specific history to enable high-fidelity modeling of individual aerospace vehicles throughout their service lives.	fidelity modeling
3	[26]	2015	Very realistic models of the current state of the process and their behaviors in interaction with their environment in the real world – typically called the "Digital Twin".	realistic model
4	[27]	2016	Digital twins are virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services.	virtual substitutes
5	[28]	2017	The term digital twin can be described as a digital copy of a real factory, machine, worker, etc., that is created and can be independently expanded, automatically updated as well as being globally available in real-time.	digital copy
6	[29]	2017	Faster optimization algorithms, increased computer power and amount of available data, can leverage the area of simulation toward real-time control and optimization of products and production systems – a concept often referred to as a Digital Twin.	real-time control and optimization
7	[30]	2017	Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level.	virtual information
8	[31]	2018.1	Digital Twins stand for a specific engineering paradigm, where individual physical artifacts are paired with digital model that dynamically reflects the status of those artifacts.	dynamic reflection
9	[32]	2018.2	A digital twin is a one-to-one virtual replica of a "technical asset" (e.g., machine, component, and part of the environment).	virtual replica
10	[33]	2018.5	The digital twin model is an exact and real-time cyber copy of a physical manufacturing system that truly represents all of its functionalities.	cyber copy
11	[34]	2018.7	DT is a multi-domain and ultrahigh fidelity digital model integrating different subjects such as mechanical, electrical, hydraulic, and control subjects.	fidelity model
12	[35]	2018.8	Digital twin represents a dynamic digital replica of physical assets, processes, and systems, which comprehensively monitors their whole life cycle.	dynamic replica
13	[36]	2018.9	This rich digital representation of real-world objects/subjects and processes, including data transmitted by sensors, is known as the digital twin model.	digital representation
14	[37]	2018.11	Digital Twin is essentially a unique living model of the physical system with the support of enabling technologies including multi-physics simulation, machine learning, AR/VR and cloud service, etc.	living model
15	[38–40]	2018.12	BIM (Building Information Model) is digital twin.	
16	[41]	2018.12	Digital twin represents physical entities with their functions, behaviors, and rules dynamically.	dynamic representation
17	[42]	2019.1	The new technology, accessing to realistic models of the current state of the process and their behaviors in interaction with their environment in the real world is called the "Digital Twin".	realistic model
18	[43]	2019.1	A digital twin is a virtual instance of a physical system (twin) that is continually updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle.	updated virtual instance
19	[21]	2019.2	DT refers to a virtual object or a set of virtual things defined in the digital virtual space, which has a mapping relationship with real things in the physical space.	mapping
20	[44]	2019.6	DT is defined as a digital copy of a physical asset, collecting real-time data from the asset and deriving information not being measured directly in the hardware.	real-time data
21	[45]	2019.8	Digital twin can be regarded as a paradigm by means of which selected online measurements are dynamically assimilated into the simulation world, with the running simulation model guiding the real world adaptively in reverse.	Dynamic, bidirectional

With the Digital Twin concept being more and more applied to industries outside manufacturing, its definition also moved from industrial products to living entities such as humans and trees [43], [64], [65].

The Digital Twin concept can be applied over the entire life cycle, from cradle-to-grave of its physical entity, from creation to disposal in case of a product [16], [36], [44], [52]. Grieves and Vickers [48], however, defined the Digital Twin concept in such a way that the virtual entity can exist before its physical twin. A review found eleven papers in which the virtual entity precedes its physical twin [63]. Furthermore, the Digital Twin concept can support the safe decommissioning of its product during its disposal stage [3], [48], supporting the design and manufacturing of the next generation of products [66].

The Digital Twin concept differs from computer models (CAD/CAE) and simulations. A computer model can be part of a Digital Twin application but doesn't have to [36]. The Digital Twin concept uses a real-time or near real-time connection to its physical entity to represent its physical twin at any given point, monitoring and understanding its behavior and making predictions about its potential future. Wright and Davidson (2020) discuss the relationship between models and the Digital Twin concept in their article "How to tell the difference between a model and a digital twin" [67], where they call a Digital

Twin without a physical twin a model. A model is also used for the generic understanding or prediction of a physical entity, but it hardly accurately represents an entity's status in real-time [3]. The missing real-time connection makes models static, so that they do not update until they receive new data from their physical twin [68]. The feedback loop from the virtual to the physical entity is another defining feature of the Digital Twin concept compared to a simulation or model. Kritzinger et al. (2018) [47] differentiate between a "Digital Model", without real-time connection, a "Digital Shadow", with unidirectional data connection from the physical to the virtual entity, and a "Digital Twin", with bidirectional communication between physical and virtual entity. Liu et al. (2020) [61] found more than half of the reviewed Digital Twin articles describing digital models or shadows rather than Digital Twin applications. Many organizations use the term "Digital Twin" interchangeably with the terms simulation or modeling, due to the unclear definition of the Digital Twin concept. The multitude of varying definitions of the Digital Twin concept in the literature makes many applications fall under the term "Digital Twin". The loose usage of the term creates confusion among practitioners and hampers the potential it has across industries.

In this dissertation, the definition by Newrzella et al. (2021) [1] mentioned at the beginning of this chapter is used. Furthermore, the capitalized spelling "Digital Twin" is utilized universally, as capitalization is used for other concepts. In other research, "Digital Twin" often only refers to the virtual entity, forgetting the connection to a physical entity. In this dissertation, the term "Digital Twin concept" is used which includes the three main parts described in Figure 3. The term "Digital Twin" is only used for the virtual entity when necessary or when the referenced paper uses it accordingly. A "Digital Twin application" applies the Digital Twin concept to a specific use case.

1.1.3. Applications

Digital Twin applications are anticipated and studied across industries (see Figure 4). Besides the manufacturing and aviation industries, applications are developed, for example, in Healthcare [65], [69]–[73], Construction [74]–[77], the Oil and Gas Industry [78]–[82], and Logistics [83]–[86]. Further application fields mentioned by Qi et al. (2019) [87] are agriculture, the automobile industry, city planning, shipbuilding, and the energy sector. The scientific publications included in this dissertation use validation examples from various industries to demonstrate the cross-industry applicability of the framework.

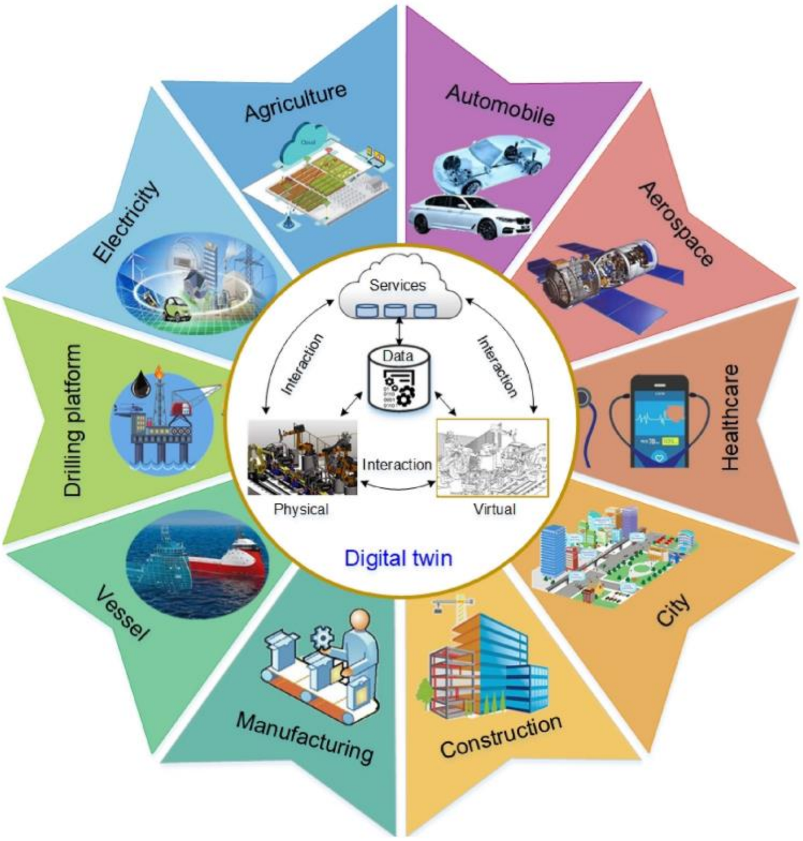


Figure 4: Illustration from Qi et al. (2019) [87]. *Different Digital Twin application fields.*

Digital Twin applications across industries enable their physical entity to provide additional capabilities. A virtual entity can capture, organize, analyze, model, and simulate scenarios in and around its physical entity through real-time or near real-time connection with its physical entity. With these enabling capabilities, specific value-adding use cases have to be driven. Liu et al. (2021) [61] describe use cases along the product life cycle (see Figure 5). Parrott and Warshaw (2017) [88] advocate broad Digital Twin use cases along life cycles to drive business value. They categorize Digital Twin business values into six categories: Quality, warranty cost and services, operations cost, record retention and serialization, new product introduction cost and lead time, and revenue growth opportunities. The validation examples used in the scientific publications of this dissertation showcase a selection of potential business values across industries.

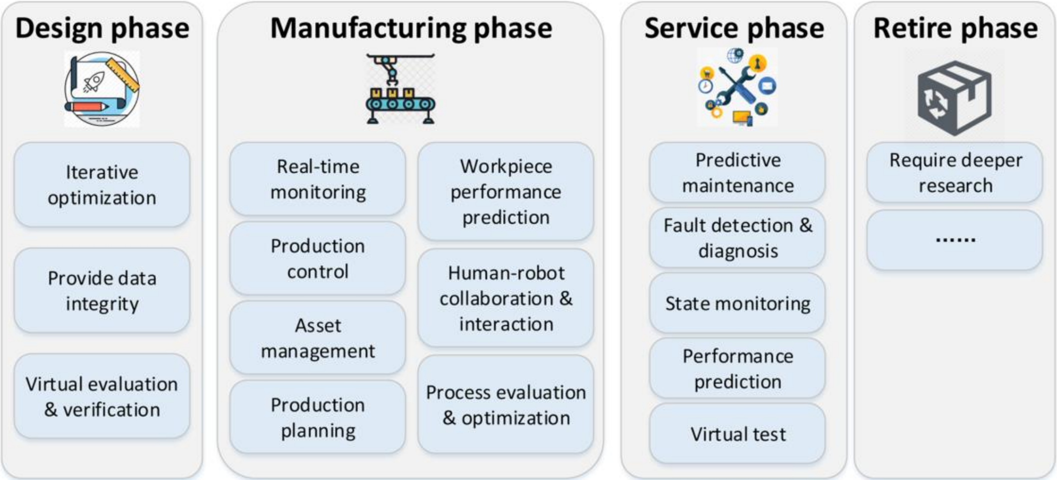


Figure 5: Illustration from Liu et al. (2021) [61]. *Industrial applications of the Digital Twin concept in different life cycle phases.*

Table 2: Digital Twin business values from Parrott & Warshaw (2017) [88]

Category of business value	**Potential specific business values**
Quality	• Improving overall quality • Predicting and detecting quality trend defects sooner • Controlling quality escapes and being able to determine when the quality issue started
Warranty cost and services	• Understanding the current configuration of equipment in the field to be able to service more efficiently • Proactively and more accurately determining warranty and claims issues to reduce overall warranty cost and improve customer experiences
Operations cost	• Improving product design and engineering change execution • Improving the performance of manufacturing equipment • Reducing operations and process variability
Record retention and serialization	• Creating a digital record of serialized parts and raw materials to better manage recalls and warranty claims and meet mandated tracking requirements
New product introduction cost and lead time	• Reducing the time to market for a new product • Reducing the overall cost of producing a new product • Better recognizing long-lead-time components and their impact on the supply chain
Revenue growth opportunities	• Identifying products in the field that are ready for an upgrade • Improving efficiency and cost to service a product

This chapter shows that the Digital Twin concept is a rather young member of the digitalization trend. The term “Digital Twin” consolidated over time, but its definition has still not found consensus.

Nevertheless, Digital Twin applications promise business values across industries when applied to the right use cases and enabled by the right technologies.

1.1.4. Research development and outlook

At the first mention of the Digital Twin concept, the technology was not yet capable of enabling it. In the following decade, advances were made in technology fields such as communication, computation, and sensors, which made the Digital Twin concept technically feasible [41], [89]. This development resulted in a sharp increase in Digital Twin research, a trend described by Tao et al. (2019) [89] (see Figure 6) and analyzed by Liu et al. (2020) [61] (see Table 3).

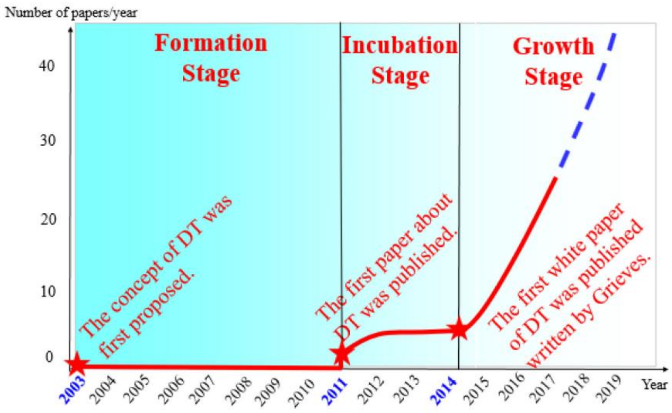
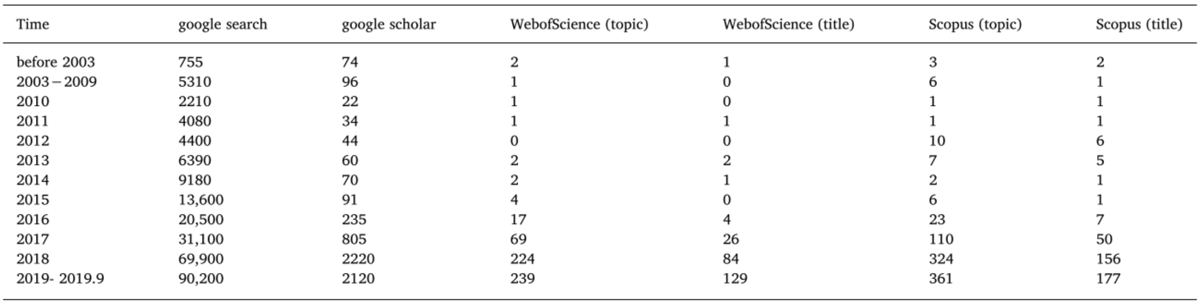


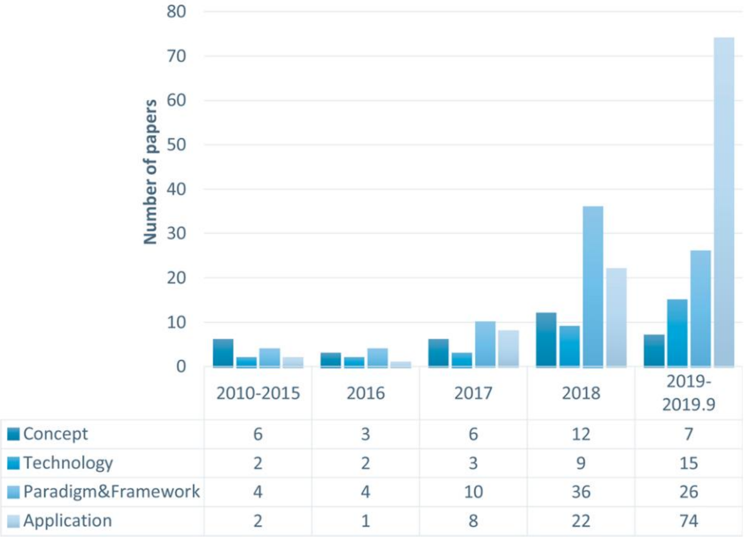
Figure 6: Illustration from Tao et al. (2019) [89]*, © 2019 IEEE. Development trend of Digital Twin research.*

Table 3: Table from Liu et al. (2021) [61]*. Amount of search results on Digital Twin in different databases.*



Time	google search	google scholar	WebofScience (topic)	WebofScience (title)	Scopus (topic)	Scopus (title)
before 2003	755	74	2	1	3	2
2003 – 2009	5310	96	1	0	6	1
2010	2210	22	1	0	1	1
2011	4080	34	1	1	1	1
2012	4400	44	0	0	10	6
2013	6390	60	2	2	7	5
2014	9180	70	2	1	2	1
2015	13,600	91	4	0	6	1
2016	20,500	235	17	4	23	7
2017	31,100	805	69	26	110	50
2018	69,900	2220	224	84	324	156
2019- 2019.9	90,200	2120	239	129	361	177

As shown in the research of Liu et al. (2020) [61] in Figure 7, the research on Digital Twin was first dominated by conceptual articles. With time, the proportion of paradigm & framework and ultimately the application research increased greatly. Applications of the Digital Twin concept exist in numerous fields [27], [80], [90]. The concept's origin can be attributed to the manufacturing industry, specifically aerospace [78]. The manufacturing industry offers great scaling potential, and aerospace/aviation contains capital-intensive projects. Both industries provide bigger leverage than other industries for riskier investments, such as early Digital Twin applications. Early research was, therefore, dominated by the manufacturing and aviation industry, as depicted in Figure 8. By now, Digital Twin application research also exists in many other industries.



	2010-2015	2016	2017	2018	2019-2019.9
Concept	6	3	6	12	7
Technology	2	2	3	9	15
Paradigm&Framework	4	4	10	36	26
Application	2	1	8	22	74

Figure 7: Illustration from Liu et al. (2021) [61]*. Content type of Digital Twin literatures.*

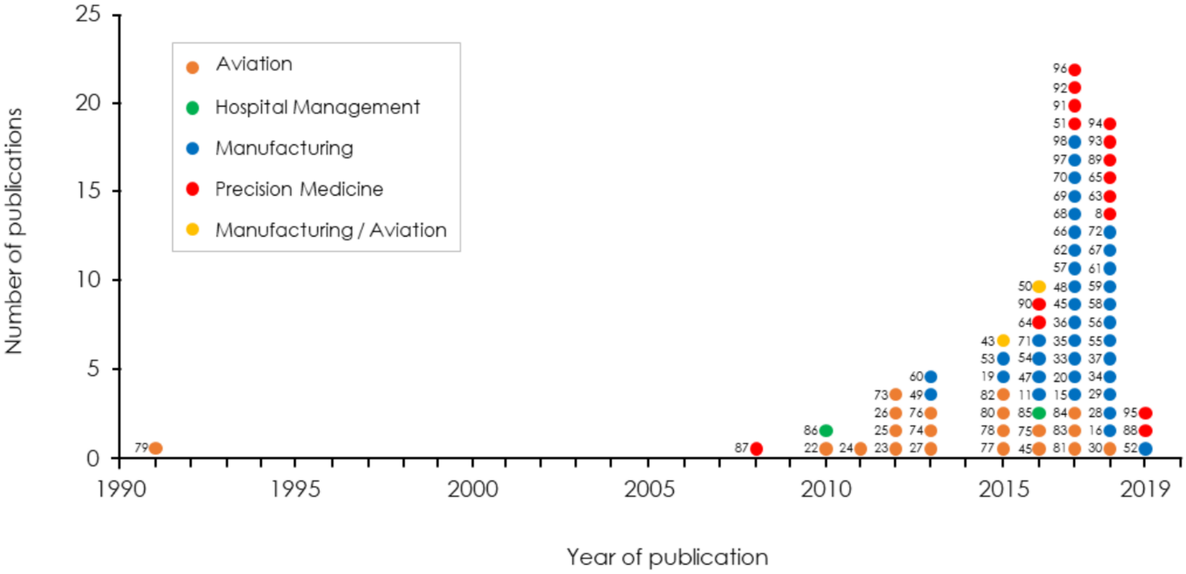


Figure 8: Illustration from Barricelli et al. (2019) [27]*. Depiction of Digital Twin application articles along a timeline, colored according to their application domain. Barricelli et al. searched for "digital twin artificial intelligence" and "digital twin model" on Google Scholar in July 2019 and from there snowballed further articles.*

Besides the explosive growth in the scientific field since 2017 [61], various corporations such as Siemens [91], GE [92], and PTC [93] have initiated research and product development on Digital Twin [1]. In 2018, the International Data Corporation (IDC) forecasted 30% improvements in manufacturing cycle times of critical processes for companies investing in Digital Twin applications [94]. In August 2018, Gartner published a report surveying 599 companies [95]. 62% of the Internet of Things (IoT) using companies were in the process or planning to implement the Digital Twin concept, and 13% were already utilizing it. A report from Research and Markets in 2017 forecasted that the global Digital Twin market will be worth USD 15.66 Billion by 2023, at a CAGR of 37.87% [4], while Grand View Research expects the market to be worth USD 155.84 Billion in 2030 [5]. Gartner identified the Digital Twin concept as one of the top 10 Strategic Technology Trends of 2017, 2018, and 2019 [96]–[98].

The Digital Twin is a promising concept that has received great interest from academia and the corporate field in recent years. It can be applied in numerous industries and promises high investment returns. Nevertheless, its loose definition and broad applicability challenge its prevalence and expectations.

1.2 Motivation

In this section, the underlying motives for this dissertation are introduced. Based on the previous development of the field, challenges are described, which form the overall goal of this dissertation and build the foundation for the individual aims of the included scientific papers.

Campos-Ferreira et al. (2019) [99] see the Digital Twin concept at its peak of inflated expectations on the Gartner technology hype cycle in 2019 (see Figure 9). They expected it to fall into the trough of disillusionment in the years after.

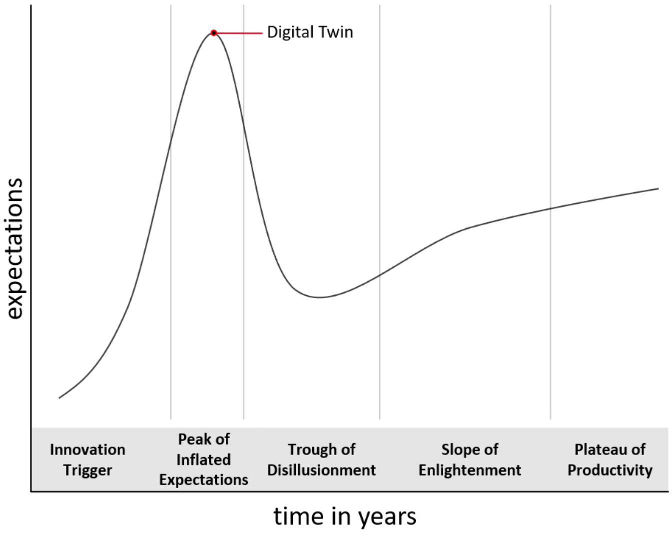


Figure 9: Illustration from Newrzella et al. (2021) [1]. *Gartner Hype Cycle and the Digital Twin concept, based on Campos-Ferreira et al. (2019)* [99].

Indications for this were already reported by Zborowski (2018) [14] in his article in 2018, where a client found the Digital Twin concept too confusing because it has a different meaning to every person using it. Instead, he suggested to “talk about the functionality of what you’re providing and not ‘digital twin.’” [14] Several other researchers have also mentioned this dilemma [100]–[106].

The presented research into scientific activities shows that numerous application scenarios are already discussed, but commercial applications and business cases are still rare. Tao et al. (2019) mention in their article “Make more digital twins” [107] the difficulty of assembling a team of multi-discipline specialists to build a precise Digital Twin as one of the main reasons for large companies such as Siemens or GE to develop Digital Twins, while smaller firms fall short.

Many benefits of Digital Twin applications are anticipated across industries. However, it is still difficult to estimate the value and effort involved and to determine Digital Twin use cases to start implementation with [88], [108]. This challenge creates uncertainty around the development of Digital Twin applications and further hampers its potential.

Furthermore, with the dissemination of the Digital Twin concept across industries, various applications are proposed, and numerous Digital Twin architectures describe specific applications differently. The Internet of Things (IoT) field has been structured through, among other things, the development of a universal reference architecture model. The field of Digital Twin still lacks standardization and common understanding, which contributes to the perceived confusion around the Digital Twin concept.

Even though the Digital Twin concept has received increased attention in academia and industry in recent years and the technology enablers are now available on the market, the commercial implementation of Digital Twin applications still presents a challenge. This dissertation aims to consolidate the field of Digital Twin by providing models and methodologies that address the challenges of deriving, designing, and describing Digital Twin use cases. The three included scientific papers contribute to this goal by addressing a specific need each.

1.3 Aims

This section describes the aims of this dissertation and of each scientific paper included in this dissertation.

This dissertation aims to consolidate the Digital Twin development cycle by introducing a Digital Twin framework for deriving, designing, and describing Digital Twin applications across industries. This is achieved through the contributions of the three entailing scientific publications.

“5-Dimension Cross-Industry Digital Twin Applications Model and Analysis of Digital Twin Classification Terms and Models” (2.1)
The first publication analyzed Digital Twin terms and models and derived main characteristics by which to describe Digital Twin applications across industries.

“Methodology for Digital Twin Use Cases: Definition, Prioritization, and Implementation” (2.2)
The second publication proposed a methodology for deriving and evaluating Digital Twin use cases, independent of the application domain.

“Three-dimension Digital Twin Reference Architecture Model for Functionality, Dependability, and Life Cycle Development across Industries” (2.3)
The third publication proposed a Digital Twin reference architecture model that considers functionality, dependability, and life cycle aspect when designing and visualizing Digital Twin applications across industries.

1.4 Related literature

Besides the related literature of the individual papers, there are Digital Twin methodologies describing the overall Digital Twin development cycle. In this section, these Digital Twin life cycles are described, and this dissertation's Digital Twin framework is allocated within them.

Parrott and Warshaw (2017) [88] propose a six-step Digital Twin development cycle to start and scale up Digital Twin application development (see Figure 10). The cycle consists of the steps imagine, identify, pilot, industrialize, scale, and monitor. In the imagine step, process opportunities for the Digital Twin concept are imagined and assessed. The most suitable Digital Twin use cases are determined in the identify step. Following, early value-creating Digital Twin applications are piloted in the pilot stage. Once success is demonstrated, the Digital Twin development and deployment process can be industrialized using established tools in the industrialize step. A successful Digital Twin application can be scaled to adjacent and interconnected processes in the scale step. Finally, in the monitor step, Digital Twin solutions should be monitored, and changes implemented accordingly to ensure value delivery.

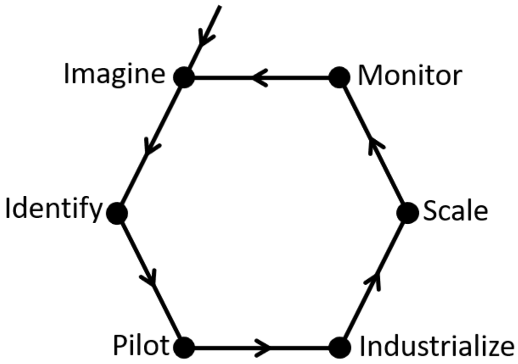


Figure 10: Illustration from Newrzella et al. (2022) [109]*, based on Parrott and Warshaw (2017)* [88]*. The Deloitte Digital Twin development cycle.*

Moyne et al. (2020) [110] introduce a high-level view of a common Digital Twin life cycle (see Figure 11). The life cycle can be broken down into two halves, the off-line (data at rest) development and the on-line (data in motion) deployment and maintenance. The first half consists of the steps envision, design, develop, verify, and validate. Historical data, analytics, and expert knowledge are used to understand the application environment, determine the feasibility of Digital Twin use cases, develop promising use cases into applications, and verify and validate them. The second half contains the steps deploy, use, evaluate, and maintain. The verified Digital Twin application is integrated into the existing system and continuously used and evaluated until maintenance is required.

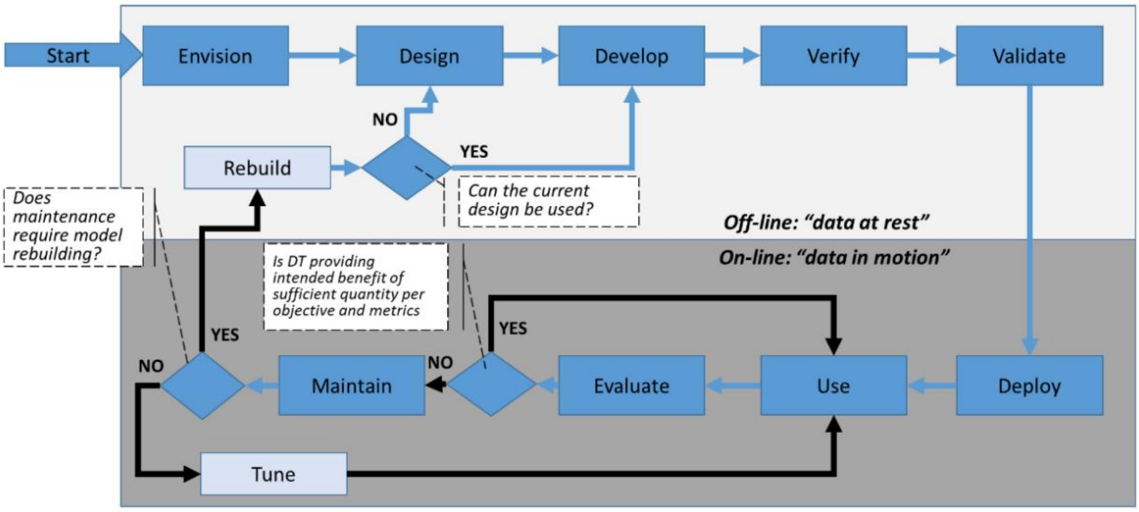


Figure 11: Illustration from Moyne et al. (2020) [110]. *Digital Twin life cycle.*

The Systems Development Life Cycle (SDLC) is commonly used in systems and software engineering to plan, create, test, and deploy an information system [111] and is also referred to in some Digital Twin development methodologies [112]. The SDLC can be applied to hardware and software projects as well as a mix of both. Numerous versions of the SDLC exist. The life cycle version discussed here consists of the six stages plan, analyze, design, develop, implement, and maintain. In the planning stage, the project manager plans for the upcoming project by defining the problem and its scope, for example. Requirements, stakeholder needs, and other project details are gathered, and ideas are derived and evaluated in the analysis stage. In the design stage, the details for the development are outlined and prepared. The actual development, such as the assembly and coding, takes place in the development stage, while when finished, it is implemented in the implementation stage. Maintenance of the project matter while in operation is taken care of at the end of the SDLC. The cycle can be reiterated for further updates or upgrades of the project matter.

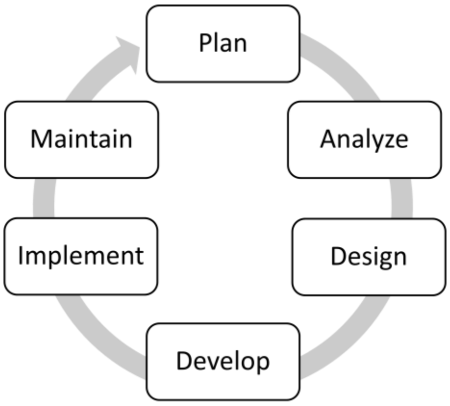


Figure 12: A six-stage version of the Systems Development Life Cycle (SDLC).

The Digital Twin framework described within this dissertation focuses on the initial stages of the Digital Twin development cycle. The aim is to derive the most promising use cases, design an architecture and communicate its concept to involved stakeholders. This process allocates the framework in the imagine and identify stages of Parrott and Warshaw (2017) [88], in the envision and design stages of Moyne et al. (2020) [110], and in the plan, analyze, and design stages of the SDLC.

1.5 Methods

At the beginning of the research period, general literature research on Digital Twin research and challenges was conducted. Strings containing "Digital Twin" in general and together with "Buildings," "Construction," "Healthcare," "Logistics," "Manufacturing," "Oil," "Gas," "Power," "Product Development," "Product Life Cycle," and "Vehicle" were searched. Google Scholar was chosen to avoid bias in favor of any specific scientific publisher, as recommended by Wohlin (2014) [113]. No time range was specified as the research field of Digital Twin is still rather young. The initial search was performed over six months, from October 2020 to March 2021, so only research published before March 2021 was considered. From the results, the Digital Twin concept and application research containing a physical entity was selected. More than 140 articles were analyzed, and the addressed and mentioned open challenges were noted. This analysis identified three open challenges that could be addressed within the scope and with the resources of this doctoral research. The three included research publications' aims were derived from this initial literature research.

During the initial literature research, besides the challenges, Digital Twin definitions, history, characteristics, classification dimensions, application examples, implementation structures, architectures, and market development research were recorded. This review was used to describe the Digital Twin research background in the first publication (2.1). In parallel to identifying the challenge of confusing Digital Twin descriptions, numerous Digital Twin terms were found and clustered into groups of similar descriptive characteristics (see chapter 2.1). The research also revealed main elements and characteristics of Digital Twin applications, which were derived based on prevalence and the authors' reputation in the field. Out of this analysis, five main characteristics for Digital Twin application descriptions were derived. Their applicability was validated by applying the description model to existing Digital Twin research from the fields of sports, transportation, construction, and manufacturing and showcasing how it facilitates understanding of Digital Twin applications.

To address the challenge of a missing Digital Twin use case development and prioritization methodology, literature research was conducted on the strings of words "Digital Twin," together with "development," "methodology," "method," and "prioritization." No time range was specified for the search performed in September 2021. Google Scholar did not show results that suffice the requirements of deriving and evaluating Digital Twin use cases. Searches of "use case prioritization" and "use case evaluation" resulted in three methodologies that could be applied in a limited form to Digital Twin use cases. These methodologies and known methodologies from manufacturing and innovation fields were analyzed for their applicability to Digital Twin use cases. The Digital Twin use case methodology described in chapter 2.2 was developed through a combination of aspects of these different methodologies. The Digital Twin use case methodology was tested and continuously improved within the theses of Schoueri (2021) [114], Castellanos (2022) [115], and Schwarz (2022) [116] (see appendix A). The Digital Twin use case development, and evaluation of a product from Siemens Healthineers was anonymized and used in parts as a validation example to showcase the applicability of the proposed methodology.

Based on the initial literature research on Digital Twin architectures and literature research conducted by Schoueri (2021) [114], additional literature research was performed on Google Scholar with the search terms “Digital Twin” together with “architecture,” “framework,” and “model.” More than 15 Digital Twin architectures were found. An analysis of the architectures identified two major dimensions considered in existing architectures: functionality and dependability. After excluding architectures that were too application-driven and did not follow a universal, cross-industry structure, 14 architectures were considered in the functionality dimension and six architectures in the dependability dimension. An analysis of commonly referenced architectures from the fields of Cyber-physical systems (CPS) and the IoT identified a focus on dependability aspects in CPS and the additional aspect of the life cycle in IoT. Other research has often mentioned the life cycle aspect as a core element of Digital Twin applications. It has been added to the other two dimensions to form the three-dimension Digital Twin reference architecture model described in chapter 2.3. The architecture model was validated by applying it to examples based on existing research and concepts from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector.

2 Publications

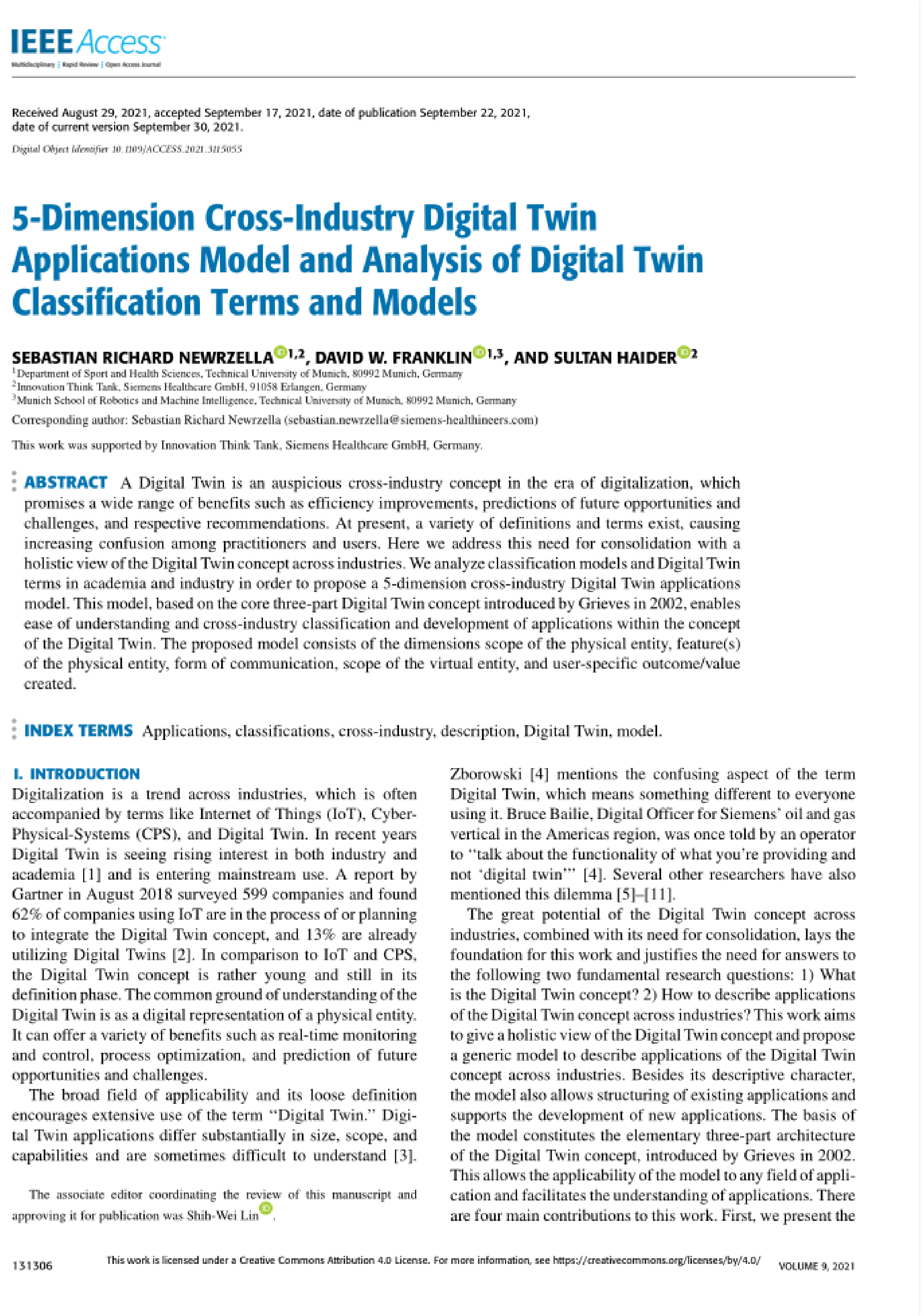
The following section presents the scientific papers included in this dissertation. All papers aim to consolidate the field of Digital Twin by each addressing one of the challenges described in chapter 1.2. The first paper considers the loose definition of Digital Twin and the often-vague description of Digital Twin applications by analyzing Digital Twin terms and models and proposing a universal Digital Twin definition and five characteristics to describe Digital Twin applications effectively (2.1). The second paper addresses the lack of a Digital Twin use case development and prioritization methodology that gives practitioners guidance on where to best start development of Digital Twin applications. A two-step methodology is proposed that derives impactful use cases based on stakeholder feedback and evaluates promising Digital Twin use cases considering stakeholder value-add, effort, and scaling potential (2.2). Finally, in the third paper, the numerous different Digital Twin architectures are consolidated into one cross-industry reference architecture model that addresses functionality, dependability, and life cycle aspects for designing and visualizing Digital Twin applications.

2.1 5-Dimension Cross-Industry Digital Twin Applications Model and Analysis of Digital Twin Classification Terms and Models

Authors: **S. R. Newrzella**, D. W. Franklin, and S. Haider

Abstract: A Digital Twin is an auspicious cross-industry concept in the era of digitalization, which promises a wide range of benefits such as efficiency improvements, predictions of future opportunities and challenges, and respective recommendations. At present, a variety of definitions and terms exist, causing increasing confusion among practitioners and users. Here we address this need for consolidation with a holistic view of the Digital Twin concept across industries. We analyze classification models and Digital Twin terms in academia and industry in order to propose a 5-dimension cross-industry Digital Twin applications model. This model, based on the core three-part Digital Twin concept introduced by Grieves in 2002, enables ease of understanding and cross-industry classification and development of applications within the concept of the Digital Twin. The proposed model consists of the dimensions scope of the physical entity, feature(s) of the physical entity, form of communication, scope of the virtual entity, and user-specific outcome/value created.

Contribution: I conducted an extensive literature review, clustered the findings, and acquired information on Digital Twin terms and models. I derived Digital Twin applications' main elements and characteristics and developed the proposed model. I wrote the original manuscript under the advisement of Prof. Sultan Haider and revised it with the assistance of Prof. Dr. David Franklin.



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5-Dimension Cross-Industry Digital Twin Applications Model and Analysis of Digital Twin Classification Terms and Models

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ABSTRACT A Digital Twin is an auspicious cross-industry concept in the era of digitalization, which promises a wide range of benefits such as efficiency improvements, predictions of future opportunities and challenges, and respective recommendations. At present, a variety of definitions and terms exist, causing increasing confusion among practitioners and users. Here we address this need for consolidation with a holistic view of the Digital Twin concept across industries. We analyze classification models and Digital Twin terms in academia and industry in order to propose a 5-dimension cross-industry Digital Twin applications model. This model, based on the core three-part Digital Twin concept introduced by Grieves in 2002, enables ease of understanding and cross-industry classification and development of applications within the concept of the Digital Twin. The proposed model consists of the dimensions scope of the physical entity, feature(s) of the physical entity, form of communication, scope of the virtual entity, and user-specific outcome/value created.

INDEX TERMS Applications, classifications, cross-industry, description, Digital Twin, model.

I. INTRODUCTION

Digitalization is a trend across industries, which is often accompanied by terms like Internet of Things (IoT), Cyber-Physical-Systems (CPS), and Digital Twin. In recent years Digital Twin is seeing rising interest in both industry and academia [1] and is entering mainstream use. A report by Gartner in August 2018 surveyed 599 companies and found 62% of companies using IoT are in the process of or planning to integrate the Digital Twin concept, and 13% are already utilizing Digital Twins [2]. In comparison to IoT and CPS, the Digital Twin concept is rather young and still in its definition phase. The common ground of understanding of the Digital Twin is as a digital representation of a physical entity. It can offer a variety of benefits such as real-time monitoring and control, process optimization, and prediction of future opportunities and challenges.

The broad field of applicability and its loose definition encourages extensive use of the term "Digital Twin." Digital Twin applications differ substantially in size, scope, and capabilities and are sometimes difficult to understand [3]. Zborowski [4] mentions the confusing aspect of the term Digital Twin, which means something different to everyone using it. Bruce Bailie, Digital Officer for Siemens' oil and gas vertical in the Americas region, was once told by an operator to "talk about the functionality of what you're providing and not 'digital twin'" [4]. Several other researchers have also mentioned this dilemma [5]–[11].

The great potential of the Digital Twin concept across industries, combined with its need for consolidation, lays the foundation for this work and justifies the need for answers to the following two fundamental research questions: 1) What is the Digital Twin concept? 2) How to describe applications of the Digital Twin concept across industries? This work aims to give a holistic view of the Digital Twin concept and propose a generic model to describe applications of the Digital Twin concept across industries. Besides its descriptive character, the model also allows structuring of existing applications and supports the development of new applications. The basis of the model constitutes the elementary three-part architecture of the Digital Twin concept, introduced by Grieves in 2002. This allows the applicability of the model to any field of application and facilitates the understanding of applications. There are four main contributions to this work. First, we present the

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history of the Digital Twin concept along with similar terms and concepts and the expected future development. Second, we provide a holistic view of the definitions of the Digital Twin concept and describe the Digital Twin concept for cross-industry application. Third, we analyze existing Digital Twin classification models and discuss Digital Twin terms used in industry and academia. Finally, out of the identified needs for explanation, we derive five elementary aspects by which to describe applications of the Digital Twin concept across industries.

II. RESEARCH BACKGROUND

In this section, we describe the development of the Digital Twin concept, how its interpretation and progress are majorly influenced by the field of manufacturing, and how other fields have slowly started participating in forming the concept. We define the concept for cross-industry application and determine its position among other trends of digitalization.

A. HISTORY OF DIGITAL TWIN

A "Twin" of a physical asset for the purpose of safe simulation and testing was first mentioned in 1970 in the aerospace industry when two space shuttles were built within the NASA Apollo program [12], [13]. The "Twin" on earth mirrored its counterpart in space and, after the oxygen tanks of the Apollo 13 mission exploded, helped develop an air purifier that the astronauts were able to build with the tools available to them. This example shows the potential of twins, especially when applied digitally [14]. David Gelernter first explained the idea of the Digital Twin concept in his 1991 book "Mirror Worlds," where he describes a virtual real-time copy of every aspect of life and how it affects business and daily life [15].

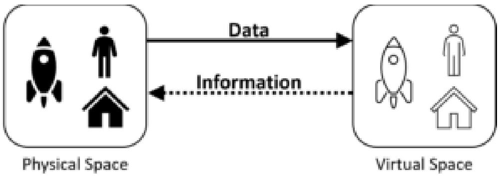

FIGURE 1. Digital Twin concept based on Grieves (2015) [16].

Michael Grieves informally introduced the concept of the Digital Twin in his product life-cycle management (PLM) presentation "Conceptual Ideal for PLM" at the University of Michigan in late 2002 (Figure 1). Grieves later accredits the minting of the term Digital Twin to his previous NASA colleague John Vickers, who named the concept in the NASA roadmap in 2010 [4], [17]. The origin of the Digital Twin can therefore be seen in manufacturing, aerospace in particular. While at its first mentioning in 2003, the concept was descriptive and the technology was not yet capable of supporting the Digital Twin idea, in the decade that followed, the enabling technology in physical and virtual space have been developed significantly and made the Digital Twin concept technically feasible [18]. The rise of the Internet of Things (IoT) (cheaper and better communicating sensors), developments in the computational field (Graphics Processing Unit (GPU), Tensor Processing Unit (TPU) and edge and cloud computing) and ultimately the outstanding success of Artificial Intelligence (AI), Machine Learning (ML) and Deep Learning (DL) lead to increased research on and use of Digital Twins. While the first definition of Digital Twin had a strong focus on products, the digitization of the manufacturing industry and the dawn of Industry 4.0 in the early 2000s widened the field of application of Digital Twins also to manufacturing systems [19]. Besides the technology push, there is a market pull with a need for greater flexibility in operation, online monitoring of processes and products, improved inventory management, and individualized services, to name a few [20].

The term and scope of Digital Twin have not been undisputed and similar concepts have been introduced. These concepts often have the same or partially the same features, but with different names such as device shadow [21], [22], virtual twin [23], virtual object [24], hyper-computational model [22], mirrored system [22], [25], synchronized virtual prototype [22], digital counterpart [26], digital surrogate [27], product agent [28], [29], avatar [30] and product avatar [26], [31].

As one example, the term Product Avatar was introduced by Hribernik *et al.* in 2006. It was described as a product-instance-centric information management concept. Each individual entity has a unique identifier, communicates with its surroundings, and can make decisions on its own future. Even though research on Product Avatar can be found before 2015 [26], [32], [33], the term Digital Twin seems to have replaced the term Product Avatar since then [34]. Other terms have not caught wider attention and mentioning in the scientific community either or stick only to specific technology fields [35]. In the field of construction, Digital Twin characteristics are often attributed to Building Information Modeling (BIM), even though BIM by itself does not work with real-time data [36], [37]. Alonso *et al.* [38] proposed a BIM Digital Twin platform to fill this gap.

While research with the term of Digital Twin has seen explosive growth in the scientific field since 2017 [34], several corporations such as Siemens [39], GE [40], and PTC [41] have adopted the term Digital Twin and contributed to its popularity also in the corporate field.

The Digital Twin was identified by Gartner to be one of the top 10 Strategic Technology Trends of 2017, 2018, and 2019 [42]–[44]. The International Data Corporation (IDC) projected 30% improvements in manufacturing cycle times of critical processes for companies investing in Digital Twins in 2018 [45]. A report from Research and Markets expects the Digital Twin market to be worth USD 15.66 Billion by 2023, at a CAGR of 37.87% [46].

Campos-Ferreira *et al.* [47] see the Digital Twin hype development at its peak of inflated expectations in mid-2019, with a trough of disillusionment and slope of enlightenment following and reaching the plateau of productivity sometime between 2024 and 2029 (see Figure 2).

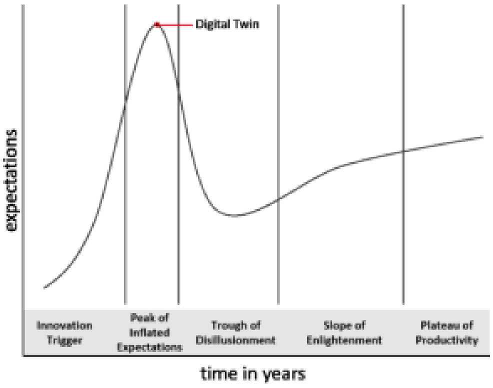

FIGURE 2. Gartner Hype Cycle and the Digital Twin concept, based on Campos-Ferreira *et al.* (2019) [47].

As demonstrated, Digital Twin is a rather young concept, still in the phase of definition. Its broad field of application holds great potential but also presents susceptibility to mismanaged expectations.

B. DEFINITIONS OF DIGITAL TWIN

Coming from a manufacturing background, the majority of existing definitions of the Digital Twin concept contain strong manufacturing and product aspects. As part of answering our first research question, we describe the Digital Twin concept in a holistic way, define it for cross-industry use, and position it among other digitalization trends.

The definition of "Digital Twin" is not commonly agreed on. Numerous review articles have been published containing analyses on existing definitions of "Digital Twin" [14], [34], [48]–[51]. Digital Twin definitions are often characterized by the field of application and the specific use case. The multidisciplinary character of the Digital Twin concept increases the difficulty of defining common ground. Engineering and IT disciplines define the concept differently, with a focus on modeling or information management, respectively [7].

NASA coined the term "Digital Twin" in 2010 and described it as a multi-physics, multi-scale simulation of an asset, incorporating high-fidelity modeling and simulation and situational awareness in real-time [17]. "Digital Twin" is defined by the International Academy for Production Engineering CIRP as "a digital representation of an active unique product (real device, object, machine, service or intangible asset) or unique product service system (a system consisting of a product and a related service) 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" [49].

The definition has continued to develop over time, with a shift in its focus depending on the character of its application. While the Digital Twin concept has its origin in a product-centric manufacturing environment, the definition has moved over time to a more generic concept, applicable to many more fields of application [11]. Further application domains so far addressed by research are for example Construction [37], [52]–[54], Healthcare [55]–[60], Oil and Gas Industry [61]–[65], and Logistics [19], [66]–[68]. Nevertheless, three main parts have been defined as essential to the Digital Twin concept in numerous research works [3], [6], [12], [69], [70] and are also referred to as the lowest common denominator of the Digital Twin concept in research [8], [9]. Michael Grieves illustrated them in 2003, and then again in 2015 (see Figure 1). They can be applied regardless of the application field. Grieves [16] describes these three main parts of a Digital Twin concept in his white paper as

a) A physical entity in real space,
b) A virtual entity in virtual space, and
c) Connections of data and information tying virtual and real entity together.

Further research works extended this three-part concept to detailed architectures [71]–[73] but the core parts remain the same.

Based on these three parts and Digital Twin descriptions, three characteristics can be attributed to the Digital Twin concept [13], [55], [74]:

- *Real-time capability*
  Tracking of the physical entity in real-time or near real-time from various types of data, such as engineering data, simulation data, and operational data.
- *Evolution*
  The Digital Twin evolves with the physical entity along the entire life cycle and always holds the current knowledge about the physical entity.
- *Functionality*
  The Digital Twin not only describes the current status and behavior of the physical entity, but derives solutions for it, such as performance optimizations and predictions.

In contrast to most product-centric manufacturing definitions of the Digital Twin concept we define the concept for cross-industry use by considering the elementary parts and characteristics. We propose the following definition: The Digital Twin concept contains a physical entity and its virtual representation, which evolves with its physical counterpart through real-time connection and offers additional value.

It must be mentioned that, even though in the Digital Twin concept, the virtual entity is always tied to its physical counterpart, one physical entity can have several virtual entities. This means several virtual entities of a single physical entity can exist within one Digital Twin application. These virtual entities can coexist and even communicate with each other, each with different features and a different purpose [6], [10], [11]. Grieves and Vickers [69] introduced the concept of a Digital Twin Aggregate (DTA), which aggregates many single virtual entities of different physical entities to represent, for example, general characteristics of a class of products. A virtual entity can, therefore, also be linked to more than one physical entity.

Semantically, the term "Digital Twin" is comprised of the words "Digital" and "Twin." While the word "Digital" refers to the virtual part of the Digital Twin concept, Dietz and Pernul [5] mention that the word "Twin" might be conflictual and should only be seen metaphorically. The Oxford dictionary defines the term "Twin" as "Something containing or consisting of two matching or corresponding parts" (Oxford University Press 2019). The virtual twin might be of different granularity and have different capabilities as its physical counterpart, which makes the term "Twin" rather misleading.

The virtual entity of a Digital Twin concept can also be referred to as a logical construct driven by use-cases. By combining various data in a structured way, a Digital Twin is defined by the use of this structured data for a specific purpose [75]. The Digital Twin concept uses a wide range of technologies but represents an idea belonging more to the semantic than the technology layer [7].

Here we universally use the capitalized spelling "Digital Twin" as we also use capitalized spelling for other concept names. The three-part Digital Twin concept is referred to as "Digital Twin concept" (see Figure 3). Within other works, the term "Digital Twin" repeatedly refers to only the virtual part of the concept, and its link to a physical entity is often overlooked. In order to avoid misconceptions, we refer to the "Digital Twin concept" with its physical and virtual entity and only use the term "Digital Twin" for the virtual entity of the Digital Twin concept when necessary or when the paper of reference uses the term accordingly. "Digital Twin application" refers to the Digital Twin concept being applied in a specific use case. Terms are placed in quotes when the terms themselves are under discussion.

Apart from Digital Twin-like terms, there are supporting technologies and concepts that often build the foundation for a Digital Twin concept implementation or enrich its functionalities. In order to clarify the position of the Digital Twin concept in relation to these technologies and concepts, we describe some of them here and explain their association to the Digital Twin concept.

1) DIGITAL THREAD

The terms "Digital Thread" and "Digital Twin" were used interchangeably by the U.S. Air Force in 2013 in its science and technology vision as a game-changer in manufacturing. It was described as having historical memory, gaining state awareness, and being able to develop prognoses by analyzing current and past knowledge [14], [76]. Further research has differentiated the Digital Thread from the Digital Twin as the "communication framework that allows a connected data flow and integrated view of the asset's data throughout its life-cycle across traditionally siloed functional perspectives"' [77]. The Digital Thread as the communication framework, therefore, enables the Digital Twin concept.

2) INTERNET OF THINGS (IoT)

The definition of IoT has developed over time and can be described as "the networking capability that allows

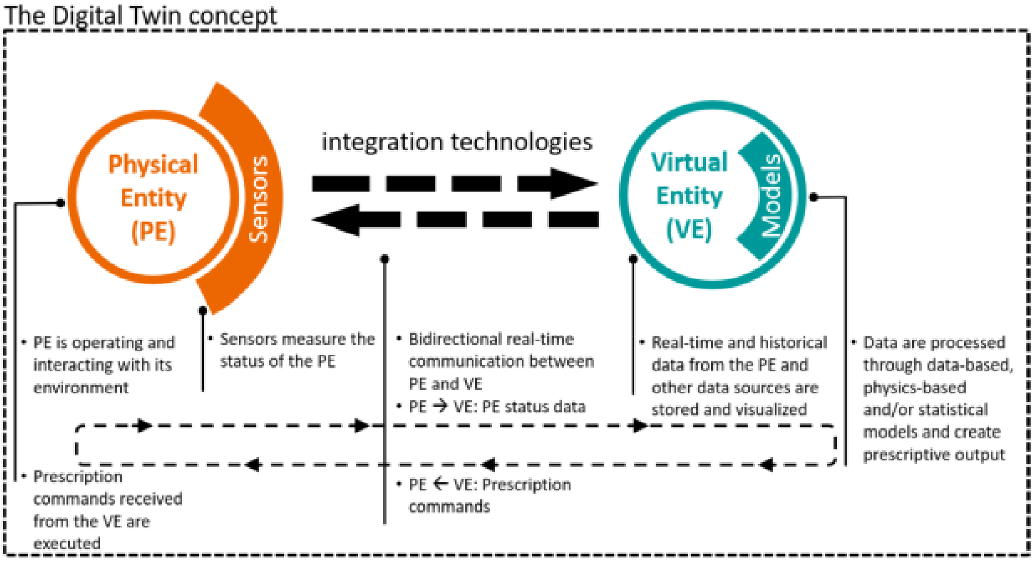

FIGURE 3. The Digital Twin concept.

information to be sent to and received from objects and devices (such as fixtures and kitchen appliances) using the Internet" [78]. IoT is often described as the enabler of the Digital Twin concept [79] because the IoT sensor data often serves as input from the physical entity. The application of IoT in different fields opens up the potential for Digital Twin applications in these fields, such as Industrial Internet of Things (IIoT), Internet of Medical Things (IoMT), and Internet of Meat (IoM).

3) CYBER-PHYSICAL SYSTEMS (CPS)

CPS represent systems where the physical world is connected to computing and communication entities over the Internet [80], [81]. Interconnected devices with extensive access to information and services have a wide range of applications, in the field of autonomous driving, manufacturing, and healthcare, among others [6], [81]. The virtual entity within the Digital Twin concept virtually models and simulates its physical counterpart and enables CPSs to provide services of self-configuration, self-adjustment, and self-optimization [6].

4) CYBERNETICS

The core goal of Cybernetics is to understand and define systems based on the concept of circular feedback [82]. A Digital Twin is self-regulating towards the set goal of its use-case by continuously updating its current status and modeling and simulating potential outcomes, which are again fed back to its physical entity. This behavior easily links the Digital Twin concept to the field of Cybernetics [20].

The Digital Twin concept has a diverse character but can be described by its core parts and characteristics. This makes the concept applicable to a wide range of industries and fit into existing technologies and concepts.

III. ANALYSIS OF EXISTING DIGITAL TWIN CLASSIFICATIONS

The many different interpretations, scopes, and fields of applications lead researchers and companies to cluster Digital Twin applications into distinct groups in order to better describe the idea behind a specific Digital Twin application. In this section, we summarize classification models and allocate and describe Digital Twin terms from academia and industry to common classification dimensions.

A. CLASSIFICATION MODELS

The development of complex systems requires structured approaches to ultimately reduce the risks of unexpected and non-favorable outcomes. Several models have been developed to classify existing applications of the Digital Twin concept for developers to learn from similar applications and to then develop new applications at better manageable risks. The purpose and dimensions of some of these models are explained in Table 1. The purpose of a model refers to its intended use mentioned by the authors, which is achieved by clustering Digital Twin applications into different categories, often called dimensions.

Deuter and Pethig [83] propose three Digital Twin classification dimensions based on the Reference Architecture Model Industrie 4.0 (RAMI 4.0), which was developed to create a common understanding of standards, use cases, and norms around Industrie 4.0 [84]. Digital Twin applications can be described and classified along the same dimensions. The Hierarchy Levels dimension is subdivided into levels of functionalities and responsibilities ranging from a single product to a connected world. The Life Cycle & Value Stream dimension puts in focus the product life cycle stages at which a Digital Twin can be applied. Starting at the development stage, a Digital Twin can also be applied in the production and usage stages. The Layers dimension describes different viewpoints on a Digital Twin. A Digital Twin can be discussed from the asset perspective, from a communication and functional viewpoint, or from a business view, among others.

In their work, Stark [85] introduce the "Digital Twin 8-dimension model" for planning the scope and type of a Digital Twin. The model can be subdivided into a Digital Twin context and environment side and a behavior and capability richness side. The former consists of the dimensions integration breadth, connection mode, update frequency, and product life cycle. The latter includes the dimensions CPS intelligence, simulation capabilities, digital model richness, and human interaction.

Enders and Hoßbach [51] analyzed Digital Twin applications across industries and derived six common dimensions for categorizing different applications. These dimensions are industrial sector, purpose, physical reference object, completeness, creation time, and connection. The purpose dimension refers to the form of outcome created by a Digital Twin, and the dimension completeness indicates the number of features included in a Digital Twin. Creation time is subdivided into before and after the physical twin creation, and connection consists of the three forms no connection, one-directional, and bi-directional.

Uhlenkamp *et al.* [86] divide Digital Twin applications into seven dimensions in order to classify future Digital Twin applications independent of their domains. Based on a thorough literature review, they derive the dimensions Goals, User focus, Life cycle focus, System focus, Data sources, Data integration level, and Authenticity. Potential goals are mentioned as information acquisition and analysis, decision and action selection, and action implementation. A single and multiple users can be addressed within the User focus dimension, and a Digital Twin can belong to one or multiple life cycle phases in the Life cycle focus dimension. The scope of the physical entity is described in the System focus dimension ranging from component to system of systems. Measurements, virtual data, and knowledge are defined as separate forms of data sources. The form of data flow is represented as manual, semi-automated, and fully automated in the Data integration level dimension. Authenticity describes the conformity of a Digital Twin with its physical twin.

Agnusdei *et al.* [87] focus on the safety domain in the field of manufacturing. They propose a framework that supports

TABLE 1. **Digital Twin classification models.**

Authors	Purpose	Dimensions
Deuter & Pethig [83]	Description and classification of Digital Twin applications	• Hierarchy levels • Life Cycle & Value Stream • Layers
Stark et al. [85]	Planning the scope and type of a Digital Twin	• Integration breadth • Connection mode • Update frequency • Product life cycle • CPS intelligence • Simulation capabilities • Digital model richness • Human interaction
Enders & Hoßbach [51]	Categorizing Digital Twin applications	• Industrial sector • Purpose • Physical reference object • Completeness • Creation time • Connection
Uhlenkamp et al. [86]	Classifying future Digital Twin applications independent of their domain	• Goals • User focus • Life cycle focus • System focus • Data sources • Date integration level • Authenticity
Agnusdei et al. [87]	Assessment of current and development of new Digital Twin applications	• Safety issue • Data acquisition • Data processing
Lechler et al. [8]	Enabling and facilitating Digital Twin application classifications	• Application level • Domain • Timing
PTC Inc. [88]	Organizing current and develop future Digital Twin applications	• Source • Contextualize • Synthesize • Orchestrate • Engage

the assessment of current and development of new Digital Twin applications, leading to improved safety designs and safety management processes. Their framework consists of three dimensions, each subdivided into categories of increasing complexity and reliability. The dimension Safety issue classifies risks into machine based, human based, and human machine interactions risks. Data acquisition can occur from random data, historical data, or in real-time. The data processing can be executed through statistical, simulation, or artificial intelligence techniques.

Lechler [8] propose the Digital Twin Structure Model, which aims to enable and facilitate Digital Twin application classifications. In their model, the Digital Twin is located in the executive layer, addressing the entire life cycle and covers products, processes, and resources. The three described Digital Twin dimensions are Application Level, Domain, and Timing. The Application Level characterizes the purpose of the Digital Twin in Visualize, Identify, Predict, and Control. The Domain dimension suggests features of the physical entity which the Digital Twin describes, such as Physical, Logistic, Software, Economic, and Derived. The last dimension focuses on the temporal quality of the communication between physical and virtual entity, taking place asynchronously, in near real-time, or in real-time.

The American computer software and services company PTC Inc. proposes five steps by which to organize current and develop future Digital Twin applications [88]. The Source step defines the data sources for the Digital Twin application. The data handling is discussed in the Contextualize step. The Synthesize step defines the types of insights the Digital Twin is driving, the Orchestrate step describes the actions triggered by the Digital Twin, and the Engage step elaborates the interaction of people with the Digital Twin.

As described, several Digital Twin classification models have been proposed so far, with between three and eight dimensions and often with a focus on applications in product-centric manufacturing. Many models have been derived from past applications in this field, which ultimately complicates cross-industry knowledge transfer.

B. DIGITAL TWIN TERMS

Besides the presented Digital Twin classification models, numerous researchers and companies have introduced specific terms to refer to certain forms of Digital Twin applications within one dimension. This serves the purpose of clarifying characteristics of Digital Twin applications and showcasing the scaling potential which results from common application clusters. A report by IoT analytics identified three dominant dimensions by which Digital Twins are commonly classified: hierarchical level, life-cycle phase, and functional use [89]. The specific Digital Twin application terms from academia and industry were found to follow these dimensions and are presented along these in the respective tables.

1) HIERARCHICAL LEVEL

The hierarchical level determines on what scope the Digital Twin is applied, from informational and component, over product and process to system and multi-system level.

General Electric (GE) categorizes its Digital Twin portfolio accordingly into the three subtypes of Asset Digital Twin, Process Digital Twin and Network Digital Twin [40]. According to GE, their Asset Digital Twin works on operational data of components or systems of assets, while the Network Digital Twin helps grid operators to manage real-time changes to the grid and focuses on interdependencies within the grid. The Process Digital Twin creates models to optimize processes to fulfill quality, cost, and volume objectives.

Zborowski [4] mentions the Siemens classification of Digital Twins with plant twin and process twin. He mentions the degree of detail or accuracy of different Digital Twins as the reason for subdividing the plant twin into equipment-level

TABLE 2. Hierarchical level Digital Twin classification terms.

<table>
<tr><th>Hierarchical Level</th><th>Informational</th><th>Component</th><th>Product</th><th>Process</th><th>System</th><th>Multi-System</th></tr>
<tr><td rowspan="2">GE [40]</td><td colspan="3" rowspan="2">Asset DT</td><td rowspan="2">Process DT</td><td>Asset DT</td><td></td></tr>
<tr><td colspan="2">Network DT</td></tr>
<tr><td>Siemens (Zborowski) [4]</td><td colspan="3">Equipment-level Twin</td><td>Process Twin</td><td>System-level Twin</td><td>Plant-level Twin</td></tr>
<tr><td>IBM [90]</td><td></td><td>Part Twin</td><td>Product Twin</td><td></td><td>System Twin</td><td></td></tr>
</table>

TABLE 3. Life-cycle phase Digital Twin classification terms.

Life-cycle Phase	Design	Building	Operation	Maintenance	Optimization
Rosen et al. [91]	Digital Product Twin	Digital Production Twin	Digital Performance Twin		Digital Performance Twin
Trauer et al. [75]	Engineering Twin	Production Twin	Operation Twin		
Siemens [92]	Digital Twin of the Product	Digital Twin of Production	Digital Twin of Performance		
Tharma et al. [93]	*Digital Model*	*Production Twin*		*Service Twin*	

TABLE 4. Functional use Digital Twin classification terms.

<table>
<tr><th>Functional Use</th><th>Digitize</th><th>Visualize</th><th>Simulate</th><th>Emulate</th><th>Extract</th><th>Orches-trate</th><th>Predict</th></tr>
<tr><td>US DoD [94], [95]</td><td></td><td>Mirror</td><td>Simulation</td><td></td><td></td><td></td><td>Predict activities or performance</td></tr>
<tr><td rowspan="4">ABB [96]</td><td colspan="3">Design</td><td></td><td></td><td></td><td rowspan="3">Prediction</td></tr>
<tr><td colspan="4">System integration</td><td></td><td></td></tr>
<tr><td colspan="5">Diagnostics</td><td></td></tr>
<tr><td colspan="7">Advanced Services</td></tr>
</table>

TABLE 5. Data type/ data flow Digital Twin classification terms.

<table>
<tr><th rowspan="2">Data Type/ Data Flow</th><th rowspan="2">Test data
(assumptions)</th><th rowspan="2">Historical data
(manual data flow and/or not continuously updated)</th><th colspan="2">Realtime data</th></tr>
<tr><th>Unidirectional automated data flow</th><th>Bidirectional automated data flow</th></tr>
<tr><td>Kritzinger et al. [97]</td><td></td><td>Digital Model</td><td>Digital Shadow</td><td>Digital Twin</td></tr>
<tr><td>Chakshu et al. [98]</td><td>Passive Digital Twin</td><td>Semi-active Digital Twin</td><td colspan="2">Active Digital Twin</td></tr>
</table>

twin, system-level twin, and plant-level twin. The equipment-level twin focuses on product life cycle management data in the form of engineering and manufacturing data, while the combination of equipment to a functioning unit is described by a system-level digital twin. The plant-level twin combines multiple systems and models the overall performance of a plant. The process twin enables automation system testing and engineering simulations.

Kienzler [90] describes the IBM hierarchical Digital Twin classification of part twin, product twin, and system twin. A part twin represents a small part of a bigger system. A product twin is made up of smaller part twins and represents an assembly of parts. A system twin consists of product twins and represents the aggregation of many products. The functionalities of all three twins are similar but with different hierarchical scopes.

As demonstrated in Table 2, the classification of Digital Twin applications by the hierarchical level of its physical entity is commonly used among corporations and divided into component, system, and multi-system levels, with the process level taking a separate spot in this subdivision. This type of classification highlights the different scopes of applications, their added value on each level, and their interaction in the bigger picture.

2) LIFE-CYCLE PHASE

While the hierarchical level does not consider the point in the product life-cycle where the Digital Twin concept is applied, the classification by the life-cycle phase of a Digital Twin application does so specifically. Common classification clusters range from design and building to operation, maintenance, optimization, and finally decommissioning. This classification of Digital Twin concepts is mostly applicable to products and only limitedly applicable to, for example, Digital Twin concepts of a living being such as a human. As no Digital Twin terms were found for the Decommission stage, it is not considered here.

Rosen *et al.* [91] define the Digital Product Twin to represent all design artifacts of a product, the Digital Production Twin to include the manufacturing models and

TABLE 6. Sophistication/maturity Digital Twin classification terms.

Sophisti-cation/ Maturity	Without unique physical entity	Digital Twin of a single physical entity			Fusion of Digital Twins of several physical entities
		Simple/ Little data (basic functionality)	Moderate complexity/ amount of data (enhanced functionality)	Complex/ Much data (e.g. environment involved)	
Grieves & Vickers [69]	Digital Twin Prototype	Digital Twin Instance			Digital Twin Aggregate
Kucera et al. [99]		Partial Digital Twin	Clone Digital Twin	Augmented Digital Twin	
Madni et al. [100]	Pre-Digital Twin	Digital Twin	Adaptive Digital Twin	Intelligent Digital Twin	
Oracle [101], [102]		Simple Device Model/ Virtual Twin	Industrial Twin		
			Predictive Twin	Twin Projections	
Hagan [95]	*Digital System Model*	*Digital Twin (enabled by Digital Thread)*			

processes, and the Digital Performance Twin to analyze operational data to assess performance and derive insights. Trauer *et al.* [75] name these three product-lifecycle-phase-based Digital Twins Engineering Twin, Production Twin, and Operation Twin. At Siemens, they are referred to as Digital Twin of the product, Digital Twin of production, and Digital Twin of performance [92].

Tharma *et al.* [93] divide the Digital Twin into three phases based on its life-cycle phase as well as the data scope. The Digital Model includes all documentation and models from product release with all products variants (as designed, 150% digital product description). The Production Twin contains all information about the manufacturing of the specific product (as-built, 100% realistic, and specific representation). The Service Twin reduces the data scope to the information necessary for operation (as maintained, <100%, without nonrelevant data for operation). These models range from including all product variants (Digital Model) to one product variant (Digital Twin) to one product variant with only information necessary for the product in operation (Service Twin). It must be mentioned that in this classification, the link of a Digital Twin to a unique product, with real-time data connection, is missing, and only pre-defined information about the product in general is considered. This does not fulfill the Digital Twin definition as mentioned before.

The classification of Digital Twin applications by the point of application in the product life-cycle is commonly used in product-centric manufacturing environments (see Table 3). The common sub-categories Design, Building, and Operation emphasize the data used as input for the Digital Twin application and indirectly suggest addressed users and their respective received value from the Digital Twin application.

3) FUNCTIONAL USE

While the classification by life-cycle phase indirectly suggests potential added value for specific users, the dimension of functional use of a Digital Twin application tries to directly subdivide applications by the form of outcome or value created by a Digital Twin application. While a digital footprint just digitizes information of the physical entity, Digital Twin concepts can, for example, predict the future behavior of the physical entity. Specific Digital Twin terms have not been found within this dimension, but descriptions of types of functional uses are often used to describe Digital Twin applications.

In its first definition by the US Department of Defense the Digital Twin was described as an as-built simulation system, to mirror and predict activities and/or performance of the physical entity [94], [95].

The electrical equipment company ABB mentions the following Digital Twin functional applications: Design, System integration, Diagnostics, Prediction, and Advanced services [96]. Design Digital Twin simulations and visualizations provide an early indication to mechanical, thermal, electrical, and interrelationships between the aspects, as for example visualization of options in the planning of Net Zero Energy Buildings' in the field of construction [54]. Digital Twins can support system integration by simulating the interplay of components reducing the integration effort and customer downtime. Zborowski (2018) [4] describes the real-time-updated Digital Twin model of an offshore oil rig in the planning stage, accessible by all relevant stakeholders, resulting in fewer reworks. Visualizations and simulations of the real-time status of the physical entity allow troubleshooting and advanced diagnostics as part of the Digital Twin usage. Based on past and present operational and sensor data, predictive algorithms of the Digital Twin are able to provide insights into the condition of the physical entity with respect to potential future developments. This helps to improve the handling of the physical entity in performance optimization and maintenance, among others. Coraddu *et al.* [103] propose a ship's real-time marine fouling diagnosis using continuous monitoring system data. Digital Twins can offer advanced services [104] by providing, for example, IoT connectivity and analytics algorithms insights to subscribing customers [96].

Rasheed *et al.* [20] mention the eight value additions of Digital Twins presented by the software and hardware manufacturer Oracle: Real-time remote monitoring and control, greater efficiency and safety, predictive maintenance and scheduling, scenario and risk assessment, better intra- and inter-team synergy and collaboration, more efficient and informed decision support system, personalization of products and services, and better documentation and communication.

As can be seen in the aforementioned cases, Digital Twin applications often provide combinations of functional uses to generate value in a specific use-case (see Table 4). A distinct separation of applications based on these functional uses is difficult to achieve, but a description of the application scenario using the applied functional uses is possible and facilitates the understanding of the application scenario.

4) DATA TYPE

Functional uses and value created by Digital Twin use-cases are driven by the data provided by the physical entities. Scully [89] therefore propose a fourth dimension called data type, in which a Digital Twin is classified by its use of data: real-time data, historical data, or test data.

Kritzinger *et al.* [97] put their focus on the automation of data flow between the physical and the virtual entity and introduced the terms "Digital Model" and "Digital Shadow," aside from the term "Digital Twin." The Digital Model manages the bidirectional data flow manually, which means there exists no real-time data flow from the physical to the digital object and the feedback loop back to the physical entity is also handled manually. The Digital Shadow, also known as digital footprint of an object, receives real-time data from the physical entity and visualizes its state, but simulation and modelling insights are only fed back to the physical entity manually. The Digital Twin ensures automated bidirectional data flow, feeding the data insights and control commands back automatically to the physical entity. The classification of Kritzinger *et al.* [97] has been accepted and used in several other research works [52], [66], [105].

Chakshu *et al.* [98] mention an active Digital Twin, which is continuously updated by its physical counterpart, a semi-active Digital Twin, which updates and analyses data in batches and not continuously, and a passive Digital Twin, which considers not continuously updated data and modeling assumptions. The authors also mention the possibility of an active-passive-mixed Digital Twin, which continuously updates some parameters and, for example, uses modeling assumptions for some other parameters.

The classification of Digital Twin applications by the type of data communication gives a good indication of the "liveliness" of a Digital Twin application and helps in addressing this important point of discussion about what a Digital Twin is and whatnot. An application can run on test data, historical data and/or real-time data (see Table 5), and discussions are still ongoing about which of these data types have to be present for an application to classify as a Digital Twin concept.

5) LEVEL OF SOPHISTICATION OR MATURITY

While the data type classification focuses on the flow of data, the level of sophistication or maturity of a Digital Twin application refers to the level of information and features generated with that data.

Grieves and Vickers [69] introduce the terms "Digital Twin Prototype" (DTP), "Digital Twin Instance" (DTI), and "Digital Twin Aggregate" (DTA). A DTP is a virtual representation of a not-yet-existing physical entity. A DTI represents a single and unique physical entity, whereas a DTA combines the data of DTIs to derive universally applicable predictions and recommendations within the aggregation of objects.

Kucera *et al.* [99] define a Partial Digital Twin to involve only a small number of data sources, a Clone Digital Twin to contain all meaningful and measurable data from the physical entity, and an Augmented Digital Twin to enhance the asset data with external data from different sources.

Madni *et al.* [100] describe a Pre-Digital Twin as a virtual system model of the not-yet-existing physical twin. The Digital Twin has a physical counterpart, learns from its data, and optimizes its behavior or provides other valuable information or services. The Adaptive Digital Twin adapts itself and especially its user interface to the users' preferences and priorities in different contexts, whereas the Intelligent Digital Twin, in addition to the features of the adaptive Digital Twin, has a high degree of autonomy by sensing its environment and learning patterns from both the environment and from previously unknown scenarios.

Oracle subdivides its Digital Twins based on the complexity and available functionalities. A Simple Device Model or Virtual Twin only contains a set number of target-values and actual-values of the physical asset, whereas an Industrial Twin consists of physics-based design information of a physical asset, which uses PLM tools and real-time data to monitor and augment the physical asset [101]. A Predictive Twin analyses data to predict its own future, while a Twin projection connects these insights with back-end business applications and enables entire intelligent systems [102].

The Defense Acquisition University defines the Digital System Model to be a digital representation of a system, integrating technical data and associated artifacts along the system life cycle [95]. While the Digital System Model only collects static development information, the Digital Thread enables data flow and interplay of data sources to inform decision-makers and provide actionable information.

As can be seen in Table 6, for classifying as a full application of the Digital Twin concept, many researchers agree that at least one unique physical entity is required. Different complexities of Digital Twin applications of a single physical entity exist under various names. Grieves described the idea of fusing several single Digital Twins into one Digital Twin Aggregate, which represents the general behavior and characteristics of a physical entity that exists in multiple copies within the field of application.

Apart from the aforementioned types of Digital Twin classifications, some research mentions the general applicability across clusters. Klostermeier *et al.* [104] present DT applications in the Aerospace industry, the simulation technology, and along the entire product life-cycle, but also mention that application scenarios in this new technology are still developing and entirely new concepts are possible.

The popularity of the Digital Twin concept benefits from the wide range of application domains, while the concept at the same time struggles with the inclusion and description of the diverse application scenarios that come along with it. In order to convey the characteristic of interest of a Digital Twin application, researchers and companies have developed Digital Twin terms that help classify Digital Twin applications. With a growing number of terms and clusters and no common ground on which they are based, this development adds to the confusion around the Digital Twin concept instead of facilitating its understanding.

IV. 5-DIMENSION CROSS-INDUSTRY DIGITAL TWIN APPLICATIONS MODEL

The missing common ground in the variety of Digital Twin classification models and terms in both academia and industry results in a variety of different classification dimensions and similar terms with different meanings as well as different terms with similar meanings. Furthermore, descriptions of Digital Twin applications often lack a common structure by which to intuitively convey their main setup and characteristics.

We propose a 5-dimension Digital Twin applications model which is based on the three core parts of the Digital Twin concept introduced by Grieves in 2002. This aims to give descriptions of Digital Twin applications an intuitive structure and facilitate the understanding of the setup and added value of Digital Twin applications. This fundamental basis for classification allows the application of our model across industries. The model can also be used for the classification of existing as well as the planning and the development of new Digital Twin applications. An allocation of the five dimensions to the three-part Digital Twin concept is demonstrated in Figure 4.

1) **Scope of the physical entity**
   A Digital Twin always refers to a specific physical entity. It is essential to define the scope of the subject for the Digital Twin to understand its application. The subject can, for example, be a specific product, a distinct manufacturing process, a unique building part, or a concrete organ of a human body.
2) **Feature(s) of the physical entity**
   A Digital Twin always focuses on certain features or properties of its physical entity. Instead of representing every little detail of its physical entity down to the atomic level, a Digital Twin only mirrors features defined by its use case. To understand the application scenario, it is important to well define the feature(s) considered for the Digital Twin. Features can, for example, include the user interaction with a product, the energy consumption of a manufacturing process, the wall integrity of a building part, or the stress sensitivity of a human organ.
3) **Form of data communication**
   The form of data communication defines the relationship between the physical and the virtual entity. Unidirectional or bidirectional communication can take place in real-time, near real-time, or batch. Depending on the use case, the communication from the physical entity can, in part, go to an edge-device (on-premise) or to the cloud. Besides data communication to the direct physical entity, the form of data communication to other data sources also has to be considered. This aspect of the Digital Twin application description goes hand-in-hand with the scope of the virtual entity.
4) **Scope of the virtual entity**
   The virtual entity handles data from different sources and combines them in a model. Defining the scope of the virtual entity lays the foundation for the understanding of the value creation of a Digital Twin application. Besides the data from the physical entity, the virtual entity can receive and analyze data from existing environmental tools, from surrounding sensors and interplaying systems, and from similar Digital Twins in other locations. This data can, for example, be combined in data-based, physics-based and/or statistical models. A Digital Twin of a human heart for stress sensitivity analysis can, for example, include live and historical pulse data from the body itself, information about the person's schedule, as well as information from persons with similar conditions and combine this data in a data-based model, simulating the stress behavior of the person's heart.
5) **User-specific output/value created**
   The Digital Twin utilizes the assimilated and processed data to create value for specific users. The form of the output created is personalized for the addressed user and defines the functionality of the Digital Twin. A Digital Twin application is not limited to a single user but can address several users in the form of several outputs. These different outputs can come from one or from several models. The form of value created can be design recommendations for the product design engineer based on a product usage model, automated process scheduling for the plant manager based on the simulation of the energy consumption of a manufacturing process, the risk assessment of a wall restoration for historical building maintenance engineers based on an emulation of the wall integrity of a building, or the stroke warning of a patient and notification of the closest emergency unit based on a statistical model prediction of the heart stress sensitivity.

To validate the general applicability of this model as well as its ease of understanding, we demonstrate its use on Digital Twin research from different scientific fields.

Following the proposed structure, the work of Barricelli *et al.* [60] can be described as a Digital Twin of a human's fitness condition combining near real-time wearables data and historical and frequently updated training performance evaluation data in a data-based model for predicting training performance and suggesting behavior modifications to the athlete. The scope of the physical entity is defined as "a human," the feature of the physical entity is specified as "fitness condition." The form of data communication is closely linked to the scope of the virtual entity by being described as "near real-time wearables data and historical and frequently updated training performance evaluation data in a data-based model for predicting training performance." The user-specific output/value created is explicitly mentioned as "suggesting behavior modifications to the athlete."

Coraddu *et al.* [103] built a Digital Twin of a ship's marine fouling condition using the vessel's continuous monitoring system data in a data-based model for support of the fleet management by scheduling hull and propeller cleaning when an unprofitable increase in speed loss and fuel consumption is estimated. In this application of our proposed model the scope of the physical entity is defined as "a ship," with its feature being the "marine fouling condition". The form of data communication is mentioned as "continuous monitoring system data," which is analyzed in "a data-based model" for estimating "speed loss and fuel consumption" as the scope of the virtual entity.

The user-specific output/value created is highlighted as "support of the fleet management by scheduling hull and propeller cleaning."

Angjeliu *et al.* [53] tested a Digital Twin of a historical masonry building's structural system integrity by considering historical construction stages, structural surveys, in situ observations and measurements, and material properties in geometric models using finite element modelling to reproduce the damage observed and enable preventive maintenance of future applications and understand past documented building failures. "Historical masonry buildings" are defined as the scope of the physical entity and its feature as the "structural system integrity". The form of data communication is mentioned as historical data. The scope of the virtual entity is described as "construction stages, structural surveys, in situ observations and measurements, and material properties, combined with a geometrical finite element model to reproduce the damage observed. While the user is not specifically mentioned in the research paper, the outcome is described as "enable preventive maintenance of future applications and understand past documented building failures".

Söderberg *et al.* [106] propose a Digital Twin of a welding process' welding quality, which takes available scan data of the welding parts as input to simulate (finite element analysis) the best combination of welding parts to achieve lowest gap/flush between the parts and return to the physical welding process the welding sequence and condition for minimized deviations, thermal stress, and maximized life of the welded assembly. In this application of our proposed model, "a welding process" is introduced as the scope of the physical entity, and its "welding quality" is defined as the feature of the physical entity considered for the Digital Twin application. The form of data communication is described by the authors as "available scan data of the welding parts", which also partly describes the data input for the virtual entity. The virtual entity also includes a simulation (finite element analysis) using said scan data to achieve the lowest gap/flush between parts with minimized deviations, thermal stress, and maximized life of the welded assembly. The user-specific output is mentioned as the welding sequence and condition for the physical welding process to follow.

The model and its five dimensions were introduced, described, and the model's applicability in different industries was validated. In comparison to other models, it is guided by the elementary parts and characteristics of the Digital Twin concept and therefore enables cross-industry application and facilitates understanding of the application by guiding the practitioner by a common and intuitive structure.

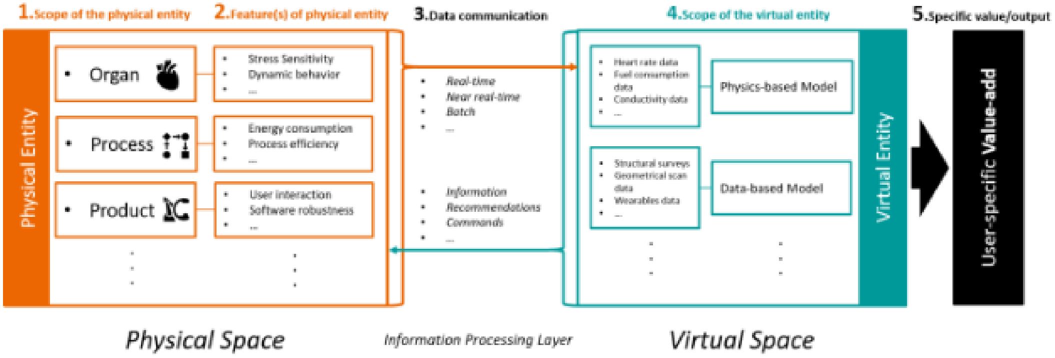

FIGURE 4. Five aspects of Digital Twin applications, allocated to the three Digital Twin parts introduced by Grieves (2015) [16].

Furthermore, the model highlights the granularity of the Digital Twin application by separately mentioning the feature of interest of the physical entity and emphasizes the added value for the user. The model's dimensions with the core three-part Digital Twin concept are visualized in Figure 4.

V. DISCUSSION

The aim of this work was to consolidate the Digital Twin concept for definition and application across industries. This was approached by answering two major research questions.

The research question ''What is the Digital Twin concept?'' has previously been answered by numerous people in academics and industry but failed to address the diverse character of the concept across industries. We define the concept as follows. The Digital Twin concept contains a physical entity and its virtual representation, which evolves with its physical counterpart through real-time connection and offers additional value. Furthermore, we mention the conflictual aspect of the term ''Twin'' in the Digital Twin concept, emphasize the potential multi-instance character of both physical and virtual entity, and allocate the Digital Twin concept as a logical construct in the semantic layer. This holistic view reflects the broad field of applications while at the same time defines the core principles of the Digital Twin concept.

The second research question further focused on applications by asking, ''How to describe applications of the Digital Twin concept across industries?''. Based on the commonly agreed three core parts of a Digital Twin architecture, we introduced five generic aspects by which to describe Digital Twin application scenarios, with the aim to reduce the perceived complexity of the Digital Twin concept and to facilitate understanding of concrete application scenarios and their value.

The first dimension, ''Scope of the physical entity,'' is also referred to as the physical reference object [51] but highlights the possibility of it being a living being. The hierarchical level or integration breadth used by other models is integrated into this dimension.

''Feature(s) of the physical entity'' refers to the characteristic of the physical entity that is of interest for the Digital Twin concept application. To some degree, this is referred to in the Domain dimension by Lechler *et al.* [8]. We deliberately separated this dimension from the scope of the physical entity to put focus on the constraint, use-case-based characteristic of Digital Twin applications. The more features are considered in a Digital Twin application, the closer it gets to representing its physical entity in its entirety. In other models, this is referred to as authenticity [86] or completeness [51].

The ''Form of data communication'' dimension is intertwined with the ''Scope of the virtual entity'' dimension. The scope considers what data is considered in the virtual entity, where and how it is handled, and in what kind of model it is combined. The communication dimension defines where the data is coming from, where it is going, and in what amount and frequency. This is closely linked because the form of data communication and handling can differ between data. Chakshu *et al.* [98] refer to this aspect as semi-active Digital Twin. The communication dimension is referred to in other models as data acquisition [87], data integration level [86], connection [51], timing [8], or connectivity modes and update frequency [49]. The scope of the virtual entity is also described as Digital model richness, Simulation capabilities, and CPS intelligence [49], purpose [51], data processing [87], application level [8], and is considered in many of the Digital Twin terms in the level of sophistication or maturity.

The virtual entity scope again is closely linked to the user-specific output/value created. The scope of the virtual entity contains the different data sources and combines them in a use case specific model. These models then create outputs that leverage the business objectives of specific users. One model can create different outputs and values for a variety of users. We have separated this aspect from the scope of the virtual entity to evoke the explicit mentioning of the concrete user-specific value. Aspects of this are considered in the dimensions human interaction [49] and goals and user focus [86] used by other models.

The dimension product life cycle phase [49], [83], [86] is strongly related to the product domain and does not allow the application to a living being, for example, as also stated by Minerva *et al.* [11], which is why it does not find explicit mentioning in our model. Nevertheless, any Digital Twin application within the product life cycle can be described with our model. Aspects from the dimension of the industrial sector [51] or the field of application are equally represented in the dimensions of our model.

Instead of clear sub-categories within the dimensions, we decided to give examples and leave room for individual and future applications. This reduces distinct comparability but also reduces complexity and therefore facilitates understanding of applications. The focus in this work was put on reduced complexity and ease of understanding, but further work can determine useful sub-categories that enrich the model completeness without substantially increasing complexity.

In comparison to models proposed in previous work, the 5-dimension cross-industry Digital Twin applications model stands out with its universal applicability across industries combined with an easy-to-understand structure of Digital Twin application descriptions. This facilitates discussing Digital Twin research and industrial applications, without the need for specific terms.

We see the naming of Digital Twin applications based on specific characteristics as critical. As soon as a Digital Twin application has characteristics across classification dimensions, its naming will become more complex and add to the confusion around the concept. The Digital Twin concept itself is simple, and given the essential information about the shape and form of an application, the general idea of a Digital Twin application can be understood easily as well. We propose our 5-dimension cross-industry Digital Twin applications model as a guideline for describing current and future applications of the Digital Twin concept.

By basing our model on the core three-part Digital Twin concept introduced by Grieves, the model deliberately allows the description of all kinds of Digital Twin and Digital Twin-like concepts. It, therefore, builds the foundation for informed discussions on what can be considered a Digital Twin concept and what not.

VI. CONCLUSION

The Digital Twin concept holds a variety of definitions and terms with differing focuses, which causes confusion and dilutes the potential impact it could have across industries. Our aim was to consolidate the concept by giving a holistic view on the Digital Twin concept, by analyzing classification terms and models from academia and industry that describe Digital Twin applications, and by proposing a 5-dimension cross-industry Digital Twin applications model that reduces the perceived complexity of applications of the Digital Twin concept and highlights their added value.

We base our definition of the Digital Twin concept on the core three-part concept introduced by Grieves and three fundamental characteristics with the goal to allow cross-industry applications of the concept.

It was demonstrated that the term "Digital Twin" has not been undisputed until recently and that Digital Twin terms describing specific aspects of applications are abundant. We analyze models that aim to structure these different aspects and derive our 5-dimensional model out of the need for a commonly accepted and easy-to-understand conceptual and graphical backbone for such a model. We base our model on the three-part Digital Twin concept by Grieves and define the five dimensions scope of the physical entity, feature(s) of the physical entity, form of communication, scope of the virtual entity, and user-specific outcome/value created.

The model avoids distinct sub-categories of its dimensions to reduce complexity and leave room for individual focuses of current and future applications. A refinement of the model can be part of future work.

Our model presents a straightforward guideline for descriptions of applications of the Digital Twin concept, starting from the physical entity and ending with the concrete value created for specific users. Furthermore, the model can be used to classify current and future applications.

Future research can focus on formal expression and relationships between Digital Twin application models. Furthermore, development and implementation of the Digital Twin concept can be targeted, as uncertainty goes along with this endeavor and competitive applications are still scarce.

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Prof. Haider is also a Principal Key Expert with Siemens Healthineers (SHS), a title awarded to him by the SHS Managing Board for his outstanding innovation track record, in 2008. Furthermore, he was awarded honorary directorships and professorships, and developed innovation infrastructures and implemented innovation management certification programs for top institutions.

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2.2 Methodology for Digital Twin Use Cases: Definition, Prioritization, and Implementation

Authors: **S. R. Newrzella**, D. W. Franklin, and S. Haider

Abstract: The cross-industry concept of Digital Twin promises numerous benefits in areas such as product customization and predictive maintenance, but many companies often struggle to determine a starting point. Digital Twin use cases are abundant, but efforts and stakeholder benefits are difficult to estimate when developing and implementing Digital Twin applications. This paper proposes a management approach to Digital Twin use case prioritization suitable for planning Digital Twin applications at an early phase of development. Considering stakeholder satisfaction, infrastructure scalability, and effort for implementation and maintenance, we present a methodology to determine the most impactful Digital Twin use cases requiring low effort and high scalability. Tools and related methods from the fields of software development, innovation, process engineering, and product development are described, and the methodology is discussed with regard to these and other research works. An example from mechatronic product development at Siemens Healthineers Innovation Think Tank validates the approach.

Contribution: I researched existing methodologies, developed the first draft of the proposed methodology, and improved it with the feedback of Schoueri (2021) [114], Castellanos (2022) [115], and Schwarz (2022) [116] (supervised theses see Appendix A). I provided the validation of the methodology by collating and anonymizing examples from the theses of Schoueri (2021) [114] and Castellanos (2022) [115]. I drafted the original manuscript under the advisement of Prof. Sultan Haider, revised it with the assistance of Prof. Dr. David Franklin, and designed all figures and tables.

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RESEARCH ARTICLE

Methodology for Digital Twin Use Cases: Definition, Prioritization, and Implementation

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ABSTRACT The cross-industry concept of Digital Twin promises numerous benefits in areas such as product customization and predictive maintenance, but many companies often struggle to determine a starting point. Digital Twin use cases are abundant, but efforts and stakeholder benefits are difficult to estimate when developing and implementing Digital Twin applications. This paper proposes a management approach to Digital Twin use case prioritization suitable for planning Digital Twin applications at an early phase of development. Considering stakeholder satisfaction, infrastructure scalability, and effort for implementation and maintenance, we present a methodology to determine the most impactful Digital Twin use cases requiring low effort and high scalability. Tools and related methods from the fields of software development, innovation, process engineering, and product development are described, and the methodology is discussed with regard to these and other research works. An example from mechatronic product development at Siemens Healthineers Innovation Think Tank validates the approach.

INDEX TERMS Digital Twin, applications, rating, methodology, product development.

I. INTRODUCTION

The Digital Twin (DT) concept consists of a physical entity and its digital representation, which evolves with its physical twin through real-time connection and provides additional value [1]. The concept promises to efficiently solve physical issues, predict potential outcomes, help to design and manufacture better products, and create additional value for its customers [2]. While many potential benefits are anticipated across industries, it is still difficult to estimate and balance the effort needed to develop and implement a Digital Twin concept and the value it creates [2], [3]. An all-embracing and in-depth Digital Twin implementation entails high costs and significant effort [4], [5], and is likely not to address any objective sufficiently [6]. Therefore, the trend is to start with the use cases that create the biggest value in the shortest amount of time [2]. Current research does not provide approaches to derive impactful Digital Twin use cases for stakeholders and evaluate them for prioritized development. While methodologies exist, for example, for prioritizing software development features, innovation projects, manufacturing data sources, and product features in product development, they have limited applicability for Digital Twin use cases.

The versatile, cross-industry character of the Digital Twin concept makes it difficult to define a universally applicable methodology for deriving and prioritizing Digital Twin use cases. We propose a two-step methodology that, in the first step, derives promising Digital Twin use cases and evaluates their value, and in the second step, evaluates their efforts and scaling potential.

For deriving promising Digital Twin use case opportunities, we see the life cycle aspect of the physical entity as the backbone for broad Digital Twin applications, as advocated

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by Parrott and Warshaw [2]. Our methodology derives and evaluates use cases based on the value-receiving stakeholders' ratings along an entity's life cycle. Other solutions than Digital Twin use cases might address the needs better and are also considered. The needs where Digital Twin use cases seem to be the best solution are taken into the second step of our methodology.

We see data as playing an essential role in estimating Digital Twin applications' effort and scaling potential. Collecting data sooner than later is critical in developing a Digital Twin service to a product. Not just having more but better data reduces developing costs and increases the value-add for the customer and user. The business value and the effort of a Digital Twin use case depend on the data driving the use cases. Therefore, the value of the use cases depends on the value of its data. The data value is not determined by the amount of data but by the importance and number of use cases driven by the data and the data's informational value of those use cases [7]. To approach this interdependence of use cases and data, the second step in our methodology identifies the data sources that enable most of the impactful use cases and require the least effort for implementation. This value is fed back to the evaluation of the use cases. Besides data, infrastructure effort and scaling potential are considered in the use case evaluation.

No other methodology has yet been introduced that addresses these Digital Twin aspects. The methodology proposed in this article reduces uncertainty in developing Digital Twin applications by serving as a guideline for practitioners to determine the most promising Digital Twin use cases for their product.

In the following, we analyze existing use case and other prioritization methodologies that impacted the development of our methodology. We present in detail our methodology in its two steps, followed by a validation of the methodology on a mechatronic product development case study. We discuss and compare the methodology with methodologies from other fields, its standing in Digital Twin research, its limitations, and future steps.

II. RELATED WORK

This article is related to use case prioritization in the field of Digital Twin. Other use case prioritization methodologies in the field of Digital Twin were not found, which is why we describe use case prioritization methodologies from different fields and other supporting methods. These methodologies (Table 1) influenced the development of our use case prioritization methodology.

Use cases describe user requirements by placing them in a usage context. They consist of a sequence of events that create value for the user [15]. Jacobson *et al.* introduced use cases in 1992 [16] as a tool to make software development more requirement-oriented. The term and concept have since received wide attention inside and outside software development. We use them in this article to describe Digital Twin applications and their requirements in a usage context.

According to Kundu and Samanta [9], use case prioritization follows a quality and business goal. When prioritizing use cases at an early development stage, more effort can be put into developing the most promising use cases, thus achieving higher quality results. Secondly, prioritizing the most promising use cases results in greater user satisfaction earlier, thus driving business.

Moisiadis [8] proposes a two-level use case and scenarios prioritization methodology for software development, considering business goals of the stakeholders, dependencies among the use cases, the satisfaction degree of each use case to the business restrictions and goals, and critical objects and actors per use case. The first level rates the use cases by their ability to satisfy the stakeholders' business and functional goals to reduce the number of use cases considered in the second level and focus only on the most important use cases from a stakeholder perspective. The second level prioritizes the steps within the important use cases by the involvement and usage of actors and objects in each step. The most important steps of the important use cases require special attention in the software development cycle.

TABLE 1. Overview of related work.

Authors/ Methodology	Application Field	Purpose
Moisiadis [8]	Software Development	Prioritization of software use cases for development
Kundu and Samanta [9]	Software Development	Prioritization of software use cases for development
Ulwick [10]	Innovation	Prioritization of product features for product development
Haider [11]	Innovation	Stakeholder-centric product development
Process Failure Mode and Effects Analysis [12]	Manufacturing and others	Identification of potential manufacturing process failures for preemptive prevention
Quality Function Deployment [13]	Product Development and Production	Identification of product functions and services that best address customer wishes
Stanula *et al.* [14]	Production	Identification of most promising data sources for analyses using machine learning algorithms
Digital Twin Development Cycle [2]	Digital Twin Development	Development cycle for iterative Digital Twin development and improvement

Kundu and Samanta [9] present a three-step methodology for use case prioritization in software development. In contrast to Moisiadis [8], they design their approach to be free from any personal influence. Their three-step methodology converts use case scenarios into a system sequence diagram and then into scenario graphs, which are analyzed for the criticality of the scenario paths. The methodology's outcome is a ranking of use case scenarios achieved by sole computing.

Ulwick [10] proposes a tool to prioritize product features based on customer goal importance and outcome satisfaction. To develop innovative products, Ulwick emphasizes the importance of inquiring from customers about their desired outcomes, not solutions. An algorithm rates these outcomes by considering the importance of an outcome for the customer and how satisfied the customer is with the current solution. The outcomes with high importance and currently low satisfaction solutions receive prioritized development.

Haider [11] first applied the Innovation Think Tank (ITT) methodology in 2005. The methodology supports innovative product development by considering stakeholders through the entire development process. It consists of four main steps: Acquire mandate and plan, big picture analysis, co-creation on decision proposition, and deploy commercialization. The authors analyzed radiology departments' challenges and solutions [17], among others.

In engineering, identifying potential failure modes in manufacturing processes and determining the most critical ones is commonly assessed using the Failure Mode and Effects Analysis (FMEA). An FMEA identifies ways of potential failure of an item or process by systematically evaluating them and their effects on themselves and their environment and personnel. Considered factors are the probability of the failure mode, the severity of its effects, and the likelihood of its detection. For critical failure modes, remedies are developed, and their impact on these three factors is reevaluated until all critical failure modes are addressed sufficiently. The Process FMEA (PFMEA) methodology takes a process as a starting point, subdivides it into smaller steps, and determines potential failure modes along with these steps. The PFMEA was first applied to manufacturing but has since caught wider attention in other fields, such as healthcare, where it is used to analyze medical procedures [12].

Quality Function Deployment (QFD) is a method for translating customer wishes and requirements into a company's concrete services and functions of a product [13]. In several steps, this method derives from a single customer requirement which product feature, function, or performance characteristic must be designed, modified, or improved to meet customer requirements. The method initially developed by Akao in Japan in 1966 [18] combines the customer requirements with the technological features in the House of Quality (HoQ), an interactive matrix. The output of this matrix are the most important technological features on which to focus from a customer satisfaction point of view. While the tool was initially developed for product design and quality management applications, the QFD has since found numerous other fields of application [13].

Stanula *et al.* [14] propose a methodology for efficient data source selection for machine learning applications in production. The approach translates business objectives into failure modes using the PFMEA and consults a cross-functional panel of experts to assess the data source correlation with the failure modes by applying the QFD. The outcome is a selection of data sources with a high likelihood to bear information regarding the business objective when used as an input for machine learning analyses.

The multinational professional services network Deloitte proposes a circular methodology to getting started with Digital Twin applications (Figure 1). The methodology describes how to start and scale up Digital Twin applications in six circular steps [2].

In its first step, "Imagine," the goal is to "Imagine and assess process opportunities for the digital twin." Even though scenarios may differ for every application, two key characteristics are likely to play a major role in the scenario assessment. Firstly, the physical entity and feature of interest are valuable enough for a Digital Twin application. Secondly, potential value exists from outstanding, unexplained issues that could be leveraged for stakeholders.

The following "Identify" step determines the most suitable Digital Twin application out of all the potential opportunities assessed in step one. Parrott and Warshaw [2] suggest considering operational, business, and organizational change management factors while focusing on areas with the potential to scale across technologies, equipment, or sites. Furthermore, they advocate broad Digital Twin applications over deep ones, as they tend to drive most support and value.

In the following steps, Parrott and Warshaw [2] propose to pilot early value-creating Digital Twin applications, industrialize the Digital Twin development and deployment process, scale the Digital Twin application to connected and similar scenarios, and finally monitor and measure the impact and outcome of the Digital Twin application.

As shown in Figure 1, the process intends to be conducted circularly, identifying improvement potentials and new opportunities across application areas. Our proposed methodology supports the first two steps, "Imagine" and "Identify," by systematically deriving potential Digital Twin applications, rating them by estimated value creation, and assessing their scaling potential and effort for implementation.

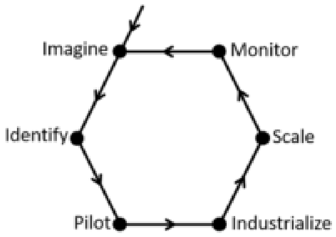


FIGURE 1. Deloitte Digital Twin development cycle, based on Parrott and Warshaw (2017) [2].

Our methodology can be applied when starting the Deloitte Digital Twin development cycle, such as designing a new product or upgrading an existing product with Digital Twin features. It also allows to reiterate the Deloitte Digital Twin development cycle by deriving the next most promising Digital Twin features to add to an already existing product with Digital Twin features.

The Digital Twin concept holds great potential across industries and product lifecycle stages. Despite the abundance of opportunities for Digital Twin applications, practitioners still struggle to identify useful use cases and derive the most promising use cases to start with. Even though methodologies for identifying aspects of interest exist in various fields, these methodologies do not consider the interdependencies of Digital Twin use cases and data sources and the implementation infrastructure with its scaling potential and efforts required. Our methodology addresses this need by starting from a customer-centric need and satisfaction evaluation. It identifies use cases where a Digital Twin is the most promising solution. It then evaluates potential data source and other infrastructure setups regarding their scalability and effort and finally determines the most promising Digital Twin use cases to start implementation with.

III. METHODOLOGY FOR DIGITAL TWIN USE CASE DEFINITION, PRIORITIZATION, AND IMPLEMENTATION

This section describes our proposed methodology, which supports the definition, prioritization, and implementation of Digital Twin use cases. The methodology combines software development, innovation, process engineering, and product development methods and adds the evaluation of efforts and data source interdependencies, which characterize Digital Twin use cases.

Our proposed methodology can be located in the imagine and identify phases of the Deloitte Digital Twin development cycle (see the top of Figure 2). Understanding the physical entity of interest and its application environments is essential to derive and evaluate digital twin use cases. It is mentioned as the initial step for the imagine and identify step. The overall methodology is then subdivided into two levels, A and B. The first level, A, is situated in the imagine phase. It derives the most promising use cases for applying the Digital Twin concept by considering market needs and the ability of use cases to address these. The second tier, B, is located in the identify phase. After an initial data source preselection, it further elaborates and evaluates the selected Digital Twin use cases by identifying the most impactful data sources and the efforts associated with a use case implementation. The outcome is a selection of use cases and data sources to start with in the pilot phase.

Figure 2 shows our general approach with the UCMEA (A) and House-of-DT (B) as center elements, placed within the Deloitte Digital Twin development cycle.

Following, we describe the methodology in theory, but we recommend taking a look at the example and figures in the validation case study section for a deeper understanding.

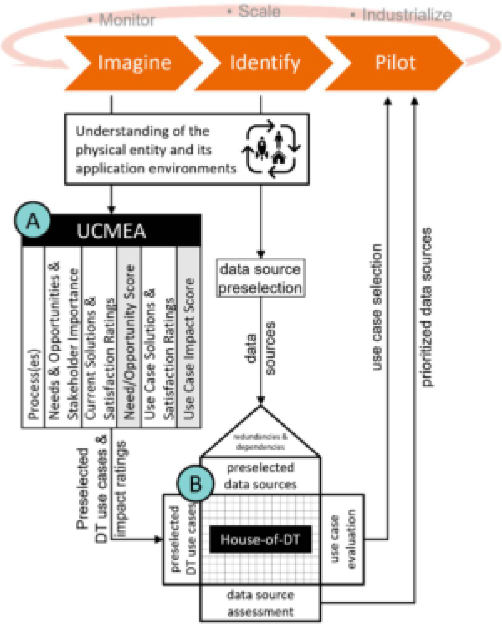


FIGURE 2. Schematic of the Innovation Think Tank methodology for Digital Twin use case creation, prioritization, and implementation.

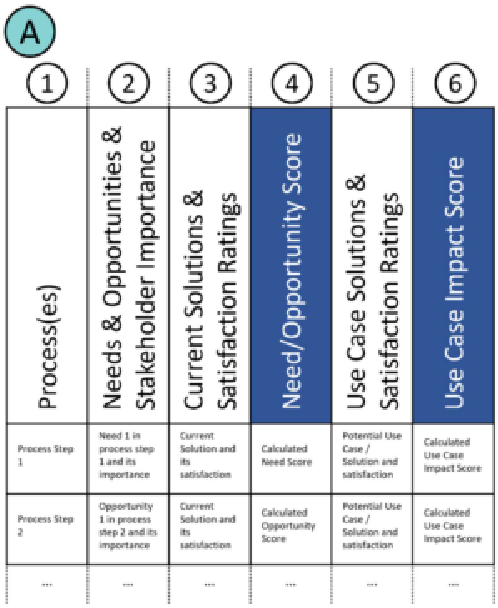
A. USE CASE MODE AND EFFECTS ANALYSIS (UCMEA)

Zborowski [19] mentions the unprofitable endeavor of creating a Digital Twin of an entire machine. General Electric's (GE) oil field services company Baker Hughes (BHGE) focuses on building high fidelity Digital Twin applications only of the parts which have a higher probability of failing than others [19]. This example of predictive maintenance as the main application of Digital Twin use cases focuses on the greatest value-add for the stakeholder by considering the parts most likely to fail. Our methodology focuses on the greatest value-add for stakeholders in Digital Twin use cases, including predictive maintenance.

We propose the Use Case Mode and Effects Analysis (UCMEA) as a methodology to develop use cases and rate their business potential. A schematic overview of the six major steps is visualized in Figure 3.

1) PROCESS(ES)

Similar to the PFMEA, this methodology is guided by a process. The process is defined by the application stage of the physical entity and the targeted stakeholders. A workflow can, for example, represent the design, build or operate stage of the physical entity, as proposed by IBM [20], and describe the view of the user, such as the manufacturer, operator, or maintainer. This workflow determination is the first step in the methodology. The more stages and users are considered, the wider the scope of use cases and the higher the potential for detecting synergy effects and scaling potential. In the case of a product, processes can be considered along the entire product life cycle.



①	②	③	④	⑤	⑥
Process(es)	Needs & Opportunities & Stakeholder Importance	Current Solutions & Satisfaction Ratings	Need/Opportunity Score	Use Case Solutions & Satisfaction Ratings	Use Case Impact Score
Process Step 1	Need 1 in process step 1 and its importance	Current Solution and its satisfaction	Calculated Need Score	Potential Use Case / Solution and satisfaction	Calculated Use Case Impact Score
Process Step 2	Opportunity 1 in process step 2 and its importance	Current Solution and its satisfaction	Calculated Opportunity Score	Potential Use Case / Solution and satisfaction	Calculated Use Case Impact Score
...	...	...	...	...	...

FIGURE 3. UCMEA schematic overview.

2) NEEDS & OPPORTUNITIES & STAKEHOLDER IMPORTANCE

After defining a process or workflow of interest, the next part of the UCMEA uses and takes inspiration from the "Opportunity Scoring" method developed by Ulwick in the 1990s [21]. This next step in the UCMEA describes user needs and opportunities along the targeted process. Needs can be pain points that create discontent in the current process. Opportunities can be potential improvements that could create additional value in the current process. These needs and opportunities ideally reflect the viewpoint of as many stakeholders as possible to consider and evaluate use cases from different fields and identify scaling potentials. Alternatively, user needs and opportunities can also be considered separately for each workflow and stakeholder by conducting the method individually with the respective stakeholder group and merging the results later. To keep the solution space open to all kinds of solutions, the needs and opportunities should be defined solution unspecific.

As in Ulwick's [21] "Opportunity Scoring" method, the user needs and opportunities for specific stakeholders are rated by their importance for each stakeholder individually. The more often a need or opportunity presents itself within the respective process, or the greater the perceived gap in revenue or effort, the higher the importance rating (1-10) of a need or opportunity for a specific stakeholder. All scaling within this methodology should be defined equally for all workflows and stakeholders within one assessment.

3) CURRENT SOLUTIONS & SATISFACTION RATINGS

Next, the satisfaction of each current solution to a need and opportunity for each stakeholder is assessed. The greater the satisfaction of a stakeholder with a current solution, the higher the satisfaction rating (1-10).

The gap between importance and satisfaction is then calculated by subtracting the satisfaction value from the importance value. The gap value can never be less than zero to consider important use cases for future solutions, as discussed by Ulwick [21].

4) NEED/OPPORTUNITY SCORE

The overall Opportunity Score of a need or opportunity, as to Ulwick [21], is calculated by adding the importance and gap value. The more important a need or opportunity is for a stakeholder, and the greater the satisfaction deficit, the greater the opportunity.

5) USE CASE SOLUTIONS & SATISFACTION RATINGS

Following the need and opportunity analysis, use case solutions are ideated, which address the mentioned needs and opportunities. A preselection can be done by only ideating use case solutions for needs and opportunities with at least a certain Opportunity Score. More than one use case solution can address a need or opportunity, but each use case solution takes up a separate row. Every use case solution is described shortly. Digital Twin use cases can be described by their scope of the physical entity, the feature of interest, and the user-specific output/value created, as proposed by Newrzella *et al.* [1]. Further specifics will be defined in the House-of-DT based on the infrastructure availability.

Next, we estimate the anticipated stakeholder satisfaction for addressing the need or opportunity with the ideated use case solution. Ideally, this estimation is verified with the stakeholders addressed. Pairwise comparison, repeat pairs techniques, and other methods can be used to support this step. The increase in satisfaction from the current solution to a potential use case solution is calculated by subtracting the status quo satisfaction value from the anticipated use case solution satisfaction value.

6) USE CASE IMPACT SCORE

Finally, we calculate the Use Case Impact Score by adding the Satisfaction Improvement to the stakeholder's importance value of the addressed need or opportunity. The Use Case Impact Score is higher the more important the addressed need or opportunity is for the stakeholder and the better suited the use case is for addressing it. Depending on their score, these need/opportunity-based and rated use cases receive prioritized development. Among the different solutions, Digital

Twin use cases can be transcribed into the House-of-Digital Twin methodology (House-of-DT) for a scalability and effort analysis.

For the use case solutions using other technologies, techniques, or concepts, further use case elaboration, visualization, and evaluation can be conducted using other methods.

B. HOUSE-OF-DIGITAL-TWIN (HOUSE-OF-DT)

The House-of-DT's structure is based on the House of Quality, a part of the Quality function deployment (QFD) method. We use the interactive matrix approach of the House of Quality to quantify the interdependencies between Digital Twin use cases and data sources.

Furthermore, our methodology takes inspiration from the data source selection methodology for machine learning applications in production [14] and applies it to the cross-industry field of Digital Twin. Stanula *et al.* [14] apply the House of Quality approach to quantify the interdependencies between failure modes and data sources in production, with the aim to analyze issues using Machine Learning algorithms. We broaden the approach by considering all kinds of Digital Twin use cases, including failure modes, and include effort estimations to implement these use cases.

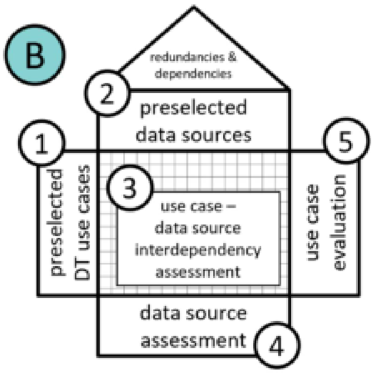


FIGURE 4. House-of-Digital Twin schematic overview.

The House-of-DT can be subdivided into four side parts and the center, conducted consecutively, as depicted in Figure 4. It can also be divided into two interconnected dimensions, the use cases, and the data sources, the "what" and the "how." Data sources drive use cases, and the value of data sources is determined by the use cases they enable. After being primarily rated in the UCMEA, Digital Twin use cases come in from the left and leave to the right. Data sources come in from the top and leave towards the bottom. Their interplay is evaluated in the center so that each dimension is rated by its ability to benefit from the other.

1) DIGITAL TWIN USE CASE INPUT

In the first step of the House-of-DT methodology, the minimal rate at which the individual use cases are updated is assessed. This rate refers to the lowest frequency at which value is still created for the stakeholder.

2) DATA SOURCE INPUT

Subsequently, data sources of interest for the Digital Twin use cases are introduced in step two. Preselection of data sources can be conducted to limit the total number of data sources to those related to the use cases. The Delphi method can be used to reduce the number of data sources to the most promising ones.

The data source dimension is defined by the scope of the physical entity of the Digital Twin. The broader the scope of the physical entity of the Digital Twin, the more local data sources can be considered. The data sources under consideration for the Digital Twin use cases are listed in the upper part of the House-of-DT. To consider data sources from different origins, we propose categorizing them into three categories "Physical entity," "On-premise," and "Off-premise" data sources. "Physical entity" data sources refer to data sources located right on or in the physical entity under consideration for a Digital Twin. "On-premise" data sources are located close to the physical entity, such as in the same local area network, and therefore provide low latency communication and can provide higher data security and privacy standards if kept on a local level. "Off-premise" data sources are often connected via the internet and have higher latency communication and data security and privacy concerns. These data source clusters are not conclusive and intend to broaden the view on potential data sources. Not yet available data sources can be considered if the available data sources do not have sufficient informational value for the use cases of interest.

Above the data sources, interdependencies between the data sources are analyzed. Data sources that complement each other are marked as such, and redundant data sources are highlighted. This information is later considered in selecting data sources for specific use cases.

Each data source's maximum possible frequency achievable is noted in the row below the data sources. This frequency refers to the sources only, without, for example, connection to the next processing unit.

3) USE CASE-DATA SOURCE INTERDEPENDENCIES

In step three, in the grid in the center of the House-of-DT, Digital Twin use cases and data sources are linked by evaluating each data source by its informational value for each use case. The better a data source is suited for supporting a use case, the higher its informational value for that use case, and the higher its rating (1-10). If a data source holds no informational value for a specific use case, no rating is done.

4) DATA SOURCE ASSESSMENT

Following, all data sources are evaluated by their potential to scale. This evaluation is achieved by considering the number of use cases a data source can drive, the informational value a data source holds for all use cases, and the opportunity score of each use case it can drive. The scaling potential value of a data source is calculated by the sum product of each use case Opportunity Score and the informational value of this data source regarding the individual use case. The Scaling Potential is higher the more use cases a data source can support, the higher the informational value it holds for all use cases, and the higher the opportunity score of all use cases a data source can drive.

In the next step, the data source implementation and data collection effort is evaluated. Data source implementation focuses on the effort needed to include a data source in or on the physical entity (rating from 1-10). Suppose a data source is not implemented in the current product, and extensive effort is required in redesigning the product and implementing the data source. In that case, the data source gets a high implementation effort rating. A data source already included and available in the current state of the physical entity receives a low effort rating.

Data collection effort emphasizes how much a data measurement process interferes with a workflow. The more negative impact a data collection process has on the workflows around the physical entity, the higher its data collection effort rating (1-10).

The total effort rating for a data source is calculated by adding both implementation and collection effort values.

Concluding the data source assessment, a data source's total data source rating is calculated by dividing its scaling potential by its total effort rating. The more scaling potential a data source has and the lower the effort for its implementation and data collection process, the higher its overall data source rating. The total data source rating supports decision-making for data source selection within the design stage of a Digital Twin-related product concerning future compatibility with Digital Twin use cases.

5) USE CASE EVALUATION

Before continuing with the use case evaluation on the right side of the House-of-DT, a selection of data sources for each use case is made. For each use case, a selection of data sources is made that could be used to drive the use case. Factors contributing to this selection can be informational value, data source interactions, scaling potential, and effort for implementation and data collection. The following steps are conducted only for each data source selection. If required, data source selections can be changed later. The right side of the House-of-DT then must be redone with the new selection.

First, in the use case evaluation, a data source selection is checked for achieving the minimum needed information frequency required by the use case. This step serves as a first feasibility check for the data source selection. Not every data source has to provide a use case's minimum needed information frequency. Still, the use case-specific data source selection must be able to provide the required information at the required frequency.

Following, the average detectability score of the data source selection is calculated. This score showcases the ability of a data source selection to describe the matter of a use case.

Afterward, the average scalability score of a data source selection is assessed. This assessment is done by calculating the average scalability score of all data sources in the selection for the individual use case. The more impactful use cases a selection of data sources can describe well, the higher its average scalability score.

To assure equal contribution to the overall assessment, the average scalability score of each data source selection is normalized to the scale from 0 to 10, with 10 being the maximum use case scalability average of all use cases.

The setup section asks fundamental questions based on the previous analysis to estimate the efforts needed for a Digital Twin use case. The data source selection and information frequency enable theoretical use case development. The following setup details are considered: Whether data from outside the physical entity is needed; Whether safety, security, or privacy concerns apply to the use case and its data; What kind of model is fed with the data; Whether the use case is updated in batch, semi-batch or real-time; Whether cloud or on-premise computing is considered for the use case.

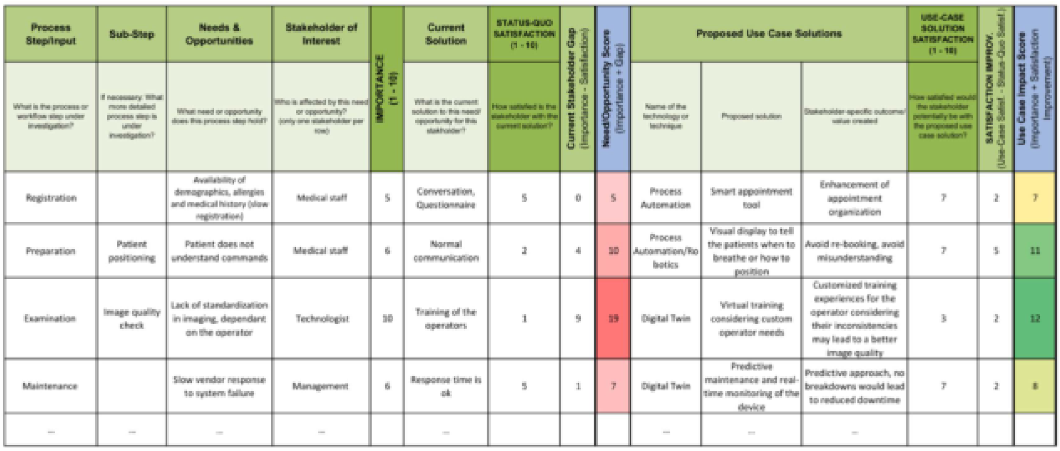
Having the setup in mind, the effort section estimates the required effort for use case implementation and maintenance based on the data collection/integration layer, communication & data management layer, and information & functional layer.

The data collection/integration layer refers to the physical nodes in the physical entity, such as sensors and low-level interfaces for data communication. The communication & data management layer is responsible for node-to-processor coupling, local-to-cloud link, DT-to-DT link, and the respective contextualization and management of the data. The information & functional layer considers data modeling, DT services, and potential human-machine interfaces.

Some effort for implementation and maintenance is required once and does not have to be repeated with additional use cases. These efforts scale with use cases and are considered by their respective use case scaling ratings. A use case scaling rating of one refers to an effort only applying to one use case, two applies to two use cases, three to three use cases, and ten to ten and more use cases. The adjusted effort equals the effort estimation divided by the use case effort's scaling potential.

The total effort is calculated by summing up the adjusted effort values of all three layers.

The Use Case Applicability Score is determined by multiplying the Use Case Impact Score with the average use case detectability score and the normalized average scalability score of the use case's data source selection and



Process Step/Input	Sub-Step	Needs & Opportunities	Stakeholder of Interest	IMPORTANCE (1 - 10)	Current Solution	STATUS-QUO SATISFACTION (1 - 10)	Current Stakeholder Gap (Importance - Satisfaction)	Need/Opportunity Score (Importance + Gap)	Proposed Use Case Solutions			USE-CASE SOLUTION SATISFACTION (1 - 10)	SATISFACTION IMPROV. (Use-Case Satisf. - Status-Quo Satisf.)	Use Case Impact Score (Importance + Satisfaction Improvement)
What is the process or workflow step under investigation?	If necessary: What more detailed process step is under investigation?	What need or opportunity does this process step hold?	Who is affected by this need or opportunity? (only one stakeholder per row)		What is the current solution to this need/ opportunity for this stakeholder?	How satisfied is the stakeholder with the current solution?			Name of the technology or technique	Proposed solution	Stakeholder-specific outcome/ value created	How satisfied would the stakeholder potentially be with the proposed use case solution?		
Registration		Availability of demographics, allergies and medical history (slow registration)	Medical staff	5	Conversation, Questionnaire	5	0	5	Process Automation	Smart appointment tool	Enhancement of appointment organization	7	2	7
Preparation	Patient positioning	Patient does not understand commands	Medical staff	6	Normal communication	2	4	10	Process Automation/Robotics	Visual display to tell the patients when to breathe or how to position	Avoid re-booking, avoid misunderstanding	7	5	11
Examination	Image quality check	Lack of standardization in imaging, dependant on the operator	Technologist	10	Training of the operators	1	9	19	Digital Twin	Virtual training considering custom operator needs	Customized training experiences for the operator considering their inconsistencies may lead to a better image quality	3	2	12
Maintenance		Slow vendor response to system failure	Management	6	Response time is ok	5	1	7	Digital Twin	Predictive maintenance and real-time monitoring of the device	Predictive approach, no breakdowns would lead to reduced downtime	7	2	8
...	...	...	...		...				...	...	...			

FIGURE 5. UCMEA validation example of a mechatronic medical device analysis at Siemens Healthineers Innovation Think Tank.

dividing it by the total accumulated estimated effort of the use case.

For ease of comparison, the Use Case Applicability Score is normalized so that the highest value among all use cases is 10. The Normalized Use case Applicability Score is a comparative rating between use cases. Use cases with high scores among the analyzed use cases are the most recommendable use cases for implementation, with the relatively best ratio of high expected value created, high scalability potential, and low effort for implementation and maintenance.

The overall methodology gives the practitioner a tool at hand to define, prioritize, and implement Digital Twin use cases. The UCMEA defines general use cases for innovative product solutions along selected phases such as the entire product life cycle and determines the use cases with the highest impact on stakeholders. Selected Digital Twin use cases can be further elaborated and evaluated in the House-of-DT, considering impact, scalability, and effort for data sources and other infrastructure. Succeeding the detailed introduction of the methodology, we present a case study to validate its applicability.

IV. VALIDATION CASE STUDY

The proposed methodology was validated by a product development application in the field of mechatronics at Siemens Healthineers Innovation Think Tank. The methodology application on this product aims to increase its value for its stakeholder in its usage context by enriching its mechatronic functionalities with Digital Twin features. In this case, the product is a medical mechatronic product in its clinical application field. The methodology is conducted, and its suitability for Digital Twin use case definition, prioritization, and implementation is shown.

A. USE CASE MODE AND EFFECTS ANALYSIS (UCMEA)

As the first step of the UCMEA, processes of interest for the Digital Twin application were defined. Usage processes in a radiography workflow, device maintenance, and lifecycle integration were selected, and sub-steps were defined where applicable. This case study has taken into consideration numerous hospital visits with questionnaires and analyses by the ITT team over the last 15 years. Along the process sub-steps, stakeholder needs and opportunities were allocated, and the affected stakeholders were defined. Stakeholders were selected from the device's clinical usage and engineering development phase. Stakeholders considered were technologists, nurses, physicists, administrators, and device manufacturers. Other stakeholders have not been specified in this analysis. The stakeholder-specific importance of each need and opportunity was rated, the current solutions were described, and the stakeholders' satisfaction ratings with the solutions were quantified. Documented solution-unspecific quantitative pain points and recommended improvements from the questionnaire ratings were implemented as importance ratings in the UCMEA. Solution-specific ratings were attributed to the status-quo solution satisfaction of the stakeholders. After calculating the need/opportunity score of each need and opportunity, use cases for each need and opportunity were ideated and described. Use case solutions were proposed mainly from the field of Industry 4.0.

More than 30 use case solutions for needs and opportunities were found. The respective stakeholder's satisfaction with the use case solutions was estimated, and each use case's impact score was calculated. The Digital Twin use cases with the highest impact scores were selected for further analysis within the House-of-DT. Non-Digital Twin use case solutions were not considered further in this case study. Exemplary

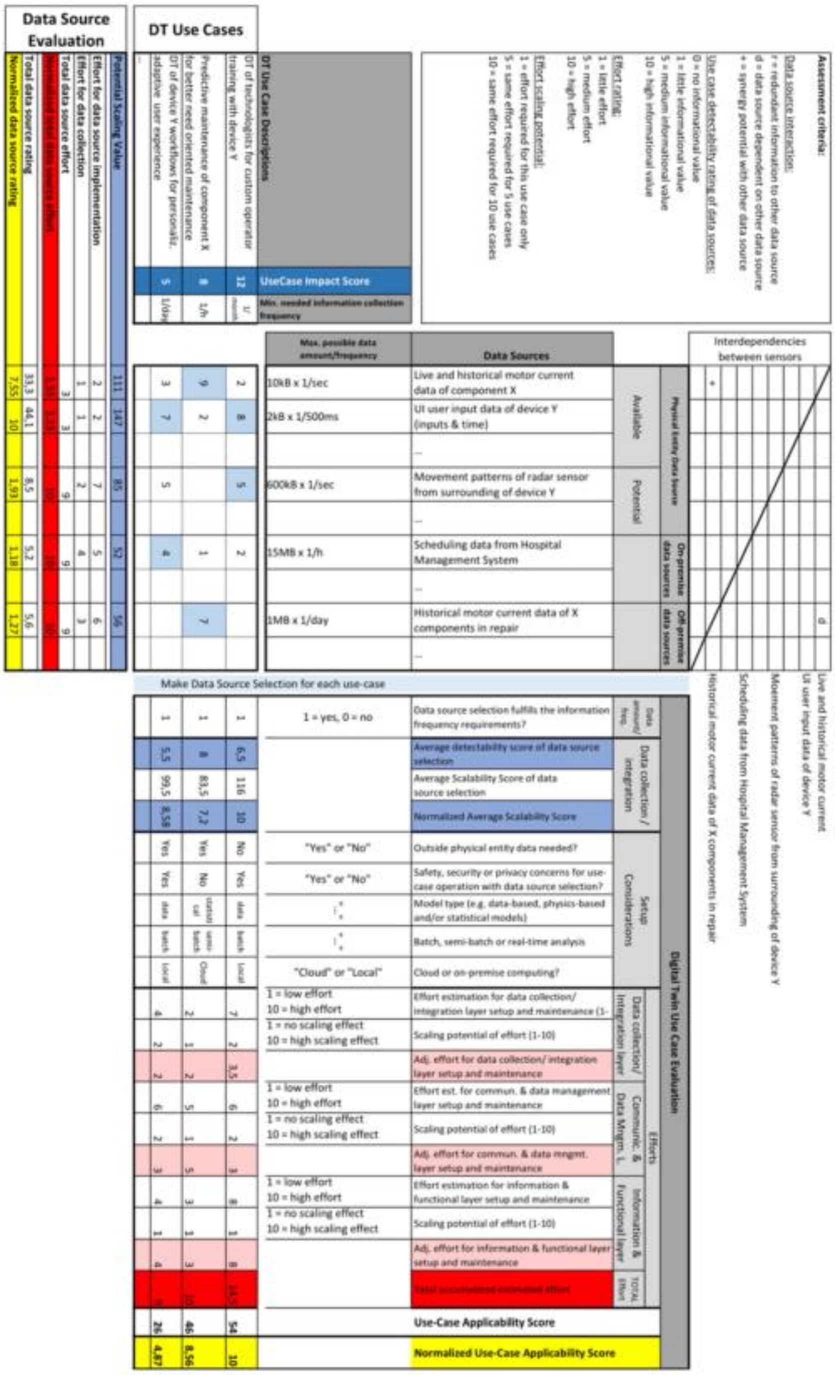


FIGURE 6. House-of-DT validation example of a mechatronic medical device analysis for Digital Twin use cases at Siemens Healthineers Innovation Think Tank.

use cases and their solutions and ratings are displayed in Figure 5.

B. HOUSE-OF-DIGITAL-TWIN (HOUSE-OF-DT)

More than 10 Digital Twin use cases along the entire life cycle of two medical mechatronic machines were considered in the analysis. An exemplary House-of-DT with anonymized Digital Twin use cases and data sources is shown in Figure 6. Device Y refers to a mechatronic subsystem of the entire medical system. Component X is a part of that subsystem that was analyzed in more depth separately.

The selected Digital Twin use cases and their impact scores from the UCMEA were placed in the left part of the House-of-DT, and the minimum needed information frequency of each use case was defined.

Data sources from the mechatronic systems of interest were derived from the product development documentation. A preselection was done by eliminating irrelevant data sources. The resulting selection of data sources was filled into the top part of the House-of-DT. Data sources were divided into physical entity, on-premise, and off-premise data sources. The maximum possible data amount/frequency was noted for each data source, and dependencies and redundancies between all data sources were assessed.

In the center matrix, we combined Digital Twin use cases with data sources. Each use case was matched with each data source that possibly holds informational value about the use case. The higher the informational value of a data source for a use case, the higher the detectability score. Within our example, the motor current data of component X holds great informational value on the state of component X and therefore gets a high rating for that use case. The motor current and motor timing also hold information about certain technologist workflows but only certain parts of it, so it receives a lower rating for that use case. Instead, the user input data holds great informational value about technologist behavior and device workflows and gets a high rating for those two use cases.

The potential to scale of each data source was calculated by combining use case impact scores and informational values of all use cases that a data source can describe. In the following step, the data source effort for each data source was estimated. The data source implementation and data collection efforts were rated, summed up, and normalized. By combining potential to scale and total normalized effort, each data source's total data source rating was calculated and normalized across all data sources. The user interface (UI) user input holds the greatest potential for our Digital Twin use cases selection in our example. It can be used for two out of the three exemplary use cases and needs little effort for implementation and data collection. The motor current is only mostly useful for one use case and is therefore rated lower. Making the UI user input data available for Digital Twin use case applications should receive higher prioritization than other data sources.

After the completed data source assessment, data source selections were made for each Digital Twin use case. Each selection considered the use case information and data source data frequencies, data source dependencies and redundancies, informational values, and data source ratings. These selections were used for further use case evaluations. In our example, for the DT of technologists for custom operator training with device Y, the UI user input data and the movement patterns of the radar sensor are selected.

A reality check was conducted concerning the required information frequency before starting the use case evaluation with specific data source selections. Data source selections that could not provide an information frequency equal to or higher than required by the use case were reconsidered until all data source selections fulfilled the information frequency requirements of the individual use cases. In the data collection/integration section, the average detectability score of each use case's data source selection was calculated. Furthermore, the average scalability score of each data source selection was determined, and the values were normalized across all use cases. In the section on setup considerations, questions were answered regarding data source location, safety, data security and privacy concerns, model type, analysis frequency, and computing location. These questions helped define each use case better and served as a basis for the following effort estimation. The effort estimation was conducted in three steps along the three elements mentioned above, with an effort and scaling potential estimation and an adjusted effort calculation for each element. After accumulating all elements' effort into the total effort, each use case's applicability score was determined. In our example, the custom operator training is most impactful, with good detectability ratings, great scalability, and above-average effort. Despite the higher effort, this use case has the highest Use Case Applicability Score among the exemplary use cases. It can therefore be recommended for starting the Digital Twin application implementation.

In this section, we showcased the validity of our methodology by applying it to a case of Digital Twin use case development of a medical mechatronic device. Exemplary use cases were derived and rated in the UCMEA, and selected Digital Twin use cases were further evaluated in interplay with anonymized data sources in the House-of-DT. As an outcome, selected data sources and Digital Twin use cases were recommended for prioritized development and implementation.

V. DISCUSSION

Our research found a need for a methodology that defines Digital Twin use cases and evaluates their efforts and benefits for prioritized implementation [2], [3], [22], [23]. So far, no methodology has been developed to address this need for the cross-industry concept of a Digital Twin. This work proposed a methodology that helps the practitioner systematically define Digital Twin use cases and find the ones with high value for stakeholders, low effort for implementation and maintenance, and high scalability potential for future use cases.

Our methodology fits well into existing, more generic Digital Twin development and innovation methodologies. While some processes for Digital Twin deployment exist [19], [24]–[26], they do not consider the challenge of which use cases to start with, independent of the application. Parrott and Warshaw's [2] Digital Twin development cycle mentions the steps "imagine" and "identify" but does not provide specific methods of how to accomplish these steps. We propose the UCMEA to "imagine" use cases and both the UCMEA and House-of-DT to "identify" the most promising Digital Twin use cases to start implementation with. The outcomes of our methodology can be reused and updated in the following iterative cycles of Parrot and Warshaw's Digital Twin development cycle. Similarly, the ITT methodology does not provide specific methods for accomplishing its steps. Our methodology provides specific tools for the "Acquire mandate and plan" and the "Big picture analysis" steps. The UCMEA considers stakeholders' needs and opportunities, identifies the most pressing and promising ones, and acquires the mandate for profitable use cases. For example, the big picture is considered by looking at processes and stakeholders from different stages along the product life cycle.

In the following paragraphs, we compare the important aspects of our methodology with methods from other fields, highlighting the advantages and limitations. Within our two-step methodology, the UCMEA provides a structured approach for defining use cases and determining their value for stakeholders. The House-of-DT estimates the scaling potential and efforts to implement and maintain Digital Twin use cases. This two-step approach is also taken in Moisiadis' [8] use case prioritization methodology in software development. He proposes first filtering use cases based on stakeholder goals to control the granularity of the use case elicitation in the second step of the methodology. This challenge has also been mentioned in the field of Digital Twin [23], and we use Moisiadis' two-step approach in our methodology, applicable to all kinds of stakeholder-driven use cases. With this two-step approach, the UCMEA filters for the most value-bringing use cases for the stakeholders so that the House-of-DT only needs to further elicit a smaller number of Digital Twin use cases. Furthermore, the UCMEA also identifies use cases that can be addressed better by other technologies or concepts. It, therefore, only passes on the Digital Twin use cases to the House-of-DT, where a Digital Twin application is one of the most promising solutions to the need or opportunity.

In our methodology, we guide the practitioner through steps to break down the process into easier to assess portions of the entire process. As a result, experts can more accurately estimate those steps, leading to a better overall process estimation. That means experts' judgment strongly influences our methodology. Kundu and Samanta [9] deprecate the influence of analysts' judgment in Moisiadis [8] methodology and propose a purely analytical software use case prioritization methodology. The field of Digital Twin is a cross-industry and ubiquitous concept that requires multidisciplinary teams and input. The field is still in its early phase, where numerous development approaches and architectures are discussed, and common ground has yet to be found. Such a complex system that is subject to constant change is difficult to assess analytically. We suggest developing a more analytical approach to Digital Twin use case prioritization once the field has settled.

Within the UCMEA, we look for stakeholder needs and opportunities along processes of interest to not miss important use cases and then detect potential synergies later in the methodology. The challenge of not missing important use cases has also been mentioned by Moisiadis [8] and Kundu and Samanta [9] in the field of software development. Nevertheless, they do not use a guiding structure to achieve this goal. In manufacturing, the PFMEA takes manufacturing processes as a guiding structure for the experts to identify potential failure modes along these processes. We apply the same principle to all kinds of processes of interest to identify stakeholder needs and opportunities, failure modes included. This approach enables broad Digital Twin use cases more than deep ones and helps focus on areas with potential to scale, which Parrott and Warshaw [2] advocate.

Part of product management is defining the product vision down to determining product features. A cornerstone of a product strategy is setting the main audience for the product and understanding their needs and wishes to address them with the product [27]. With Digital Twin applications being a product, we see the value of the use cases being defined by the stakeholders' goals. Ulwick [10], Moisiadis [8], and the PFMEA take a similar approach in the fields of innovation, software development, and manufacturing, respectively. We use Ulwick's "Opportunity Scoring" method by assessing stakeholder needs and opportunities and the satisfaction of the current solution. Moisiadis rates business goals by importance but does not consider the current solution satisfaction. We see the stakeholder satisfaction with the current solution as essential for identifying opportunities.

The PFMEA addresses potential failures but not opportunities for improvement. Every opportunity can be described by underlying pain points and every need by an improvement. The authors intended to address both negatively and positively connotated use case potentials and define one methodology to handle them. Nevertheless, occurrence, severity, and detection as rating characteristics of the PFMEA can all be used to define the importance rating of the UCMEA. This means that use cases commonly handled by a PFMEA can also be analyzed with our methodology.

Ulwick's "Opportunity Scoring" method stops at determining opportunities for innovation without considering existing solutions to those opportunities. We see the rating of potential solutions as essential for finding the right solution to a need or opportunity. Within our methodology, we rate the value of use case solutions. To achieve this, we ideate use case solutions along the needs and opportunities and estimate the use case solutions' stakeholder satisfaction. This process highlights the most promising use cases and allows identifying important needs and opportunities that can so far not be addressed by the proposed solutions. This approach is inspired by the remedy actions section in the PFMEA but uses Ulwick's stakeholder satisfaction to rate the use case solutions. Parrot and Warshaw (2017) [2] mention valuable processes and unexplained issues as indicators for good Digital Twin use cases. These indicators relate to the importance and satisfaction gap in our methodology.

The UCMEA defines use cases for many needs and opportunities which stakeholders express. Several use cases might be the same but address different needs and opportunities or stakeholders. To better manage the number of use cases, we recommend merging the same use cases that address different stakeholders' needs and opportunities and adding up their impact scores for further evaluation in the House-of-DT.

The House-of-DT uses the QFD method to combine use cases (customer requirements, the ''what'') with data sources (engineering characteristics, the ''how''). Similar to the House of Quality within the QFD, the House-of-DT interdependency analysis identifies the most promising and DT-irrelevant technical features (data sources) and most promising and non-addressable customer requirements (use cases). Unlike the QFD and the work of Stanula *et al.* [14], our methodology uses the rating of data sources again as input to evaluate use cases. This feedback closes the loop to having data source usability and scalability across use cases affect the prioritization of use cases. While in the QFD, the main output is the selection of technical features to focus on in development, the output of the House-of-DT is prioritized use cases to focus on in development and data sources to start the use case implementation with.

Stanula *et al.* concept of data source selection for machine learning algorithms (2018) [14] is embedded in our methodology as the option of Digital Twin use cases with data-based models. Besides data-based models, our methodology is applicable to all kinds of Digital Twin models requiring physical entity data. Besides manufacturing, our methodology can be applied to Digital Twin development across industries, such as healthcare, construction, logistics, and many more. Furthermore, it considers data sources and further implementation and maintenance efforts for a use case evaluation.

There are several needs and challenges that have been brought up as points for the Digital Twin field. Here we outline how our approach addresses these issues. Redelinghuys *et al.* [28] mention the challenge of keeping the amount of data to the maximum possible at a low level. We address this challenge by considering data amount and frequency in the decision process of the data source selection of each use case. Additionally, choosing data sources with great scaling potential keeps the amount of data low in the future, as the data can be used for multiple use cases. Wanasinghe *et al.* [23] point out considerations for Digital Twin implementation setups in terms of cloud or on-premise processors with batch, semi-batch, or real-time analysis. We address this point by including the required and available data amount and frequency and potential safety, security, and privacy concerns with data sources. These preliminary analyses set the ground for better decision-making regarding the processing location and data analysis frequency. Further work can look into deepening these analyses and setup recommendations.

Our methodology contributes to the existing literature by closing the research gap for a methodology assessing and prioritizing Digital Twin use cases. The Digital Twin concept is still rather young, and clear definitions and characteristics have not yet been determined. We identify data as an essential value aspect in Digital Twin use cases. We use aspects from methods from other fields to build a Digital Twin use case definition and prioritization methodology, with data as a central element.

For practitioners, this implies reduced uncertainty and a higher probability of profitable Digital Twin applications. Digital Twin use cases are ideated along entire processes of interest to identify broad Digital Twin use cases, which bring a higher value than deep ones [2]. Stakeholder needs and opportunities and their importance and satisfaction values give the practitioner an indication for opportunities for Digital Twin use cases. The use case ideation identifies solutions from all kinds of backgrounds. Their rating presents the practitioner with the Digital Twin use cases that are the preferred solution compared to other solutions. This rating reduces the probability of finding Digital Twin use cases for every need or opportunity, even though other solutions might be better suited for addressing them. By applying the House-of-DT, a practitioner is guided step-by-step through a data source and infrastructure evaluation for effort and scalability estimation. This evaluation helps the user come to a Digital Twin use case and data source prioritization for implementation, even if the Digital Twin concept is still new to the user. For further evaluation and visualization of the outcomes of the House-of-DT, the most promising use cases can be clustered in a Value versus Complexity diagram. This clustering separates the quick wins from the impactful long-term use cases.

We demonstrated the influence established methods from other fields had on developing our methodology, compared these methods with our approach, and showed how it further adds value to the field of Digital Twin development. We discussed remarks made by other researchers in the field and how we implemented their points into our methodology. Limitations were showcased, and further improvements were recommended.

VI. CONCLUSION

With the Digital Twin concept receiving more and more attention across industries, practitioners are faced with the challenge of identifying the most valuable and least effortful Digital Twin use cases to start implementation with. We proposed the Innovation Think Tank Methodology for

Digital Twin Use Case Definition, Prioritization, and Implementation. Our two-step methodology guides the definition and prioritization of Digital Twin use cases to support the implementation of Digital Twin applications. The methodology was validated on a product development example in the field of medical mechatronics at Siemens Healthineers Innovation Think Tank. It was shown that a broad field of use cases could be defined through the application of the UCMEA, and the most promising ones for stakeholders can be determined. An analysis of data source-use case interdependence and effort estimation through the House-of-DT brought out the most promising Digital Twin use cases regarding stakeholder satisfaction, scalability, and effort.

To the authors' knowledge, no research exists so far that aims to define and prioritize Digital Twin use cases. Our proposed methodology is guided and inspired by various existing methods from software development, innovation, process engineering, and product development. It was demonstrated how each step in our methodology took inspiration from methods from other fields. We discussed the advantages and disadvantages of these methods and why we implemented certain aspects at certain points in our methodology. Furthermore, we analyzed existing Digital Twin research and implemented aspects mentioned as needed in the Digital Twin development.

With our methodology, we give practitioners a tool at hand to define and assess Digital Twin use cases in any field of application. Based on stakeholder satisfaction, effort for implementation and maintenance, and use case scalability potential, practitioners can identify promising use cases and determine the ones to start implementation with. This approach reduces uncertainty and results in a higher probability of profitable Digital Twin applications.

As limitations, the methodology's dependency on experts' judgment and the young field of Digital Twin, which further develops and consolidates, were mentioned. We propose our methodology as a first step to structuring the Digital Twin development process but would suggest adapting and updating the methodology to emerging needs. A more analytical approach to Digital Twin use case prioritization can be developed in future work once the field has settled.

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2.3 Three-dimension Digital Twin Reference Architecture Model for Functionality, Dependability, and Life Cycle Development across Industries

Authors: **S. R. Newrzella**, D. W. Franklin, and S. Haider

Abstract: The Digital Twin concept promises numerous applications across industries and across its physical twin's entire life cycle. Although numerous architectures have been proposed to develop and describe the setup of Digital Twin applications, current Digital Twin architectures do not address the versatile cross-industry character of the Digital Twin concept, its safety, security, and privacy aspects, and are often use case-specific and inflexible. We propose a three-dimensional Digital Twin reference architecture model for application across industries, considering functionality, dependability, and life cycle aspects. Our model provides practitioners a common platform to develop and discuss Digital Twin applications of different complexities, and dependability aspects along varying life cycles and independent of the industry. We validate and showcase its applicability on examples from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector. We compare our reference architecture model to existing architectures, discuss its advantages and limitations, and position the model within previous literature.

Contribution: Based on the initial research of Schoueri (2021) [114], I researched additional Digital Twin architectures and structured and analyzed them all. I developed the proposed reference architecture model and validated its applicability on applications from Mahmeen et al. (2022) [117], Schoueri (2021) [114], and further research examples. I wrote the original manuscript under the advisement of Prof. Sultan Haider, revised it with the assistance of Prof. Dr. David Franklin, and designed all tables and figures.

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RESEARCH ARTICLE

Three-Dimension Digital Twin Reference Architecture Model for Functionality, Dependability, and Life Cycle Development Across Industries

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ABSTRACT The Digital Twin concept promises numerous applications across industries and its physical twin's entire life cycle. Although numerous architectures have been proposed to develop and describe the setup of Digital Twin applications, current Digital Twin architectures do not address the versatile cross-industry character of the Digital Twin concept, its safety, security, and privacy aspects, and are often use case-specific and inflexible. We propose a three-dimensional Digital Twin reference architecture model for application across industries, considering functionality, dependability, and life cycle aspects. Our model provides practitioners a common platform to develop and discuss Digital Twin applications of different complexities and dependability aspects along varying life cycles and independent of the industry. Its applicability is validated and showcased by examples from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector. We compare our reference architecture model to existing architectures, discuss its advantages and limitations, and position the model within previous literature.

INDEX TERMS Applications, cross-industry, digital twins, framework, planning, visualization.

I. INTRODUCTION

As part of the digitalization trend, the Digital Twin concept is seeing rising interest in academia and industry [1], with Grand View Research expecting a market worth of USD 155.84 Billion in 2030 [2]. The three-part Digital Twin concept was informally introduced by Grieves (see Figure 1), while the enabling technologies only made it technically feasible in the last decade [3]. Digital Twin can be defined as a cross-industry concept containing a physical entity and its digital representation, which evolves with its physical twin in real-time and provides additional value [4]. Digital Twin research can be found in Manufacturing, Aviation, Healthcare, Construction, Oil and Gas Industry, Transportation [5], [6], [7], and many more. In the case of products, Digital Twin research can be found along the entire product

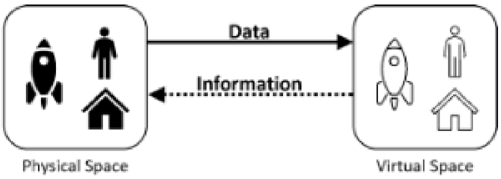

FIGURE 1. Illustration from Newrzella *et al.* [4]. The Digital Twin concept based on Grieves [12].

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life cycle [8], [9], with use cases such as optimization of process performance and prediction of potential disruptions. In healthcare, human Digital Twin research exists along pathways in domains such as fitness [10] and disease diagnosis and treatment [11], with use cases such as personalized health diagnosis and fitness recommendations.

With this cross-industry dissemination and growth of the Digital Twin concept arise challenges. Confusing terminologies [4], unclear development strategies [13], and a variety of different architectures confuse developers and users and hamper the potential of the Digital Twin concept. This article proposes a cross-industry Digital Twin reference architecture model that aims to consolidate the variety of Digital Twin architectures under three dimensions: Functionality, dependability, and life cycle. Research has shown functional elements' dominant and important role in Digital Twin architectures. Dependability aspects gain more and more importance with Digital Twins becoming further integrated into our lives, becoming more complex, and more reliant on computational intelligence than human decision-making [14]. Therefore, we see designing dependable, reliable, safe, and secure Digital Twins as essential to the concept's success. Finally, a broad life cycle application of the Digital Twin concept is often promoted [8], [9], [15], [16], with such applications tending to drive the most support and value [17].

We see the establishment of a practical reference architecture model that addresses the functional, dependability, and life cycle aspects of Digital Twin applications as a key to the success of the Digital Twin concept across industries. Numerous Digital Twin architectures exist, but none provides a cross-industry reference architecture model with flexible functionality, dependability, and life cycle dimensions. We propose a Digital Twin reference architecture model with these dimensions to address this need. The reference architecture model's independent dimensions enable developers to design and visualize Digital Twin applications of different complexities and industries. This approach allows a structured development and easy comparison of a wide range of Digital Twin applications and their architectures.

In this article, existing Digital Twin and related architectures are analyzed, and their relation to functional, dependability, and life cycle aspects is showcased. From this analysis, we derive our three-dimensional Digital Twin reference architecture model, which is validated on examples from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector. Concluding, we discuss our reference architecture model, its relation to other architectures, its limitations, and potential next steps.

II. RELATED WORK

Since early in Digital Twin research, Digital Twin architectures have been proposed with different focuses, application fields, and levels of detail. This section analyzes Digital Twin architectures proposed in 2021 and earlier and describes their shortcomings. The short descriptions of the architectures showcase the differences between the architectures, while the overview tables demonstrate commonalities. The overview tables mention the application or purpose of each architecture and place the architectures' functional elements in relation to underlying functionalities (Table 1 and Table 2) and dependability aspects (Table 3). The differences in architectures justify the need for a reference architecture model, while the commonalities demonstrated in the overview tables justify two of the dimensions considered in this article's model.

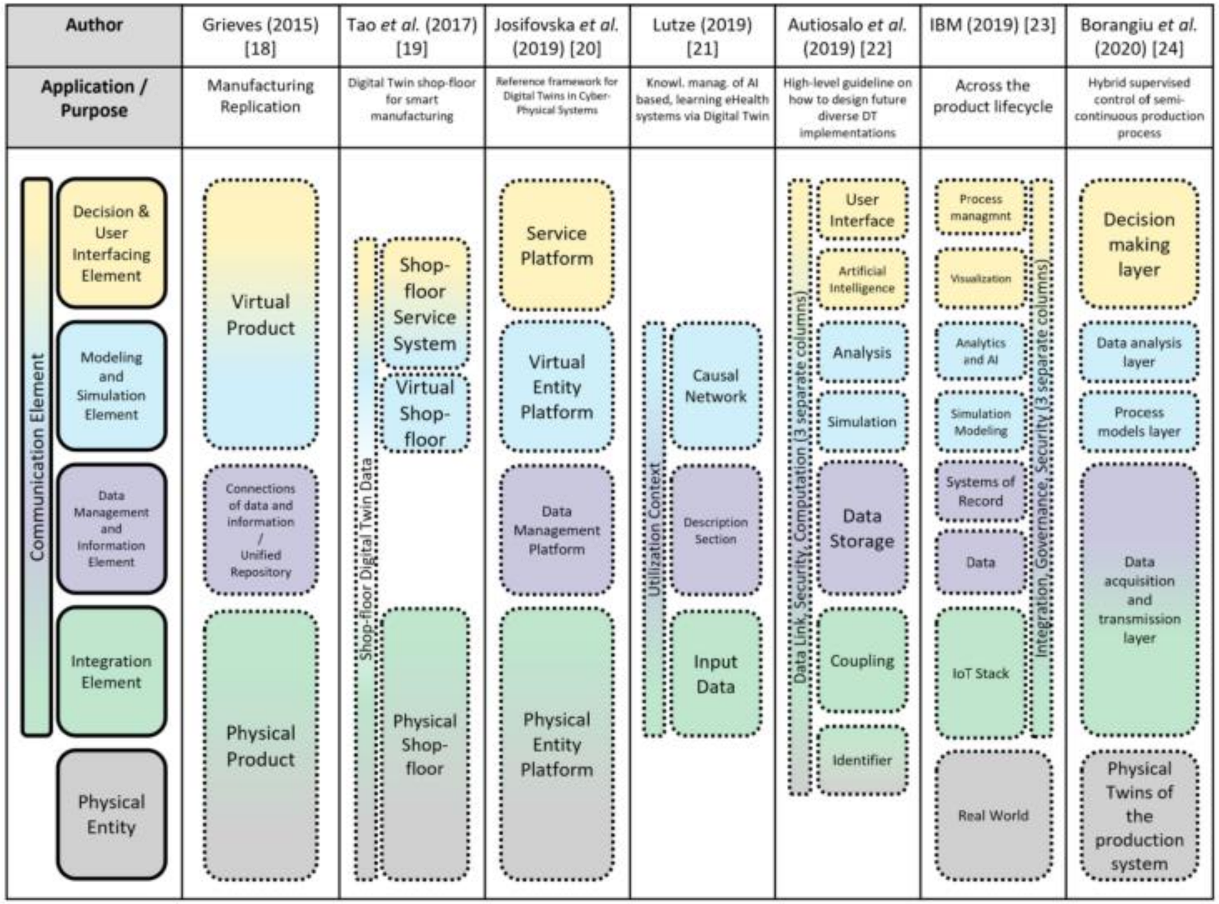
Grieves first proposed the general idea of a Digital Twin [18] and further described it later in his White Paper [12]. The fundamental structure consists of the physical product, the virtual product, and the connections of data and information that connect both (see Figure 1). He also refers to the connection part as a unified repository. Grieves illustrates his idea of a closely linked physical and virtual factory for quicker and more intuitive design and execution comparison of manufactured products. Grieves describes the core elements of the Digital Twin concept upon which later architectures are built. His work has not defined further functional, dependability, and life cycle aspects.

Tao *et al.* [19] propose a four-component Digital Twin shop-floor architecture comprising a physical shop-floor, a virtual shop-floor, a shop-floor service system, and the shop-floor Digital Twin data tying all dimensions together. The physical shop floor includes humans and machines. The virtual shop-floor dimension consists of geometry-, physics-, behavior-, and rule-based models of its physical counterpart and evolves with its physical counterpart through the data connection between the two. The shop-floor service system contains services for specific demands from the physical and virtual shop floor. These services comprise sub-services in the form of computer-aided tools, Enterprise Information Systems, models and algorithms, etc. The shop-floor Digital Twin data is the center element of the model connecting the other three components and enabling interaction and iterative optimization. The data is integrated, resulting in no distinct data storage entity. While Tao *et al.* mention dependability and life cycle applications, they are not distinctively considered in the architecture.

Josifovska *et al.* [20] analyzed existing Digital Twin literature to identify four main building blocks for their Digital Twin framework, which they propose for application in Cyber-Physical Systems. The framework consists of the physical entity platform, which incorporates the physical entity (objects and humans) and physical nodes (sensors, actuators, user interfaces), the data management platform, which is responsible for data acquisition, management, and storage, the virtual entity platform, which hosts various Digital Twin models (geometric, physical, behavioral, rule, process), and the service platform, which handles the goals of the Digital Twin. Dependability and life cycle aspects cannot be found in the framework.

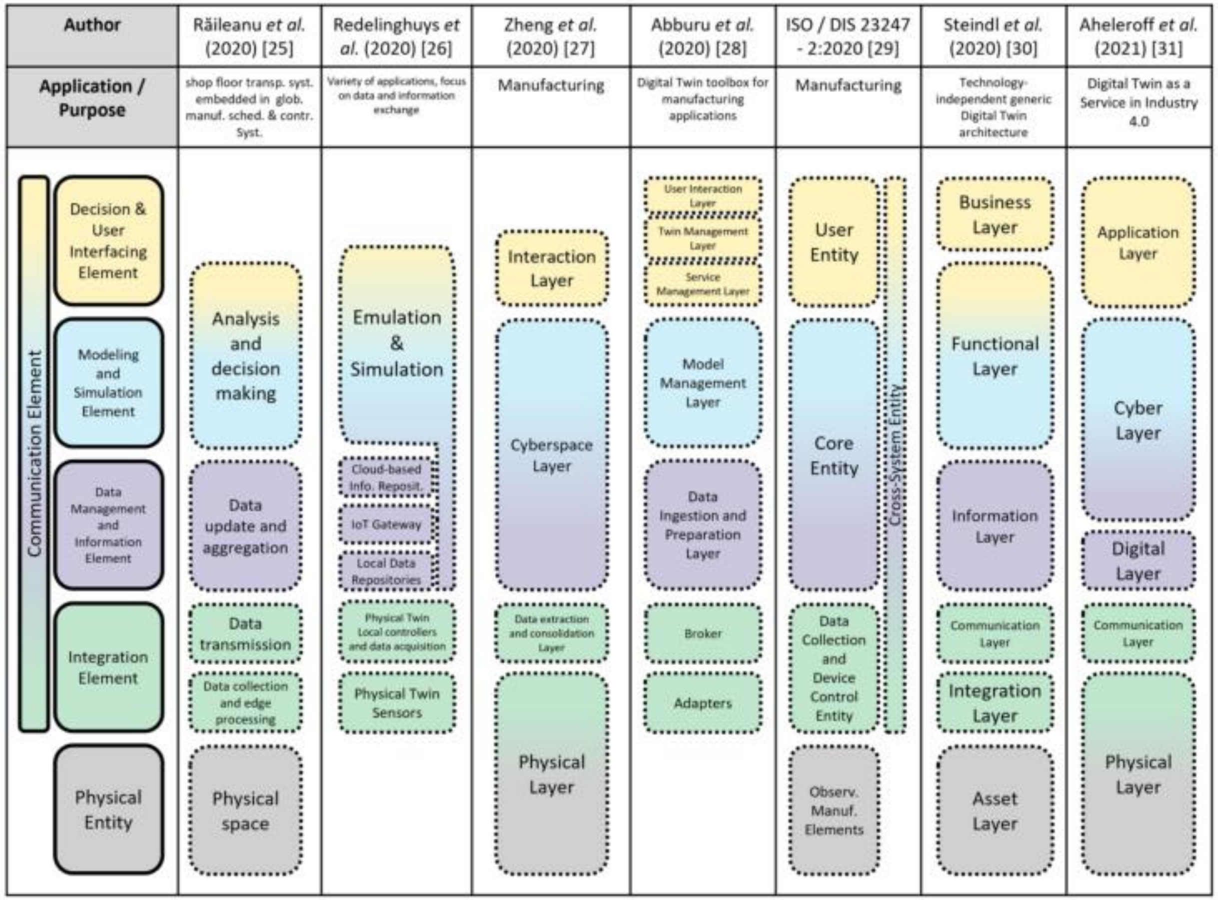
Lutze [21] focuses on Digital Twins in eHealth and divides his proposed architecture into four general Digital Twin constituents and three different manifestations of Digital Twins.

TABLE 1. Overview of existing Digital Twin architectures within the functionality dimension - part 1.



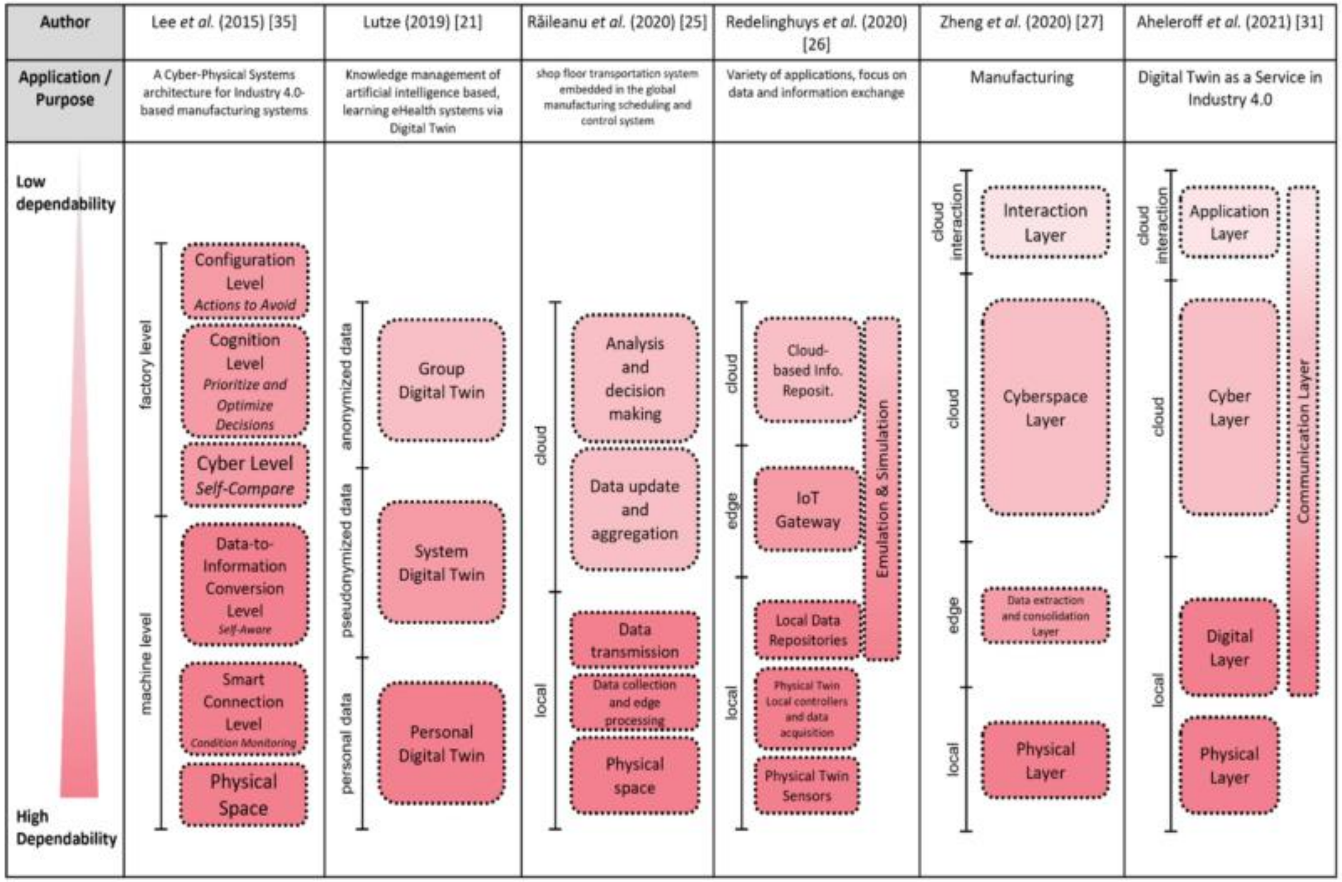
Author	Grieves (2015) [18]	Tao *et al.* (2017) [19]	Josifovska *et al.* (2019) [20]	Lutze (2019) [21]	Autiosalo *et al.* (2019) [22]	IBM (2019) [23]	Borangiu *et al.* (2020) [24]
Application / Purpose	Manufacturing Replication	Digital Twin shop-floor for smart manufacturing	Reference framework for Digital Twins in Cyber-Physical Systems	Knowl. manag. of AI based, learning eHealth systems via Digital Twin	High-level guideline on how to design future diverse DT implementations	Across the product lifecycle	Hybrid supervised control of semi-continuous production process
Decision & User Interfacing Element	Virtual Product	Shop-floor Service System	Service Platform		User Interface Artificial Intelligence	Process managmnt Visualization	Decision making layer
Modeling and Simulation Element		Virtual Shop-floor	Virtual Entity Platform	Causal Network	Analysis Simulation	Analytics and AI Simulation Modeling	Data analysis layer Process models layer
Data Management and Information Element	Connections of data and information / Unified Repository		Data Management Platform	Description Section	Data Storage	Systems of Record Data	Data acquisition and transmission layer
Integration Element	Physical Product	Physical Shop-floor	Physical Entity Platform	Input Data	Coupling	IoT Stack	
Physical Entity					Identifier	Real World	Physical Twins of the production system
Communication Element		Shop-floor Digital Twin Data		Utilization Context	Data Link, Security, Computation (3 separate columns)	Integration, Governance, Security (3 separate columns)	

TABLE 2. Overview of existing Digital Twin architectures within the functionality dimension - part 2.



Author	Räileanu *et al.* (2020) [25]	Redelinghuys *et al.* (2020) [26]	Zheng *et al.* (2020) [27]	Abburu *et al.* (2020) [28]	ISO / DIS 23247 - 2:2020 [29]	Steindl *et al.* (2020) [30]	Aheleroff *et al.* (2021) [31]
Application / Purpose	shop floor transp. syst. embedded in glob. manuf. sched. & contr. Syst.	Variety of applications, focus on data and information exchange	Manufacturing	Digital Twin toolbox for manufacturing applications	Manufacturing	Technology-independent generic Digital Twin architecture	Digital Twin as a Service in Industry 4.0
Communication Element Decision & User Interfacing Element	Analysis and decision making	Emulation & Simulation	Interaction Layer	User Interaction Layer Twin Management Layer Service Management Layer	User Entity Cross-System Entity	Business Layer Functional Layer	Application Layer
Modeling and Simulation Element			Cyberspace Layer	Model Management Layer	Core Entity		Cyber Layer
Data Management and Information Element	Data update and aggregation	Cloud-based Info. Reposit. IoT Gateway Local Data Repositories		Data Ingestion and Preparation Layer		Information Layer	Digital Layer
Integration Element	Data transmission Data collection and edge processing	Physical Twin Local controllers and data acquisition Physical Twin Sensors	Data extraction and consolidation Layer Physical Layer	Broker Adapters	Data Collection and Device Control Entity	Communication Layer Integration Layer	Communication Layer Physical Layer
Physical Entity	Physical space				Observ. Manuf. Elements	Asset Layer	

TABLE 3. Overview of existing Digital Twin architectures within the dependability dimension.



Author	Lee *et al.* (2015) [35]	Lutze (2019) [21]	Răileanu *et al.* (2020) [25]	Redelinghuys *et al.* (2020) [26]	Zheng *et al.* (2020) [27]	Aheleroff *et al.* (2021) [31]
Application / Purpose	A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems	Knowledge management of artificial intelligence based, learning eHealth systems via Digital Twin	shop floor transportation system embedded in the global manufacturing scheduling and control system	Variety of applications, focus on data and information exchange	Manufacturing	Digital Twin as a Service in Industry 4.0
Low dependability **High Dependability**	factory level: Configuration Level *Actions to Avoid* Cognition Level *Prioritize and Optimize Decisions* Cyber Level *Self-Compare* machine level: Data-to-Information Conversion Level *Self-Aware* Smart Connection Level *Condition Monitoring* Physical Space	anonymized data: Group Digital Twin pseudonymized data: System Digital Twin personal data: Personal Digital Twin	cloud: Analysis and decision making Data update and aggregation local: Data transmission Data collection and edge processing Physical space	cloud: Cloud-based Info. Reposit. edge: IoT Gateway local: Local Data Repositories Physical Twin Local controllers and data acquisition Physical Twin Sensors Emulation & Simulation	cloud interaction: Interaction Layer cloud: Cyberspace Layer edge: Data extraction and consolidation Layer local: Physical Layer	cloud interaction: Application Layer cloud: Cyber Layer local: Digital Layer Physical Layer Communication Layer

The constituents are a unique identifier of the twin, a causal network that maps symptoms to conclusions, a structured description containing inherent characteristics and states of the physical entity, and a utilization context for linking twin manifestations. Lutze's three manifestations of Digital Twins are called Personal Digital Twin, System Digital Twin, and Group Digital Twin. Personal Digital Twins represent individual persons with their personal, behavioral, and clinic data, symptoms, and conclusions. Numerous Personal Digital Twins are used to train an artificial intelligence software system called System Digital Twin, which provides diagnostic recommendations for a group of individuals with similar characteristics and states. Such a group of similar Personal Digital Twins is represented by depersonalized Group Digital Twins, which serve as characteristics check for new Personal Digital Twins and which System Digital Twins they can be applied to for diagnostic recommendations. Lutze's architecture aims to enable eHealth Digital Twins compliance with the EU General Data Protection Regulation. This proposal includes functional elements and data privacy-based dependability levels. However, life cycle aspects are not considered.

Autiosalo *et al.* [22] analyze existing Digital Twin publications and derive ten distinguishable features in a Digital Twin that they propose allocating in a star structure around the data link feature. The features are the data link, coupling, identifier, security, data storage, user interface, simulation, analysis, artificial intelligence, and computation. The data link is the center element of the architecture, connects digital things to each other, and acts as the hub for all physical twin information. The coupling feature is a two-way interface connecting the physical entity to its Digital Twin. At the same time, the identifier uniquely identifies a Digital Twin in the physical and digital world. Security must be embedded in the entire Digital Twin architecture to fulfill the specific use case's needs. Data storage can be located locally and globally and stores all the Digital Twin's data, and the user interface lets users interact with the Digital Twin. Simulation provides the Digital Twin with dynamic, steady, visual, graphical, or numerical approximations of its physical twin's behavior. An analysis uses these simulations and the physical twin data to generate recommendations for the Digital Twin for decision making. A Digital Twin with an artificial intelligence feature is able to make autonomous decisions. Computation is required across the entire Digital Twin and is an essential feature. The framework of Autiosalo *et al.* mentions ten interconnected functional elements of a Digital Twin but does not provide dependability and life cycle aspects for developing Digital Twin applications.

In 2019, IBM proposed a Digital Twin reference architecture for products across the entire product life cycle [23]. It consists of seven layers of information management and manipulation and three columns that ensure secure, suitably governed and coupled Digital Twin operation. The seven layers consist of IoT (Internet of Things) Stack, Data, Systems of Record, Simulation Modelling, Analytics and Artificial Intelligence (AI), Visualization, and Process management. The authors mention that Digital Twins integrate into existing enterprise applications which can be allocated to the seven functional layers. Dependability and life cycle aspects are not considered in IBM's reference architecture.

Borangiu *et al.* [24] applied the new four-layer ARTI reference architecture to the production process of radiopharmaceuticals to enable collective and predictive situation awareness and bring software control and real process closer together. The data acquisition and transmission layer acquires and pre-processes process data. The process models layer represents and emulates individual processes, which the data analysis layer uses together with device data to predict equipment status, product characteristics, and process parameters and detect anomalies. The decision-making layer applies these insights to operate the supervised production control. While functional elements are represented, the architecture does not include dependability and life cycle aspects.

Răileanu *et al.* [25] apply their four-layer Digital Twin control architecture to a shop floor transportation system embedded in the global manufacturing scheduling and control system. The data collection and edge processing layer creates information from the data of the physical entity, forwards it to the data transmission layer, and executes orders received from the upper layers. The data transmission layer communicates with the two upper layers in the cloud. The data update and aggregation layer contains, for example, database storage, CAD models, and transportation graphs. At the same time, the analysis and decision-making layer makes decisions based on AI techniques to send the decisions back down through the layers for execution. Răileanu *et al.*'s architecture links functional and dependability aspects by placing the data update and aggregation and the analysis and decision-making layer in the cloud. Therefore, the architecture only applies to the mentioned application and restricts local Digital Twin applications from being represented. Furthermore, a life cycle aspect is not considered.

Redelinghuys *et al.* [26] propose a six-layer digital twin architecture for various applications, highlighting the exchange of data and information between the physical twin and remote simulation or emulation. The architecture consists of sensor and local controller/data acquisition layers, a local data repositories layer, an IoT Gateway layer, a cloud-based information repositories layer, and an emulation and simulation layer. Users interface with the Digital Twin through the emulation and simulation layer, whereas the IoT Gateway layer also provides a GUI. The architectural elements can be divided into three dependability levels, local, edge, and cloud. This allocation shows the fusion of functional and dependability aspects, highlighted by data storage located on both the local and cloud levels. Digital Twin implementations across life cycles are difficult to visualize.

Zheng *et al.* [27] propose a generic system architecture for Digital Twin establishment consisting of four layers, the physical layer, the data extraction and consolidation layer, the cyberspace layer, and the interaction layer. The physical layer contains the physical system, its environment, and its data outputs and sensors. The data extraction and consolidation layer processes the data from the physical layer and passes it on to the cyber layer. The cyberspace layer establishes the Digital Twin by containing models of the physical entity and provides universal access to the physical entity by being located in the cloud. The interaction layer allows users to interact with the physical entity through the Digital Twin in the cloud. Zheng *et al.*'s architecture combines functional and dependability aspects while not considering life cycle aspects. Digital Twin applications cannot be represented at different dependability levels and across life cycle stages.

Abburu *et al.* [28] propose three different capability versions of Digital Twins: Digital Twin, Hybrid Digital Twin, and Cognitive Digital Twin. These three layers are based on isolated models, then interconnect the models and extend them with expert and problem-solving knowledge. The autonomous Cognitive Digital Twin consists of five main layers, adapters, and a broker for data acquisition from the physical entities. The data ingestion and preparation layer pre-processes and stores data for further usage. The model management layer ensures efficient storage and access to models called by different services from the service management layer. The service management layer resolves domain problems by orchestrating services. The user interaction layer supports a user in exploring the Cognitive Digital Twin and its characteristics. The twin management layer ensures the interconnection of the physical entity and its digital representation. Abburu *et al.*'s architecture provides functional elements but does not include dependability and life cycle aspects.

The International Organization for Standardization (ISO) issued an international standard draft in 2020 to propose a Digital Twin framework for manufacturing to support the creation of Digital Twins in manufacturing [29]. Part 2 explains the reference architecture consisting of four entities, the data collection and device control entity, the core entity, the user entity, and the cross-system entity. The observable manufacturing elements are outside the Digital Twin framework but are mentioned to facilitate understanding of the framework. The data collection and device control entity monitors and collects data from the physical devices and controls and actuates these. The core entity handles the overall operation and management of the manufacturing Digital Twin, hosts applications and services such as analysis and simulation, and guarantees interoperability with other entities. The user entity provides interfaces for any entity that utilizes the Digital Twin for manufacturing, such as humans, devices, enterprise resource planning (ERP) systems/manufacturing execution system (MES), and other core entities. The cross-system entity is allocated across entities and provides common functionalities such as data assurance, data translation, and security support. The ISO/DIS 23247-2 elaborates various functional elements but planning the dependability and life cycle aspects of Digital Twin applications is difficult.

Steindl *et al.* [30] criticize the often application-specific Digital Twin solutions without general architectural concepts and propose a generic Digital Twin architecture that can be applied technology-independent. From an overview of concepts, architectures, and frameworks for Digital Twins, they derive a generic 6-layer architecture. The asset layer contains the physical entity, whereas the integration layer makes run-time and engineering data available. The communication layer ensures the correct data transfer protocols to the information layer, which pre-processes and stores the data. The functional layer provides simulation, monitoring, diagnostics, prediction, control, and reconfiguration services. Those services are equipped with an appropriate human-machine interface to engage with humans. The business layer hosts the business logic that defines the Digital Twin's overall objectives. Steindl *et al.*'s architecture describes functional elements and targets the "instance-phase" in the life cycle dimension of the RAMI4.0. Therefore, an application across all life cycle stages is difficult, and dependability aspects cannot be explicitly planned.

Aheleroff *et al.* [31] divide their Digital Twin reference architecture model into three dimensions, Digital Twin layers, value life cycle steps, and level of integration. This division aims to facilitate the understanding of complex interrelations by breaking them into smaller and simpler clusters. The dimension of the Digital Twin layers consists of the physical layer, the communication layer, the digital layer, the cyber layer, and the application layer. The physical layer contains the physical assets, sensors, and actuators. The communication layer handles inter-layer communication, and the digital layer incorporates static data locally, such as CAD files. The cyber layer includes cloud processing, storage, simulation, and modeling. The application layer makes the outcomes available through user interfaces. The dimension of the value life cycle mentions the iterative, incremental value life cycle. The dimension of the level of integration contains the three types of data flow of Kritzinger *et al.* [32] and the Digital Twin predictive as a cloud-enabled Digital Twin using Big Data and Machine Learning. Aheleroff *et al.*'s architecture merges functional and dependability aspects in their Digital Twin layers and involves dependability aspects in their level of integration. This merging restricts the model from being applied to Digital Twin applications with different dependability characteristics on these layers and levels.

Cyber-Physical Systems (CPS) are physical systems connected to communication and computation entities over the internet [33], [34]. Digital Twins enable CPSs to self-configure, self-adjust, and self-optimize [20], and both concepts are often mentioned together. Lee *et al.*'s [35] 5-layer architecture for CPS in Industry 4.0-based manufacturing systems is often referred to in Digital Twin architectures [25], [26], [27], [30], [36]. The architecture often referred to as 5C architecture consists of five "C" levels, the smart connection level, the data-to-information conversion level, the cyber level, the cognition level, and the configuration level. Each level enables different functions based on its complexity and connectivity. The smart connection level acquires accurate and reliable data from the physical entity. The data-to-information conversion level brings self-awareness to the machines by calculating condition values, remaining lifetime, etc. The cyber level connects all machines to a central information hub to compare performances and predict future behavior. The cognition level visualizes individual and comparative information to prioritize the optimization tasks. The resulting corrective and preventive decisions are returned from cyber space to physical space at the configuration level. The 5C architecture is built around types of use cases enabled by functional elements and connectivity capabilities on each level. The architecture merges use-cases with functional and dependability aspects by assigning the connection and conversion level to the machine and the cyber, cognition, and configuration level to the factory layer. Alternative allocations of functional elements on different levels can therefore not be represented. Furthermore, the architecture does not consider cross-life cycle applications.

The term "Industry 4.0" stands for the fourth industrial revolution, where humans, objects, and systems are interconnected to achieve real-time analysis and optimization. The Digital Twin is seen as a key concept for Industry 4.0 [37], [38], and Digital Twin applications are often found in manufacturing as part of Industry 4.0 [19], [26], [30], [31], [38]. In 2015 the joint project "Plattform Industrie 4.0" consisting of associations and companies developed the Reference Architecture Model Industry 4.0 (RAMI4.0) [39]. The model aims to satisfy the need for a unified reference architecture model to discuss interdependencies and details of Industry 4.0 matters, particularly standards and norms. This reference architecture model is often referred to in Digital Twin architectures [30], [31] and is also considered in this article's Digital Twin reference architecture model. RAMI4.0 consists of three dimensions: Layers for representing different information views, life cycle & value stream for dividing matters into different life cycle stages, and hierarchy levels for assigning functional models to specific levels. View layers range from asset, integration, and communication to information, functional, and business. Life cycle & value stream stages are divided into type (general product development information) and instance (unique manufactured product) and show development/production and maintenance/usage stages. The hierarchy levels range from product, field device, control device, and station to work centers, enterprise, and connected world. RAMI4.0 provides functional elements, hierarchy levels which can be seen as a type of dependability classification, and life cycle aspects. We see these dimensions as equally important for Digital Twins and utilize them to visualize networks of Digital Twin elements and their interplay across these dimensions. While RAMI4.0 uses these dimensions to classify Industry 4.0 norms and standards, the proposed reference architecture model uses these dimensions to visualize entire Digital Twin architectures.

The analyzed Digital Twin architectures focus on functional elements, sometimes combined with dependability aspects. Life cycle applications are mostly only mentioned without the aspect being explicitly integrated into an architecture for the life cycle planning of an application. This lack of flexibility prevents the application of different kinds of Digital Twin use cases across industries, as they can be applied across the entire life cycle of its entity and at different levels of dependability. We present a Digital Twin reference architecture model that addresses this research gap. The model independently considers functionality, dependability, and life cycle aspects in its design, enabling a broad range of applications to be designed and visualized.

III. REFERENCE ARCHITECTURE MODEL

We see the need to develop a uniform architecture model as a reference based on which interrelationships and details of Digital Twin applications can be discussed. We propose the Innovation Think Tank Digital Twin Reference Architecture Model, which contains the essential aspects of a Digital Twin. Figure 2 shows a schematic overview of our Digital Twin reference architecture model. A three-dimensional model can best represent the Digital Twin space. The model is inspired by RAMI4.0. It was adapted based on the Digital Twin requirements. The vertical axis describes possible functional elements that can be used to implement a Digital Twin application. The depth axis divides the Digital Twin components into application-specific dependability levels for better safety, security, and privacy planning. The horizontal axis represents the life cycle aspect of a Digital Twin, where Digital Twin components and their interrelationships can be mapped along the life cycle of the physical entity. Thus, the special characteristics of the reference architecture model are the combination of functionality, dependability, and life cycle aspects. These aspects provide a high degree of flexibility for describing Digital Twin applications. The approach also allows the encapsulation of dependability cages, as proposed by Aniculaesei *et al.* for autonomous systems [40]. Compared to most other Digital Twin architectures, this article's reference architecture model provides a sufficient level of abstraction rather than a concrete architecture to enable the development and description of Digital Twin applications of different complexity and from different industries. The reference architecture model defines a basic structure and the main dimensions and components for Digital Twin applications without confining it to specific technologies. Thus, the prerequisites are created to describe and realize highly flexible Digital Twin architectures through the reference architecture model proposed in this article.

The model allows the step-by-step development from simple to complex Digital Twins and the definition of applications with distinct specifications and requirements. For realizing a Digital Twin application based on this reference architecture model, functional elements with different complexities can be allocated at different dependability levels at

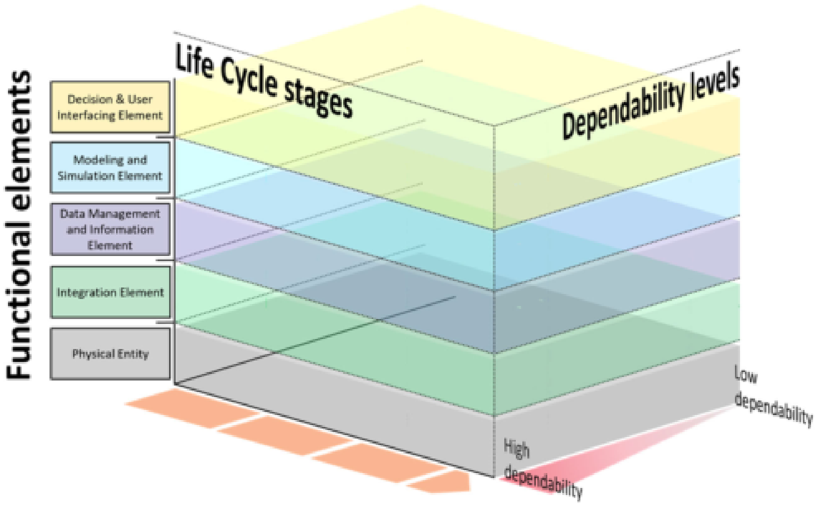


FIGURE 2. Schematic of the Innovation Think Tank Digital Twin reference architecture model.

different life cycle stages. The interrelationships and communication between the functional elements further define the Digital Twin applications in the proposed model. This approach means that specific technologies are defined by the functional elements, depending on the application. These elements can be allocated at different dependability levels, only adapting their communication and security setups to account for different dependability requirements, for example. The allocation of the functional elements at different life cycle stages does not require additional technologies either. The functional elements and their technologies might, for example, communicate with different functional elements depending on their life cycle stage. The three dimensions are described in more detail further below, while specific application examples are given in the validation case study section.

A. FUNCTIONAL DIMENSION

The vertical axis in Figure *2* displays the functional dimension, which consists of functional elements. These elements provide logical groupings of functionalities and tasks which a Digital Twin application can use. This element-based design helps break down complex applications into building blocks of specific functionality. This division bears advantages such as reuse of solutions, reconfigurability, modular analysis and validation, and controllability [41]. Elements can be omitted, used multiple times in different orders, and interact with each other in various ways. The displayed order of the functional elements in the proposed reference architecture seems common across numerous analyzed architectures (Table 1 and Table 2). Still, the number of used elements, their capabilities, and interactions are application-specific. The analysis further identified six ubiquitous functional elements with distinct sets of tasks, inspired by Schoueri [42]. The physical entity is the basis for any Digital Twin application and builds the functional dimension's basis. The integration element consists of data sources that record and transfer data from and around the physical entity. Low-level pre-processing can also be executed within the integration element. The data management and information element further pre-processes the data, creates information out of it by putting the different data sources in context, and stores the data in a format convenient for further analyses. The modeling and simulation element combines data to digitally represent the physical entity in time and space and simulate potential future scenarios. The decision and user interfacing element orchestrates goals and priorities of the Digital Twin with the user having access in, for example, either read or write mode. The communication element is not considered a distinct element in the reference architecture model as its functionality is spread across the other elements. Communication between the elements and outside entities can be visualized through different kinds of arrows and their annotations between the involved parties.

B. DEPENDABILITY DIMENSION

The depth axis in Figure *2* represents the dependability dimension. "Dependability" can be defined as "The quality of being trustworthy and reliable." [43]. In autonomy, "dependability" is often used when referring to safety, security, and privacy issues as a whole [40]. The same definition is used in this article. Dependability aspects can be quite versatile and depend on the application. For example, in autonomous systems, a Digital Twin in a safety-critical application requires very low latency to provide the safety level required. A human Digital Twin handling personal data requires different levels of data privacy depending on the anonymization of the data. A Digital Twin with access to critical information and actions requires different security levels depending on the application. The analysis of CPS and Digital Twin architectures identified different levels of dependability. In manufacturing, common dependability levels are local, edge, cloud, and cloud interaction or machine and factory level. Human Digital Twin dependability levels can be categorized into personal, pseudonymized, and anonymized data. We separate the dependability dimension from the functional dimension. This separation allows the development and visualization of Digital Twin applications with different functionalities at different dependability levels. The exact dependability levels are left open to allow the use of the reference architecture model across industries and applications. The examples are supposed to give the reader an understanding of possible dependability levels.

C. LIFE CYCLE DIMENSION

The horizontal axis in Figure 2 depicts the life cycle dimension. The term "life cycle" used in this article refers to "the series of changes that a product, process, activity, etc. goes through during its existence" [44]. Digital Twin functional building blocks, connections, and dependability levels depend on the life cycle stage where the physical twin(s) of a Digital Twin reside(s). The types of life cycle stages depend on the application. Digital Twins of products can be mapped along their product life cycle. Human Digital Twins can be considered along a disease pathway or across an athlete's routine activity zones. In logistics, a Digital Twin can be used along the logistics supply chain. Life cycle stages do not have to represent chronological time frames but can also represent reoccurring time frames, such as in the example of an athlete's activity zones. The reference architecture model's concrete life cycle stages are left open to allow application-specific time frames across industries. The mentioned examples intend to give the reader an idea of possible applications.

We proposed a three-dimensional Digital Twin reference architecture model based on functionality, dependability, and life cycle aspects. This separation provides great flexibility for applications of different complexities and industries. To demonstrate the model's versatile applicability, validation examples are shown from six different industries.

IV. VALIDATION CASE STUDY

The applicability of the reference architecture model is demonstrated in six examples. The examples represent Digital Twins from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector. The examples only present a selection of functional elements to facilitate the understanding of potential applications.

A. MECHATRONIC PRODUCT

The first example in Figure 3 features a Digital Twin setup in the field of medical mechatronic products along the product lifecycle, which was developed and tested at the Siemens Healthineers Innovation Think Tank. The Digital Twin is visualized along the three product life cycle stages "Development & Manufacturing," "Operation," and "Maintenance." The dependability dimension considers privacy and safety aspects and is subdivided into "Device level," "Room/Factory level," and "Cloud level." Functional elements are allocated across these dimensions and represent two interconnected Digital Twin applications described separately below. The application elements in the "Operation" stage have been developed and tested at the Siemens Healthineers Innovation Think Tank. The other life cycle stages elements have been added for demonstration purposes. The first application represents the work of Mahmeen *et al.* [45] and can be described according to the Digital Twin applications model of Newrzella *et al.* [4] as follows. Mahmeen *et al.* describe a Digital Twin of a Radiography device's environment using real-time device encoder data and point cloud data from room depth cameras in a rule-based model for enabling autonomous collision avoiding movement of the device. The functional elements involved in this application in Figure 3 reside in the "Operation" stage and constitute the Radiography device as the physical entity on the device level, encoders as an integration element on the device level as well as room cameras as an integration element on the room level of the hospital. On the room level also lie a local data storage as data management and information element and a room computing unit as modelling and simulation element. The encoders send the device's position to the room data storage, where also the point cloud data of the radiography room is received. This data storage directly interacts with the Robot Operating System (ROS) on the room computing unit, where point clouds are merged, obstacles are detected and recognized, and the motion planning subsystem calculates the planned path and outputs control commands to the radiography device's motors. This setup enables the device to detect and identify objects in the room and adapt its movement accordingly without human intervention.

The second application is a Digital Twin predictive maintenance application along the three mentioned product life cycle stages. It can be described as a Digital Twin of a Radiography device's condition using endurance test data, technician maintenance data, and operational encoder data in a data-based model for enabling usage-based maintenance. In the "Development & Manufacturing" stage, data is gathered during the endurance test (integration element) of a ceiling-mounted radiography device in testing (physical entity). This data is stored in the factory data storage (data management and information element) before being uploaded to a cross-life cycle stages cloud storage (data management and information element). In the "Maintenance" stage, a technician analyzes

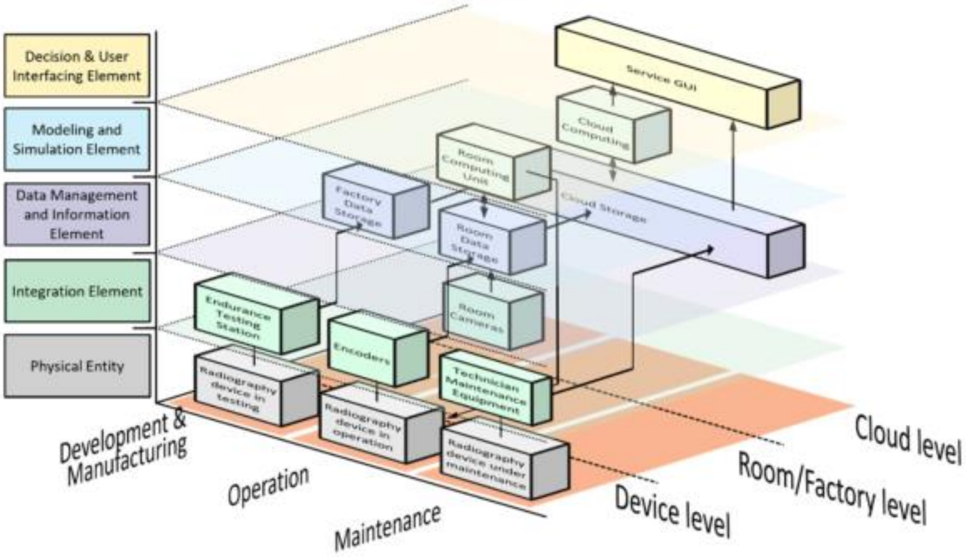


FIGURE 3. Architecture validation example of a medical mechatronic Digital Twin along a product life cycle at the Siemens Healthineers Innovation Think Tank.

(integration element) the Radiography device in operation (physical entity) and uploads the diagnosis to the cross-life cycle cloud storage (data management and information element). The technician can also access the service Graphic User Interface (GUI) on the cloud level (decision & user interfacing element) to get insights from the device's historical data before going to the device. In the "Operation" stage, the encoders (integration element) of the radiography device in operation (physical entity) send their data to the room data storage on the room level (data management and information element). The data is sent to the cloud level's cross-life cycle stage cloud storage (data management and information element). The data is summarized in a histogram model on the cloud computing unit (modeling and simulation element) and visualized through Power BI for the health assessment by a technician on the service GUI (decision & user interfacing element).

The 3D architecture model can be reduced to certain 2D section views to showcase certain aspects in more detail (see Figure 4). This reduction can be compared to 2D section views in a CAD file. An example is given on the predictive maintenance application with a section view of the "Operation" life cycle stage (see Figure 5). The 2D section view shows the Digital Twin setup in more detail, as also described by Schoueri [42].

B. HEALTHCARE

The second example in Figure 6 illustrates a human precision medicine Digital Twin concept across a disease pathway (Figure 6). The life cycle stages are subdivided into the "Prevention & Symptoms," "Diagnosis & Therapy," and "Rehabilitation & Follow-up" stages, as suggested by the Innovation Think Tank disease pathway framework by Haider *et al.* [46]. The dependability levels consist of "Personal data," "Pseudonymized data," and "Anonymized data." The functional elements and their connections are allocated across life cycle and dependability stages and represent an example from precision medicine. The dependability levels consist of "Personal data," "Pseudonymized data," and "Anonymized data." The functional elements and their connections are allocated across life cycle and dependability stages and represent an example from precision medicine. In the "Prevention & Symptoms" stage, individuals collect data through personal smart devices such as smartphones

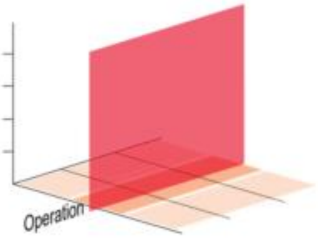


FIGURE 4. Schematic illustrating the reduction of a 3D architecture model to a 2D section view.

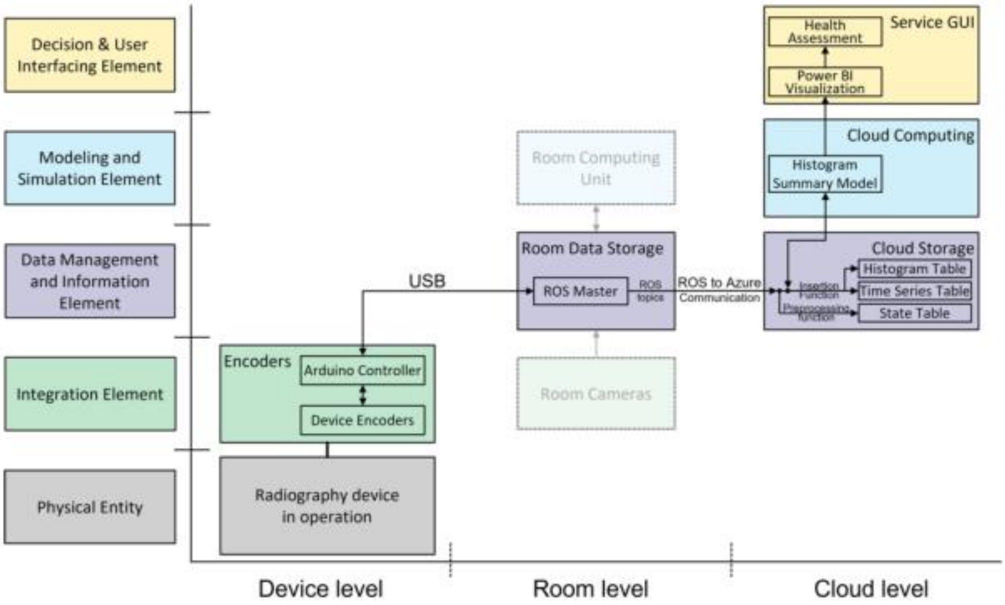


FIGURE 5. 2D section view of the Digital Twin predictive maintenance application example in the "Operation" life cycle stage.

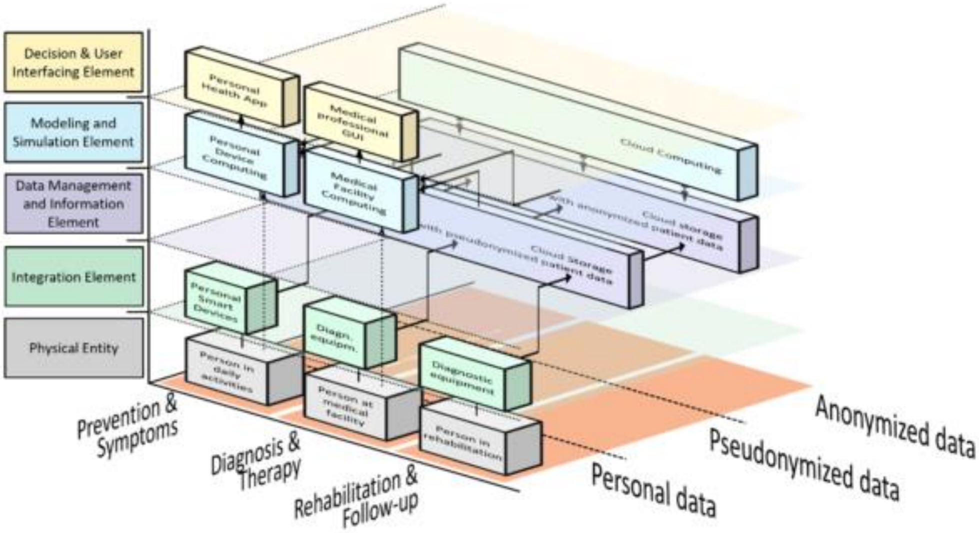


FIGURE 6. Architecture validation example of a human precision medicine Digital Twin along a disease pathway.

and smartwatches (integration element). The data collected can be, for example, lifestyle, environmental, and health data. This data is de-identified and marked with an artificial identifier before being transmitted to cloud storage, where many individuals' pseudonymized data is stored (data management and information element).

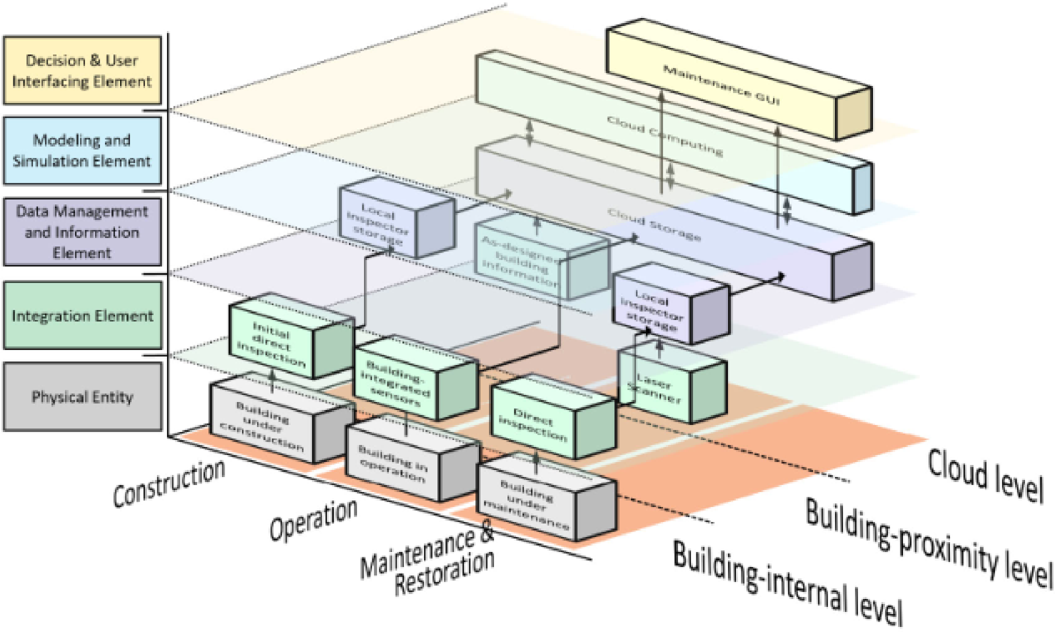


FIGURE 7. Architecture validation example of a building Digital Twin along a building's life cycle.

In the "Diagnosis & Therapy" stage, the individual is diagnosed and/or treated. Data is generated in the form of imaging, laboratory, genomics, and other diagnostic data (integration element) and shared with the pseudonymized cloud storage (data management and information element). During the "Rehabilitation & Follow-up" stage, data about the efficacy of treatments and rehabilitation measures are gathered (integration element) and associated with the individual's pseudonymized data in the cloud storage (data management and information element). The collections of all individuals' data sets on the pseudonymized cloud storage are copied, fully de-identified, and sent to the anonymized cloud storage (data management and information element). Data-based algorithms for detecting various diseases are trained on the cloud computing element (modeling and simulation element), considering all the available data. The resulting disease diagnosing and broadly trained algorithms are stored in the anonymized cloud storage and can be requested from the personal device and medical facility computing (modeling and simulation element) in the "Prevention & Symptoms" and "Diagnosis & Therapy" stages, respectively. The algorithms can be fed with the individual's data by personalizing the data again through the individual's personal key. Combining broadly trained algorithms with personal data enables consistent and reproducible diagnostic results, which can be displayed to the individual and the medical professionals through the personal health app and the medical professional GUI, respectively (decision & user interfacing element). This setup provides a holistic and precise understanding of an individual's condition, which enables personalized diagnosis and treatment tailored to both the individual and the disease, avoiding unnecessary or ineffective therapies. A patient can go to a medical professional, get checked, and get a diagnosis based on a worldwide repository of health conditions and treatments.

C. CONSTRUCTION

Figure 7 visualizes the example of a building Digital Twin, inspired by Angjeliu *et al.* [47]. The life cycle stages consist of "Construction," "Operation," and "Maintenance & Restoration." The dependability levels are subdivided into the building-internal, building-proximity, and cloud level. In the "Construction" stage, as-designed building information such as geometry, material properties, and construction techniques are created and stored in the building's cloud storage. Construction inspectors review the quality of the finished building and document their findings in their local storage before uploading their report to the building's cloud storage. In the "Operation" stage, inbuilt sensors such as accelerometers, pressure, and stress sensors provide real-time data of the building's structural integrity and send it to the building's cloud storage. In the "Maintenance & Restoration" stage, inspectors check the building's structural integrity directly on the building-internal and building-proximity levels through

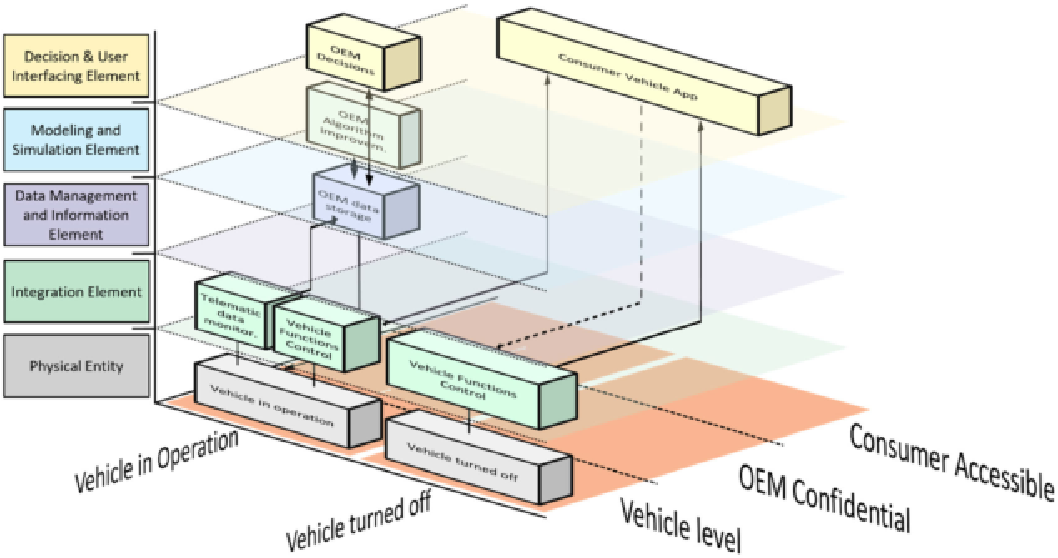


FIGURE 8. Architecture validation example of a vehicle Digital Twin along different vehicle life cycle states.

laser scanners and image-based methods. The final report is uploaded to the building's cloud storage. On the cloud level, historical and real-time data from all three life cycle stages are processed in various mathematical models in the cloud computing element to assess the building's structural integrity, predict potential failures, and schedule predictive maintenance and restoration. The building operators can access these reports via the building's maintenance GUI on the cloud level. This setup allows the building operators to get notified of potentially critical building degradations and proactively address them before they cause any harm.

D. TRANSPORTATION

An example from the transportation industry is visualized in Figure 8. It shows the Digital Twin functionalities of a vehicle as an example for a consumer product, as inspired by the analysis of Ried [48]. The life cycle dimension consists of the states "Vehicle in operation" and "Vehicle turned off." The dependability levels are vehicle level, OEM confidential, and consumer accessible. While the vehicle is in operation, it monitors telematic data and controls the vehicle's functions. The telematic data is streamed confidentially to the OEM's data storage. The OEM's modeling and simulation element can model and predict vehicle performance and improve functionalities such as autonomous driving from simulations and data models from other vehicles. Once approved by the OEM's decision entity, these outcomes are sent back to the vehicle in the form of maintenance alerts and software updates. A remote control can be granted to the user through the consumer vehicle app, which connects to the vehicle functions control. The user can inquire about vehicle information such as location and energy level and enable or disable vehicle settings such as heating. When the vehicle is turned off, the OEM does not have access to the telematic data, and the user must activate the vehicle when requesting access to the vehicle's functions control. Once remotely activated, the user can access the vehicle functions control again. This setup allows the OEM to optimize the driver's driving experience based on individual and global vehicle data. The vehicle user stays informed about and can control the vehicle remotely.

E. ASTRONAUTICS

Figure 9 showcases an example of a spacecraft Digital Twin along different space flight phases, as inspired by Yang *et al.* [49]. The life cycle dimension is made up of three space flight phases, "Spacecraft on Earth," "Spacecraft in Earth orbit," and "Spacecraft in outer space." In this example, the dependability dimension represents the safety aspect by allocating different functionalities along the dependability levels real-time, low latency, and high latency. While the spacecraft is still on Earth, its position sensors and flight controls are calibrated, and their settings are communicated to the Mission Control Center (MCC) data storage. These settings are considered in the mission planning being executed on the MCC computing unit. Once the MCC flight controller team approves, the mission plan is transmitted to the spacecraft. After launch, while in high latency communication range to satellites in Earth orbit, the spacecraft sends its sensed

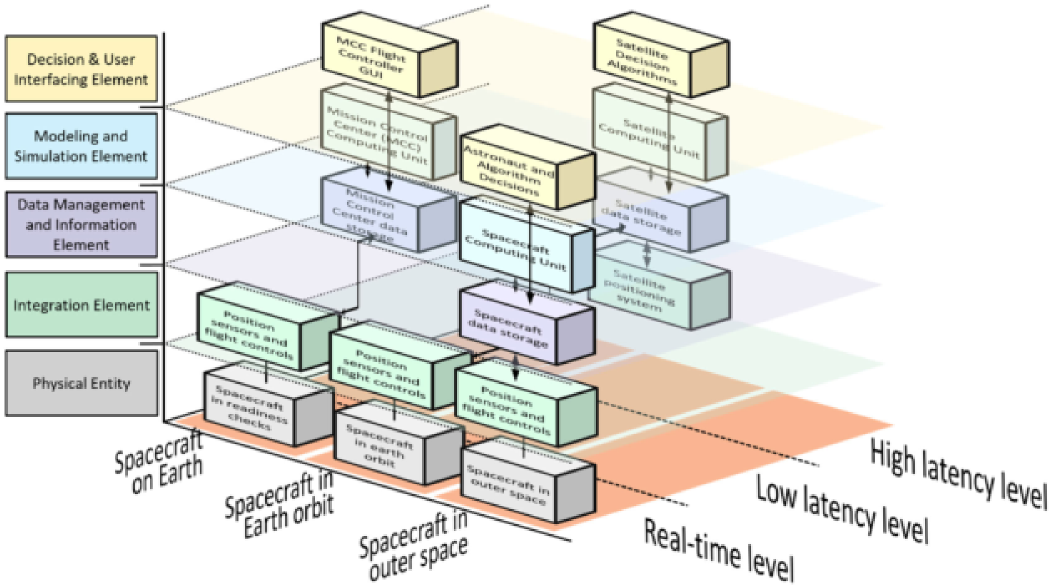


FIGURE 9. Architecture validation example of a spacecraft Digital Twin along different space flight phases.

position to nearby satellites. These satellites independently determine the spacecraft's position (integration element) and adjust the mission plan when necessary (satellite computing unit and decision element). The updated mission plan is then communicated back to the spacecraft. When in outer space, the spacecraft acts autonomously with its own set of data storage, computing unit, and astronaut and algorithm decision element. Mission plan adjustments are calculated with the sensory and computational resources available. This setup allows the spacecraft always to consider the most reliable and available location information and plan further mission plans accordingly. It aims to reduce late correction maneuvers and increase the probability of a safe and efficient mission.

F. ENERGY SECTOR

An example of critical national infrastructure, the energy sector, a cluster of windmills during different cyber-attack incidence stages, is visualized in Figure 10. The life cycle dimension portrays different cyber-attack scenarios according to the Cybersecurity & Infrastructure Security Agency (CISA) National Cyber Incident Scoring System (NCISS) [50]. The dependability dimension represents security aspects and is divided into IEC 62443 security levels (SL) [51], where the levels include protection against intentional violation using simple means (SL2), sophisticated means (SL3), and protection against intentional attacks with sophisticated means (SL4). The Digital Twin architecture is designed to guarantee functionalities depending on the severity of an incidence. In case of a major incident with a likely to an imminent threat to the provision of national infrastructure services, individual windmills must comply with SL4 standards. They are designed to locally sense and store their state (integration, data management, and information element), model the effects of their behavior, and make and act on decisions based on that (decision element).

In addition to this functionality, in case of a less severe attack with unlikely or potential impact on national infrastructure services, windmill clusters must be designed to follow SL3 standards by guaranteeing inter-windmill data collection (data management and information element), analysis of network power generation and distribution (modeling and simulation element) and acting based on the decisions made from this analysis (decision element). In the case of a baseline (level 0) event, SL2 standards must be met to guarantee the collection of windmill data in the cloud (data management and information element), its analysis for predictive analytics (modeling and simulation element), and visualization on the power grid surveillance dashboard (user interfacing element). This setup protects critical functionalities depending on the level of a cyber-attack incidence, promising continuous and safe operation of the windmill. This structure helps the windmill operations staff better react to different cyber-attack severities.

In the related work section, the shortcomings of existing architectures were described. In this section, the applicability of the reference architecture model was validated on examples from six different fields of application. The usage of the model was showcased, and how different Digital Twin

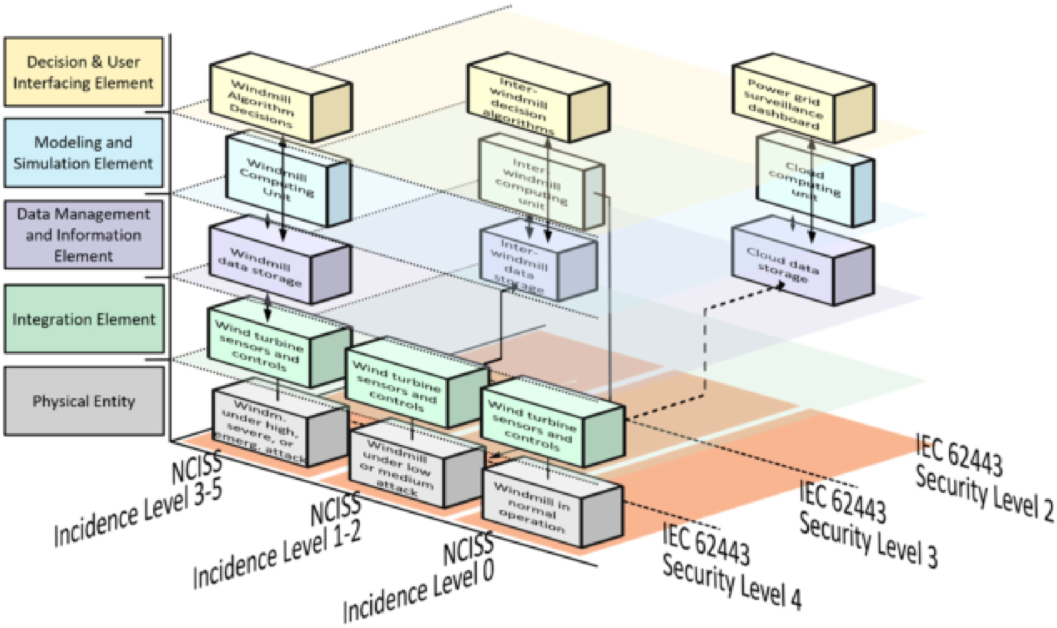


FIGURE 10. Architecture validation example of a national infrastructure Digital Twin during different cyber-attack incidences.

applications can be visualized with it. In the next section, the compatibility of the reference architecture model with the existing architectures is demonstrated, and the model's limitations are discussed.

V. DISCUSSION

This article aimed to propose a Digital Twin reference architecture model for application across industries, focusing on functionality, dependability, and life cycle aspects. While the Digital Twin concept is often described as being applicable to any field and across the entity's life cycle, with varying degrees of complexity and dependability, none of the researched architectures address these aspects in one single approach. Aheleroff *et al.* [31] propose a three-dimensional reference architecture model that combines functionality and dependability in one dimension. This combination reduces the flexibility of applications being representable by the architecture model. We separate these aspects in our reference architecture model and show its versatile applicability in validation examples from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector. Through the simultaneous consideration of functionality, dependability, and life cycle aspects, existing architectures can be described by our reference architecture model within these dimensions.

Following, all three dimensions are described, how they relate to existing architectures, and what limitations they face.

Within the functionality dimension, the physical entity is mentioned by other architectures as physical product [12], physical shop-floor [19], physical entity platform [20], real world [23], physical twin [24], physical space [25], physical layer [27], [31], observable manufacturing elements [29], and asset layer [30]. Some do not consider the physical entity part of the architecture [29]. Still, we see it as an essential part of the Digital Twin concept where the type and whereabouts of the physical entity greatly impact the rest of the Digital Twin architecture. Therefore, we specifically include the physical entity in the reference architecture model.

The integration element is referred to by other architectures as input data [21], coupling [22], IoT stack [23], data collection and edge processing [25], physical twin sensors and physical twin local controllers and data acquisition [26], data extraction and consolidation layer [27], adapters [28], data collection and device control entity [29], and integration layer [30]. Some architectures do not separate the integration element from the physical entity [12], [19], [20], [27], [31] or the data management and information element [24]. We see data about the physical entity not necessarily coming from the physical entity itself, as demonstrated in the validation example of the medical mechatronic product collision avoidance application. The data management can also be handled separately from the origin of the data; hence, the integration element is considered a separate element in our reference architecture model.

The data management and information element is considered by other architectures as unified repository [12], data management platform [20], description section [21], data storage [22], data and systems of record [23], data update and aggregation [25], local data repositories and cloud-based information repositories [26], data ingestion and preparation layer [28], information layer [30], and digital layer [31]. Several architectures combine the data management and information element with the modeling and simulation element [27], [29], [31] or the integration element [24]. We consider allocating the data management and information element independent from other elements. This was demonstrated in the mechatronic product and healthcare validation examples, where the data management and information element was allocated on different dependability levels. This requires the element to be separate from the other elements, hence its distinction from other elements in our reference architecture model.

The modeling and simulation element is often referred to as the core element of a Digital Twin. In other architectures, it goes by virtual product [12], virtual shop floor [19], virtual entity platform [20], causal network [21], simulation and analysis [22], simulation modelling and analytics and AI [23], process models layer and data analysis layer [24], emulation and simulation [26], model management layer [28], and functional layer [30]. Besides the previously mentioned overlapping functionalities to the data management and information element, some architectures consider decision and user interfacing functionalities within their modelling and simulation element [25], [26], [30]. We see decision and user interfacing functionalities applicable in different simultaneous types on different dependability levels, hence the independent functional element in our reference architecture model.

Other architectures specify the decision and user interfacing element as shop floor service system [19], service platform [20], artificial intelligence and user interface [22], visualization and process management [23], decision making layer [24], interaction layer [27], service management layer, twin management layer and user interaction layer [28], user entity [29], business layer [30], and application layer [31]. We see the user interaction often being the decision input and therefore decided to merge these two aspects into one functional element. Nevertheless, applications with separate decision and user interfacing elements can be visualized with this article's reference architecture model by instantiating two separate building blocks within the element, one responsible for decision making and one for user interaction.

The communication element is considered by some architectures at a specific point in the architecture [25], [26], [30], [31]. We see communication as an essential part of any Digital Twin application, which is ubiquitously distributed across all functional elements, as also proposed by [19], [22], [23], [29]. We, therefore, consider it in the reference architecture model in the form of communication arrows between the functional elements. Communication hardware can be attributed to the physically closest functional element.

The presented functional elements are a common denominator across the researched architectures. The naming of these elements was conducted to enable an intuitive understanding of what these elements do. Future work can look into a more detailed definition of these elements as the field of Digital Twin further develops.

Additional elements proposed by some architectures, such as security [22], [23], and governance [23], are not explicitly considered within our reference architecture model but can be implicitly built into an application's architecture through careful development and allocation of the other functional elements. Security, for example, is a ubiquitous undertaking spread across functional elements. Each element and the group of elements have to consider security in its development's planning and execution phase.

Dependability aspects are considered in many existing architectures. They are often combined with functional aspects, reducing flexibility for different applications. Manufacturing-based architectures often consider machine and factory level elements [35] or local and cloud elements [25], [31], sometimes enriched with edge elements [26], [27]. Lutze [21] divides his Digital Twin concept into different types of Digital Twin handling personal, pseudonymized, and anonymized data. Tesla's Digital Twin functionalities can be divided into different privacy levels. Some functionalities are "OEM Confidential," and some are "Consumer Accessible," with some data being only on the vehicle level, only in the cloud, or stored on both [48].

Digital Twin applications are often characterized by being highly interconnected. Nevertheless, some applications require high levels of autonomy, reliability, and safety, even in the absence of communication opportunities, such as in deep-sea or space missions [40], [52], [53]. Digital Twins are part of the trend to rely less on human decision-making and more on computational intelligence. This trend bears the challenge of designing dependable, reliable, safe, and secure systems [14], [26]. While some functionalities may require planning to proceed parallel to plan execution, others may not require such low latency. Functionalities can be subdivided into separate Digital Twin applications with different capabilities. Breaking larger Digital Twin applications down into smaller Digital Twin applications with a subset of functionalities reduces complexity and is known as the concept of separation of concerns [26]. The development and visualization of Digital Twin applications with different levels of dependability and their interplay are possible with our reference architecture model.

We purposely leave the definition of specific dependability levels open to enable the use of this reference architecture model for all kinds of applications. Our Digital Twin reference architecture model can visualize all the existing architectures. The existing architectures with dependability aspects are showcased in Table 3. Different dependability level categorizations are demonstrated in the six validation examples. The medical mechatronic product example uses the dependability levels: device level, room/factory level, and cloud level. The precision medicine example applies the dependability levels: personal, pseudonymized, and anonymized data. Other levels are possible; the examples are only given to showcase applicability and inspire usage for different applications. One limitation of this article's reference architecture model is that simultaneous clustering into different dependability aspects such as privacy and safety is currently impossible. However, we propose that, if necessary, integrating such aspects into a fourth dimension could be done through color-coding. Future work can look into other ways of visualizing different dependability aspects simultaneously.

The life cycle aspect of Digital Twin applications is mentioned by several research works [8], [9], [15], [16] but considered in a Digital Twin architecture only by Aheleroff *et al.* [31]. Their architecture highlights Digital Twin applications' agile and iterative development process along their value life cycle dimension. A Digital Twin application can develop and mature over time. All development stages can be represented with our reference architecture model through different combinations of functional elements and their levels of complexity at different positions in the reference architecture model. Nevertheless, our reference architecture model cannot visualize these development stages simultaneously. Future work can look into integrating the iteratively improving aspect of Digital Twin applications.

The life cycle dimension in our reference architecture model refers to the life cycle of the physical entity and not of the Digital Twin concept itself. With a virtual entity representing its physical entity, the data sources, models, and functionalities can differ across the life cycle stages of a physical twin. Some applications may require data from across the life cycle stages, as demonstrated in the six validation examples. A similar application is mentioned by Sifakis [54] as design-time knowledge and run-time knowledge of autonomous systems. With Parrott and Warshaw [17] advocating broad Digital Twin applications over deep ones, we see the integration of cross-physical twin life cycle Digital Twin aspects as essential for the reference architecture model.

Digital Twin applications with different capabilities ([24], [28]) can be represented by our reference architecture model. A simple Digital Twin application might only consist of a few data sources, a simple data model, human decision-making, and no automated feedback loop. In contrast, a more complex Digital Twin application combines numerous data sources into complex simulation models, makes decisions on its own, and sends commands back to its physical twin. Both complexities of Digital Twin applications can be visualized with our reference architecture model in the form of different implementations of the functional elements, dependability levels, and life cycle stages. Besides the elements' location and interplay, their capabilities can be described in more detail and represent different complexities of Digital Twin applications. For example, a modeling and simulation element can simply aggregate and visualize data or use historical and real-time data from several Digital Twins to predict future behaviors.

The reference architecture model proposed in this article can be applied to Digital Twin use cases across industries and is, therefore, use case-independent. Its applicability was demonstrated with validation examples from six different industries. If some Digital Twin use cases are not yet representable with this reference architecture model, future work can adapt the reference architecture model to achieve universal applicability.

The versatile applicability of the proposed reference architecture model allows researchers and developers to more easily design Digital Twin applications and compare them to each other. Such a flexible yet rigid architecture model serves as a foundation for critical analyses and discussions of different kinds of Digital Twin applications. We hope that this Digital Twin reference architecture model serves as or develops into a cornerstone of Digital Twin development that consolidates the field of Digital Twin as the RAMI4.0 did for the field of IoT.

This Digital Twin reference architecture model serves as the next step in a series of publications aiming at facilitating the development of Digital Twin applications across industries (Figure 11). Newrzella *et al.* [13] propose a methodology for identifying promising Digital Twin use cases and prioritizing them based on estimated value, effort, and scalability. That article extends this work by proposing a structured approach for developing an architecture for Digital Twin applications concerning functionality, dependability, and life cycle aspects for the prioritized Digital Twin use cases. Finally, Newrzella *et al.* [4] serves as a guideline for describing and categorizing Digital Twin applications across industries based on five dimensions. This guideline helps to properly communicate Digital Twin capabilities and manage stakeholders' expectations along the entire Digital Twin development cycle.

For example, this framework can be used by innovation departments with direct access to stakeholders, such as the Siemens Healthineers Innovation Think Tank [55]. Conducting a broad stakeholder needs and opportunities analysis and co-ideating potential solutions with stakeholders for identifying promising Digital Twin use cases is a solid foundation for further development of Digital Twin applications. Co-creation with product stakeholders, and therefore adding the knowledge of the physical entity and the existing infrastructure to the analysis, results in prioritized Digital Twin use cases and product data sources. These steps enable the design of a comprehensive Digital Twin architecture considering functionality, dependability, and life cycle aspects with an increased probability of profitable and scalable Digital Twin applications.

This section highlighted the need for the reference architecture model and its advantages over other three-dimensional architectures. The three dimensions were compared to other Digital Twin architectures, these architectures' shortcomings were discussed, how the reference architecture model addresses these, and what limitations the model has. Aspects from other architectures that are not directly

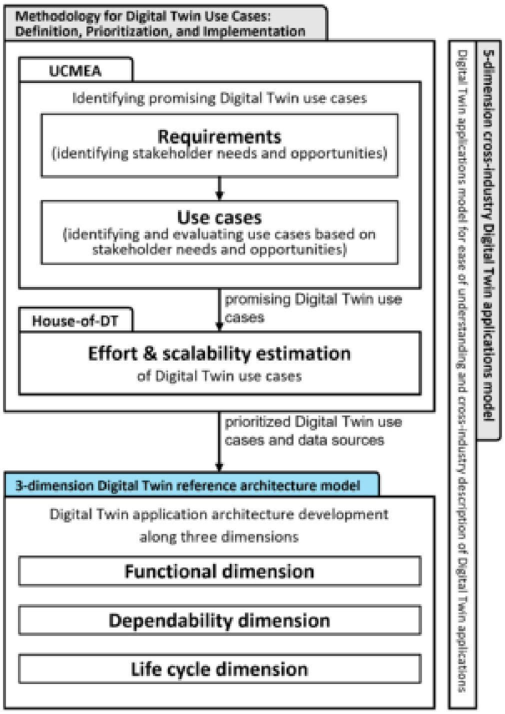


FIGURE 11. **Schematic of the role of this reference architecture model within the authors' Digital Twin framework.**

considered in this article's reference architecture model were mentioned, and it was described how these could be indirectly considered in this article's model. Finally, we discussed the positioning of this article within our previous work on Digital Twin methodologies and highlighted the applicability within an innovation department.

VI. CONCLUSION

The Digital Twin concept promises to create new business opportunities, gain insights, and improve the efficiency of products. Research and applications can be found across industries such as Manufacturing, Aviation, Healthcare, Construction, Oil and Gas Industry, and Transportation. Previous research proposed various Digital Twin architectures applicable to their individual domain, not separating functional, dependability, and life cycle aspects of Digital Twin applications. We addressed this research gap by proposing the cross-industry Innovation Think Tank Digital Twin reference architecture model focusing on functional, dependability, and life cycle aspects. Its applicability was showcased in six examples from the fields of mechatronic products, healthcare, construction, transportation, astronautics, and the energy sector.

The reference architecture model was discussed and compared with previous research. The importance of separating the functional and dependability dimension was highlighted, and the necessity for the life cycle dimension was described. The compatibility of the reference architecture model with existing architectures was showcased, and its advantages and limitations were presented.

The reference architecture model allows practitioners to more easily plan, develop, and implement Digital Twin applications, independent of the field, the use case, or the complexity of the application. By applying our model, the practitioner is guided through three dimensions of Digital Twin architecture development, functional elements, dependability levels, and life cycle stages. Considering all three dimensions, the outcome will be a detailed description of a Digital Twin application architecture. The model creates a common platform for practitioners to discuss Digital Twin applications, their architectures, capabilities, and further improvement potentials.

The model purposely leaves distinct dependability levels and life cycle stages open to allow flexibility for various use cases, but it hinders the comparability of different Digital Twin applications. The dependability dimension considers aspects such as safety, security, and privacy. Simultaneous visualization of different dependability aspects with this article's reference architecture model remains an open task and can be addressed in future work.

We see the development of a suitable visualization tool for Digital Twin architectures based on the reference architecture model as a promising next step in consolidating the Digital Twin concept across industries.

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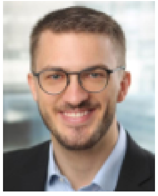

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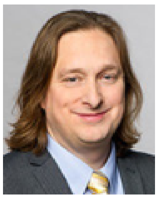

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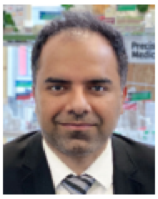
He investigates the physiological and computational principles of human neuromuscular motor control. His research examines how the nervous system controls the mechanical properties of the body to adapt to our external environment and produce skillful movement. To examine the computations underlying sensorimotor control, he blends computational and experimental approaches including robotics and virtual reality.



SULTAN HAIDER is currently the Global Head of Siemens Healthineers Innovation Think Tank (ITT), which was established, in 2005. His inspiring vision of innovation culture formed Innovation Think Tank to become a global infrastructure of 72 activity locations (Innovation Laboratories, Innovation Think Tank certification programs) in Germany, China, U.K., India, USA, United Arab Emirates, Turkey, Canada, Australia, Egypt, Saudi Arabia, Portugal, Switzerland, Brazil, and South Africa. He has filed over 500 inventions and patents and under his leadership, ITT teams have worked on over 2500 technology, strategy, and product definition projects worldwide. He is also a Principal Key Expert at Siemens Healthineers (SHS), a title awarded to him by the SHS Managing Board, in 2008, for his outstanding innovation track record.

Furthermore, he has been awarded honorary directorships, professorships and has developed innovation infrastructures and implemented innovation management certification programs for top institutions.

• • •

3 Results

This chapter describes the results of this dissertation. The outcome is a framework of models and methodologies that links the individual scientific papers together and gives a practitioner in the field of Digital Twin a guideline for effective analysis and design of Digital Twin applications. The framework supports the practitioner in deriving, designing, and describing Digital Twin use cases, as introduced in chapter 1.2. A schematic of the framework is visualized in Figure 13.

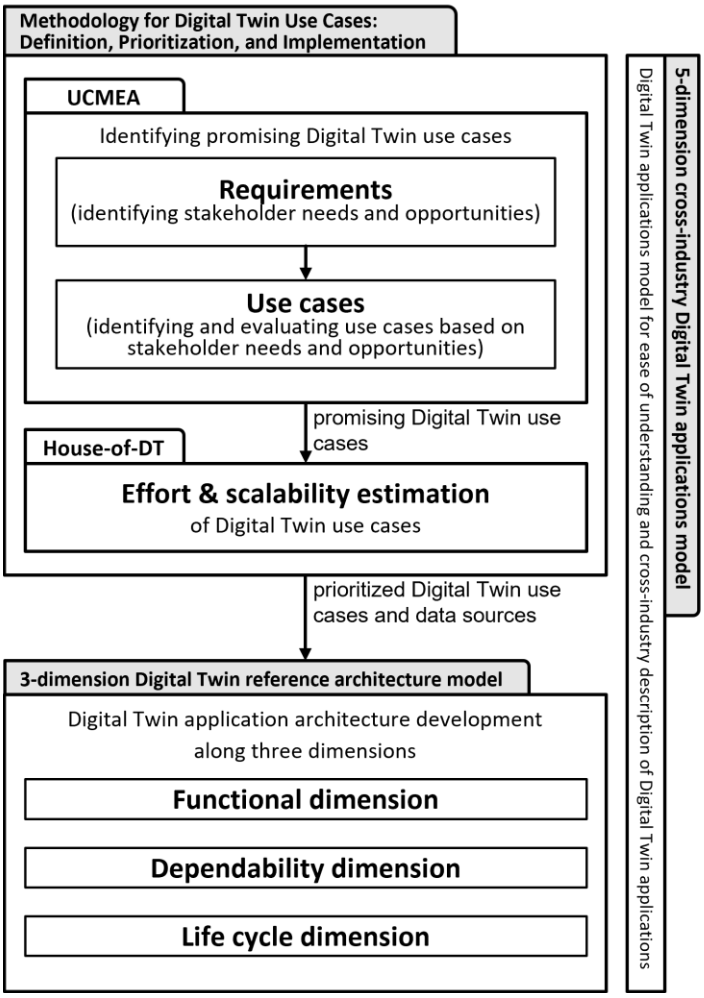


Figure 13: Illustration based on Newrzella et al. (2022) [118]. *Schematic of this dissertation's Digital Twin framework*

The methodology proposed in the second paper (2.2) guides the practitioner in deriving and evaluating Digital Twin use cases. Starting from a workflow or process that the physical entity of a Digital Twin is following, the practitioner follows the UCMEA method. They identify stakeholder needs and opportunities and develop and rate use cases for these. Promising Digital Twin use cases are entered into the House-of-DT, where data sources in and around the physical entity are evaluated based on their ability to address the selected Digital Twin use cases. The output of this methodology is a selection of promising data sources and prioritization of use cases based on value, effort, and scalability.

The use cases and data sources of choice are then brought into the design stage of the architecture model of the third paper (2.3). Through the reference architecture model, the practitioner divides the Digital Twin use case into specific functional building blocks and determines their dependability aspects. The allocation of building blocks along the physical entity’s life cycle is considered as well as communication between them. This cross-industry architecture model allows universal discussion and visualization of Digital Twin applications within interdisciplinary teams and stakeholders.

Along the entire process of deriving and designing Digital Twin applications, they must be described to the people involved. The first paper's model (2.1) can be used to describe a Digital Twin application to other practitioners, users, and customers. It allows the practitioner to describe the main elements of a Digital Twin application required for understanding it without using the confusing term “Digital Twin.”

The framework consolidates the Digital Twin concept and gives developers from any field a guideline for developing Digital Twin applications. The applicability of the individual models and methodology was presented in the respective scientific publications. An application for the entire framework is described in the following chapter.

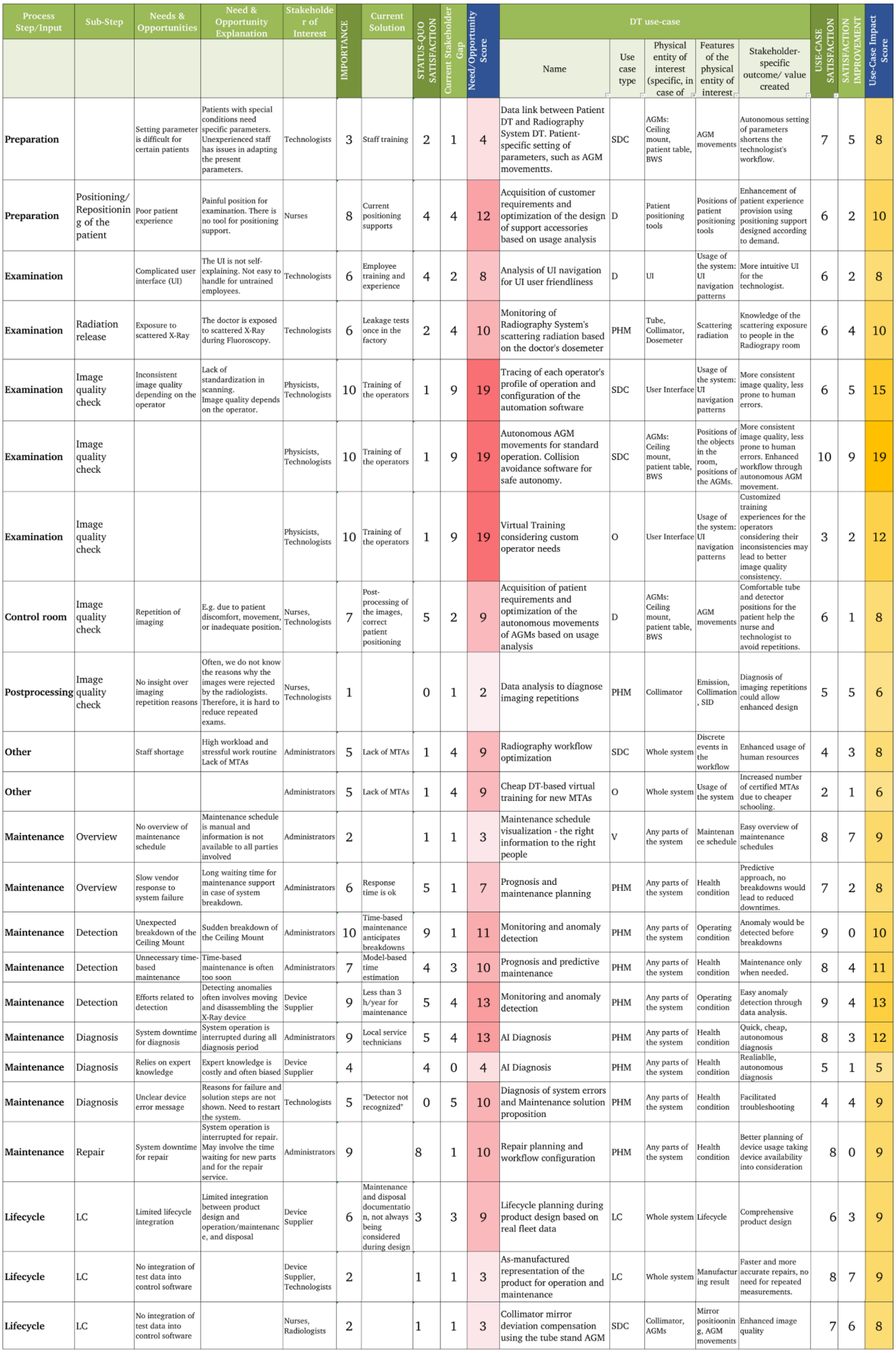
4 Validation Case Study

This chapter presents a validation example developed at the Siemens Healthineers Innovation Think Tank. The validation example consists of a Digital Twin application development of a radiography device. The Digital Twin environment was analyzed, and use cases were derived using the Digital Twin use case development methodology (2.2). A selected use case was designed and visualized using the Digital Twin reference architecture model (2.3). The resulting Digital Twin application is described by applying the Digital Twin applications model (2.1). Finally, the resulting Digital Twin proof-of-concept is described.

4.1 Digital Twin use case development and evaluation (2.2)

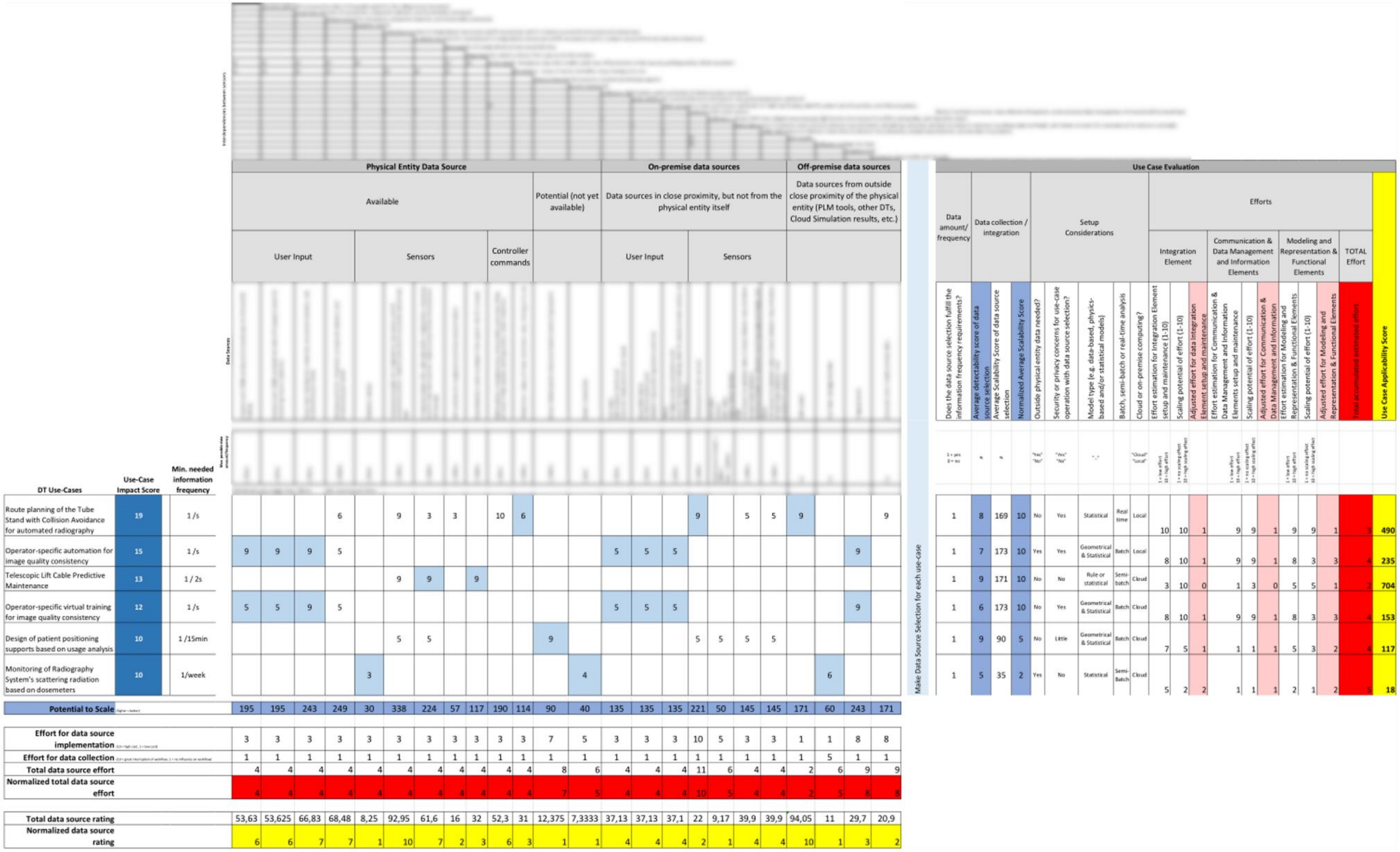
A medical radiography device uses x-ray techniques to visualize internal body parts [119]. Radiography devices are commonly found in hospitals. To derive Digital Twin use cases of a medical radiography device, radiography workflows in hospitals were analyzed by inquiring the database of hospital visits and surveys conducted by the Siemens Healthineers Innovation Think Tank across the world over the last years. This inquiry resulted in various identified needs and opportunities from stakeholders around the radiography device along its clinical workflow. These rated needs and opportunities were combined with a rating of currently implemented solutions. Promising needs and opportunities for Digital Twin use cases were identified by calculating their need/opportunity score. Only Digital Twin use cases were ideated for the needs and opportunities in this case study. Their stakeholders' satisfaction ratings were estimated, and their use case impact score was calculated. The outcome is a rating of potential Digital Twin use cases that address needs and opportunities from stakeholders along the workflow of a medical radiography device. The overall UCMEA table is visualized in Figure 14.

A selection of promising Digital Twin use cases was further evaluated in the House-of-DT in Figure 15. The use cases' minimum need information frequency was determined, and data sources from and around the device were investigated. Besides the existing data sources, potential future data sources were ideated and added to the data source input section in the House-of-DT in Figure 15. All data sources are blurred due to confidentiality reasons. Following, the data sources were rated by their ability to hold informational value for the respective use cases (see the center matrix in Figure 15). The data sources' potential to scale and effort for data source implementation and data collection was estimated, and the total data source rating was calculated. In the use case evaluation part on the right side of the House-of-DT, data sources were selected for each use case. After checking the data sources' ability to provide the information frequency required by each use case, each data source selection's average detectability and scalability score was determined. Setup considerations were made for each use case and their data source selection, and their efforts for integration and maintenance were estimated. Concluding, the use case applicability score of each use case was calculated.



Process Step/Input	Sub-Step	Needs & Opportunities	Need & Opportunity Explanation	Stakeholder of Interest	IMPORTANCE	Current Solution	STATUS-QUO SATISFACTION	Current Stakeholder Gap	Need/Opportunity Score	DT use-case					USE-CASE SATISFACTION	SATISFACTION IMPROVEMENT	Use-Case Impact Score
										Name	Use case type	Physical entity of interest (specific, in case of	Features of the physical entity of interest	Stakeholder-specific outcome/ value created			
Preparation		Setting parameter is difficult for certain patients	Patients with special conditions need specific parameters. Unexperienced staff has issues in adapting the present parameters.	Technologists	3	Staff training	2	1	4	Data link between Patient DT and Radiography System DT. Patient-specific setting of parameters, such as AGM movementts.	SDC	AGMs: Ceiling mount, patient table, BWS	AGM movements	Autonomous setting of parameters shortens the technologist's workflow.	7	5	8
Preparation	Positioning/ Repositioning of the patient	Poor patient experience	Painful position for examination. There is no tool for positioning support.	Nurses	8	Current positioning supports	4	4	12	Acquisition of customer requirements and optimization of the design of support accessories based on usage analysis	D	Patient positioning tools	Positions of patient positioning tools	Enhancement of patient experience provision using positioning support designed according to demand.	6	2	10
Examination		Complicated user interface (UI)	The UI is not self-explaining. Not easy to handle for untrained employees.	Technologists	6	Employee training and experience	4	2	8	Analysis of UI navigation for UI user friendliness	D	UI	Usage of the system: UI navigation patterns	More intuitive UI for the technologist.	6	2	8
Examination	Radiation release	Exposure to scattered X-Ray	The doctor is exposed to scattered X-Ray during Fluoroscopy.	Technologists	6	Leakage tests once in the factory	2	4	10	Monitoring of Radiography System's scattering radiation based on the doctor's dosemeter	PHM	Tube, Collimator, Dosemeter	Scattering radiation	Knowledge of the scattering exposure to people in the Radiograpy room	6	4	10
Examination	Image quality check	Inconsistent image quality depending on the operator	Lack of standardization in scanning. Image quality depends on the operator.	Physicists, Technologists	10	Training of the operators	1	9	19	Tracing of each operator's profile of operation and configuration of the automation software	SDC	User Interface	Usage of the system: UI navigation patterns	More consistent image quality, less prone to human errors.	6	5	15
Examination	Image quality check			Physicists, Technologists	10	Training of the operators	1	9	19	Autonomous AGM movements for standard operation. Collision avoidance software for safe autonomy.	SDC	AGMs: Ceiling mount, patient table, BWS	Positions of the objects in the room, positions of the AGMs.	More consistent image quality, less prone to human errors. Enhanced workflow through autonomous AGM movement.	10	9	19
Examination	Image quality check			Physicists, Technologists	10	Training of the operators	1	9	19	Virtual Training considering custom operator needs	O	User Interface	Usage of the system: UI navigation patterns	Customized training experiences for the operators considering their inconsistencies may lead to better image quality consistency.	3	2	12
Control room	Image quality check	Repetition of imaging	E.g. due to patient discomfort, movement, or inadequate position.	Nurses, Technologists	7	Post-processing of the images, correct patient positioning	5	2	9	Acquisition of patient requirements and optimization of the autonomous movements of AGMs based on usage analysis	D	AGMs: Ceiling mount, patient table, BWS	AGM movements	Comfortable tube and detector positions for the patient help the nurse and technologist to avoid repetitions.	6	1	8
Postprocessing	Image quality check	No insight over imaging repetition reasons	Often, we do not know the reasons why the images were rejected by the radiologists. Therefore, it is hard to reduce repeated exams.	Nurses, Technologists	1		0	1	2	Data analysis to diagnose imaging repetitions	PHM	Collimator	Emission, Collimation, SID	Diagnosis of imaging repetitions could allow enhanced design	5	5	6
Other		Staff shortage	High workload and stressful work routine Lack of MTAs	Administrators	5	Lack of MTAs	1	4	9	Radiography workflow optimization	SDC	Whole system	Discrete events in the workflow	Enhanced usage of human resources	4	3	8
Other				Administrators	5	Lack of MTAs	1	4	9	Cheap DT-based virtual training for new MTAs	O	Whole system	Usage of the system	Increased number of certified MTAs due to cheaper schooling.	2	1	6
Maintenance	Overview	No overview of maintenance schedule	Maintenance schedule is manual and information is not available to all parties involved	Administrators	2		1	1	3	Maintenance schedule visualization - the right information to the right people	V	Any parts of the system	Maintenance schedule	Easy overview of maintenance schedules	8	7	9
Maintenance	Overview	Slow vendor response to system failure	Long waiting time for maintenance support in case of system breakdown.	Administrators	6	Response time is ok	5	1	7	Prognosis and maintenance planning	PHM	Any parts of the system	Health condition	Predictive approach, no breakdowns would lead to reduced downtimes.	7	2	8
Maintenance	Detection	Unexpected breakdown of the Ceiling Mount	Sudden breakdown of the Ceiling Mount	Administrators	10	Time-based maintenance anticipates breakdowns	9	1	11	Monitoring and anomaly detection	PHM	Any parts of the system	Operating condition	Anomaly would be detected before breakdowns	9	0	10
Maintenance	Detection	Unnecessary time-based maintenance	Time-based maintenance is often too soon	Administrators	7	Model-based time estimation	4	3	10	Prognosis and predictive maintenance	PHM	Any parts of the system	Health condition	Maintenance only when needed.	8	4	11
Maintenance	Detection	Efforts related to detection	Detecting anomalies often involves moving and disassembling the X-Ray device	Device Supplier	9	Less than 3 h/year for maintenance	5	4	13	Monitoring and anomaly detection	PHM	Any parts of the system	Operating condition	Easy anomaly detection through data analysis.	9	4	13
Maintenance	Diagnosis	System downtime for diagnosis	System operation is interrupted during all diagnosis period	Administrators	9	Local service technicians	5	4	13	AI Diagnosis	PHM	Any parts of the system	Health condition	Quick, cheap, autonomous diagnosis	8	3	12
Maintenance	Diagnosis	Relies on expert knowledge	Expert knowledge is costly and often biased	Device Supplier	4		4	0	4	AI Diagnosis	PHM	Any parts of the system	Health condition	Realiablle, autonomous diagnosis	5	1	5
Maintenance	Diagnosis	Unclear device error message	Reasons for failure and solution steps are not shown. Need to restart the system.	Technologists	5	"Detector not recognized"	0	5	10	Diagnosis of system errors and Maintenance solution proposition	PHM	Any parts of the system	Health condition	Facilitated troubleshooting	4	4	9
Maintenance	Repair	System downtime for repair	System operation is interrupted for repair. May involve the time waiting for new parts and for the repair service.	Administrators	9		8	1	10	Repair planning and workflow configuration	PHM	Any parts of the system	Health condition	Better planning of device usage taking device availability into consideration	8	0	9
Lifecycle	LC	Limited lifecycle integration	Limited integration between product design and operation/maintenance, and disposal	Device Supplier	6	Maintenance and disposal documentation, not always being considered during design	3	3	9	Lifecycle planning during product design based on real fleet data	LC	Whole system	Lifecycle	Comprehensive product design	6	3	9
Lifecycle	LC	No integration of test data into control software		Device Supplier, Technologists	2		1	1	3	As-manufactured representation of the product for operation and maintenance	LC	Whole system	Manufacturing result	Faster and more accurate repairs, no need for repeated measurements.	8	7	9
Lifecycle	LC	No integration of test data into control software		Nurses, Radiologists	2		1	1	3	Collimator mirror deviation compensation using the tube stand AGM	SDC	Collimator, AGMs	Mirror positiooning, AGM movements	Enhanced image quality	7	6	8

Figure 14: Illustration from Schoueri (2021) [114]. *UCMEA applied to the workflow of a radiography device. Only Digital Twin use cases were considered.*



			Physical Entity Data Source													On-premise data sources							Off-premise data sources			
			Available											Potential (not yet available)		Data sources in close proximity, but not from the physical entity itself							Data sources from outside close proximity of the physical entity (PLM tools, other DTs, Cloud Simulation results, etc.)			
DT Use-Cases	Use-Case Impact Score	Min. needed information frequency	User Input				Sensors					Controller commands				User Input			Sensors							
Route planning of the Tube Stand with Collision Avoidance for automated radiography	19	1 /s				6		9	3	3		10	6						9		5	5	9			9
Operator-specific automation for image quality consistency	15	1 /s	9	9	9	5										5	5	5							9	
Telescopic Lift Cable Predictive Maintenance	13	1 / 2s						9	9		9															
Operator-specific virtual training for image quality consistency	12	1 /s	5	5	9	5										5	5	5							9	
Design of patient positioning supports based on usage analysis	10	1 /15min						5	5					9					5	5	5	5				
Monitoring of Radiography System's scattering radiation based on dosemeters	10	1/week					3								4									6		
Potential to Scale			195	195	243	249	30	338	224	57	117	190	114	90	40	135	135	135	221	50	145	145	171	60	243	171
Effort for data source implementation			3	3	3	3	3	3	3	3	3	3	3	7	5	3	3	3	10	5	3	3	1	1	8	8
Effort for data collection			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	1	1
Total data source effort			4	4	4	4	4	4	4	4	4	4	4	8	6	4	4	4	11	6	4	4	2	6	9	9
Normalized total data source effort			4	4	4	4	4	4	4	4	4	4	4	7	5	4	4	4	10	5	4	4	2	5	8	8
Total data source rating			53,63	53,625	66,83	68,48	8,25	92,95	61,6	16	32	52,3	31	12,375	7,3333	37,13	37,13	37,1	22	9,17	39,9	39,9	94,05	11	29,7	20,9
Normalized data source rating			6	6	7	7	1	10	7	2	3	6	3	1	1	4	4	4	2	1	4	4	10	1	3	2

Make Data Source Selection for each use-case

Use Case Evaluation																			
Data amount/ frequency	Data collection / integration			Setup Considerations					Efforts										
									Integration Element			Communication & Data Management and Information Elements			Modeling and Representation & Functional Elements			TOTAL Effort	
Does the data source selection fulfill the information frequency requirements?	Average detectability score of data source selection	Average Scalability Score of data source selection	Normalized Average Scalability Score	Outside physical entity data needed?	Security or privacy concerns for use-case operation with data source selection?	Model type (e.g. data-based, physics-based and/or statistical models)	Batch, semi-batch or real-time analysis	Cloud or on-premise computing?	Effort estimation for Integration Element setup and maintenance (1-10)	Scaling potential of effort (1-10)	Adjusted effort for data Integration Element setup and maintenance	Effort estimation for Communication & Data Management and Information Elements setup and maintenance	Scaling potential of effort (1-10)	Adjusted effort for Communication & Data Management and Information	Effort estimation for Modeling and Representation & Functional Elements	Scaling potential of effort (1-10)	Adjusted effort for Modeling and Representation & Functional Elements	Total accumulated estimated effort	Use Case Applicability Score
1 = yes 0 = no				"Yes" "No"	"Yes" "No"	"-"		"Cloud" "Local"	1 = low effort 10 = high effort	1 = no scaling effect 10 = high scaling effect		1 = low effort 10 = high effort	1 = no scaling effect 10 = high scaling effect		1 = low effort 10 = high effort	1 = no scaling effect 10 = high scaling effect			
1	8	169	10	No	Yes	Statistical	Real time	Local	10	10	1	9	9	1	9	9	1	3	490
1	7	173	10	Yes	Yes	Geometrical & Statistical	Batch	Local	8	10	1	9	9	1	8	3	3	4	235
1	9	171	10	No	No	Rule or statistical	Semi-batch	Cloud	3	10	0	1	3	0	5	5	1	2	704
1	6	173	10	No	Yes	Geometrical & Statistical	Batch	Cloud	8	10	1	9	9	1	8	3	3	4	153
1	9	90	5	No	Little	Geometrical & Statistical	Batch	Cloud	7	5	1	1	1	1	5	3	2	4	117
1	5	35	2	Yes	No	Statistical	Semi-Batch	Cloud	5	2	2	1	1	1	2	1	2	5	18

Figure 15: Illustration from Schoueri (2021) [114]. *House-of-DT applied to selected Digital Twin use cases from the UCMEA. Data sources are blurred due to confidentiality reasons.*

This value proposition was presented to the product manager of x-ray products at the mechatronic products location of Siemens Healthineers in Kemnath, Germany, and is considered in the future product portfolio. The Digital Twin of a radiography device's telescopic lift column cable for predictive maintenance was selected as a proof of concept. The following development is based on a model of an autonomous radiography device at the Siemens Healthineers Innovation Think Tank Mechatronic Products location, described by Mahmeen et al. (2022) [117], and enhanced by a Digital Twin application described by Schoueri (2021) [114].

4.2 Digital Twin architecture (2.3)

The Digital Twin use case of a radiography device's telescopic lift column cable for predictive maintenance was applied to the radiography model mentioned above. It was visualized and described as a validation example in the third paper (2.3). The cross-life cycle Digital Twin application was showcased in the three-dimensional model seen in Figure 16.

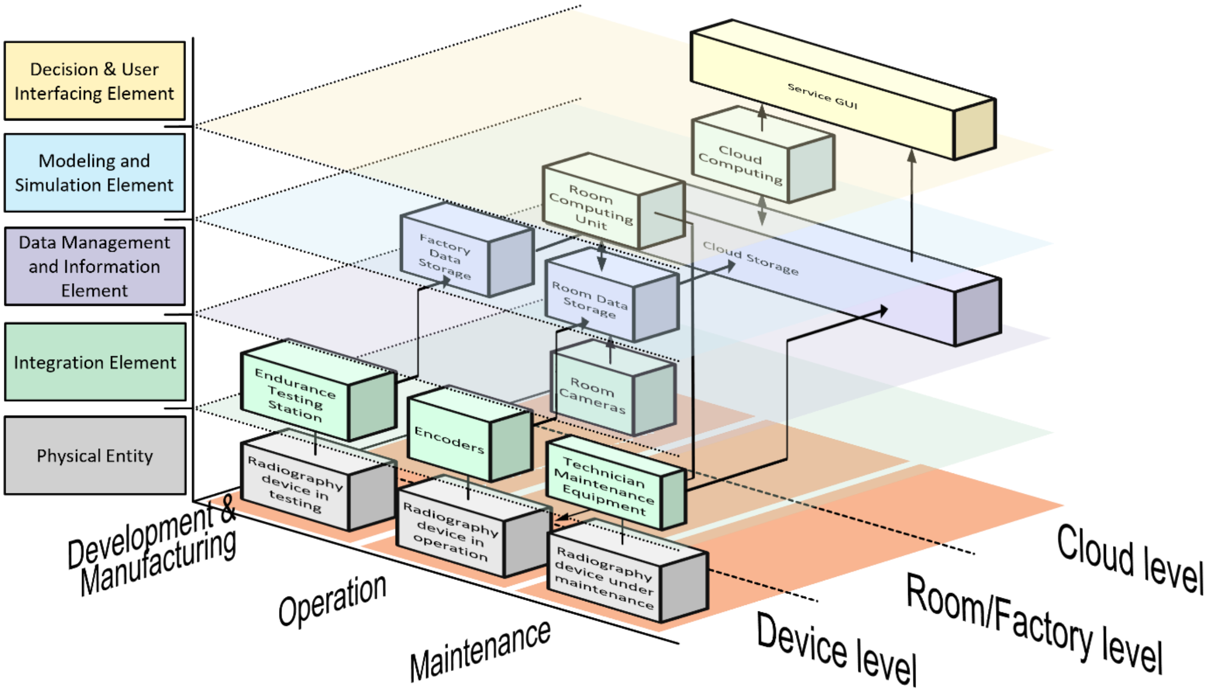


Figure 16: Illustration from Newrzella et al. (2022) [118]*. Digital Twin architecture model representing the Digital Twin use case of a radiography device's telescopic lift column cable for predictive maintenance. Infrastructure from Mahmeen et al. (2022)* [117] *is added, and fictive elements in the development & manufacturing, and maintenance life cycle stage are shown.*

A 2D section view with details of the sub-elements and communication is presented in Figure 17. The radiography model works under the Robot Operating System (ROS), using the Gazebo Simulator for the 3D room simulation and Moveit! for the motion planning of the ceiling-mounted telescopic arm (see Figure 18). ROS is located in the room data storage (data management and information element on the room level in Figure 17). It serves as a transfer point for the telescopic arm location data. In the integration element on the device level, data from the model's motors is communicated to a local Arduino controller, which sends it to the room-level room data storage via USB. A ROS node preprocesses the lift position data by extracting the vertical lift coordinate and samples it so that the information is only passed on when the movement stops or a change of direction occurs. Another local ROS node fetches this information with the device ID, date, and time. It transmits it to the Azure cloud storage (data management and information element on the cloud level in Figure 17). On the Azure cloud, the state table holding the current state is updated with the latest vertical position. The latest positions are also added to the time series table on the cloud. The histogram table collects the information on cable sections that were stressed through the latest movement. The computing is handled on the cloud computing element, and the Service graphical user interface (GUI) visualizes the handled information to service technicians through Power BI (decision & user interfacing element on the cloud level, see Figure 19).

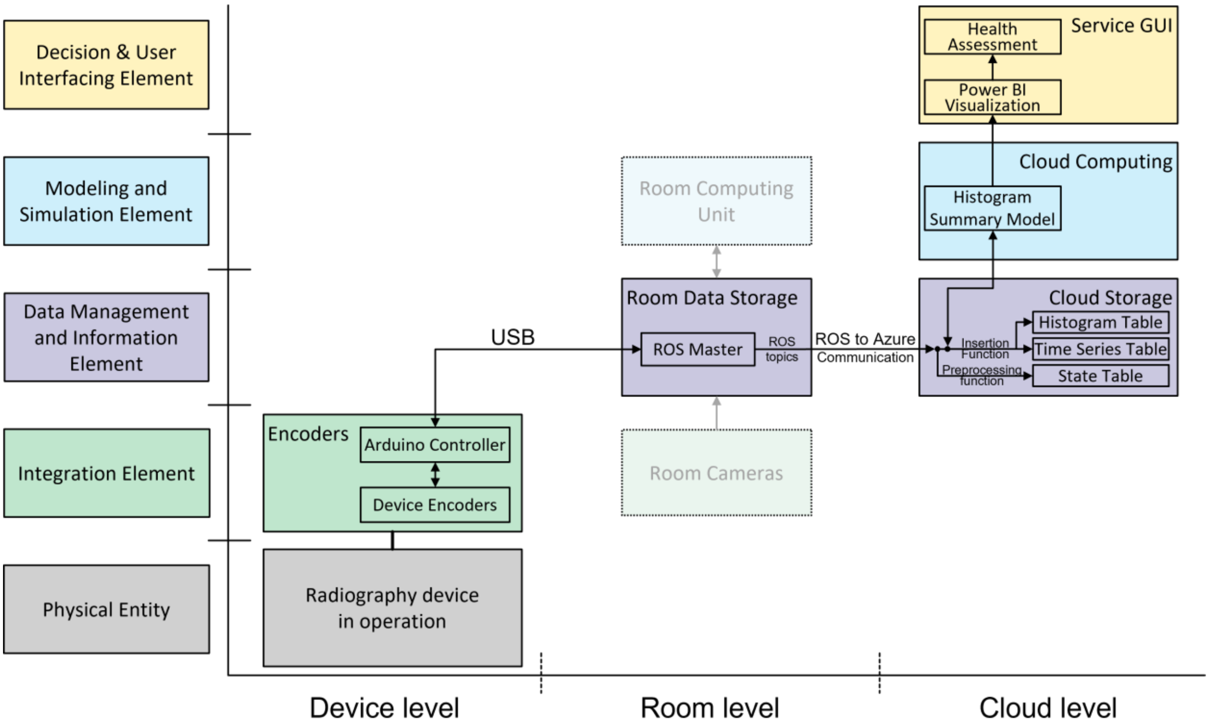


Figure 17: Illustration from Newrzella et al. (2022) [118]*. 2D section view of the Digital Twin predictive maintenance application example in the "Operation" life cycle stage. Elements from the radiography model not actively used by the Digital Twin application are made semi-transparent.*

The technical description of the Digital Twin application followed the Digital Twin reference architecture model proposed in the third publication (2.3) and was visualized in Figure 16 and Figure 17. To convey the essential elements of the Digital Twin application to stakeholders involved, a shorter description is required.

4.3 Digital Twin application description model (2.1)

The validation example described in this chapter can be summarized using the Digital Twin application description model (2.1). The application is a Digital Twin of a radiography device's telescopic arm's lifting cable's condition using near real-time motor encoder data in a rule-based histogram model to suggest maintenance interventions to service technicians. The description highlights the essential elements for an initial understanding of the application. More detailed descriptions can follow using the architecture model (2.3).

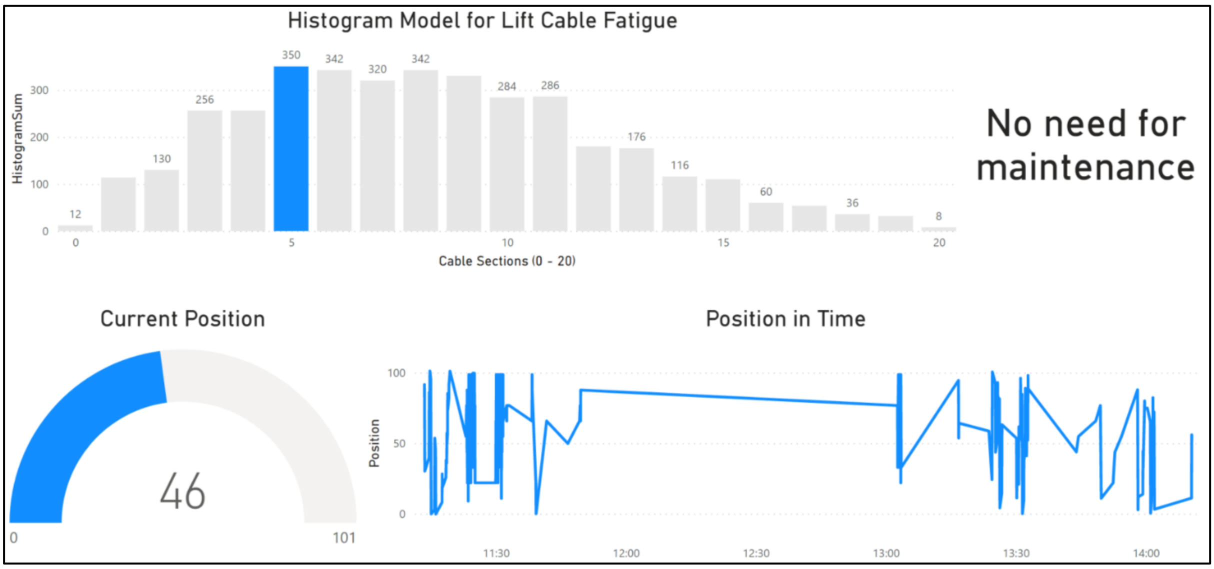
4.4 Digital Twin proof-of-concept

The Digital Twin use case described before was derived using the Digital Twin use case development and evaluation methodology (2.2). The application was designed, and its details were described with the help of the Digital Twin architecture (2.3). Its essential elements were summarized and described using the Digital Twin application description model (2.1).

A proof-of-concept of the Digital Twin application was developed at the Siemens Healthineers Innovation Think Tank Mechatronic Products location in Kemnath, Germany. The prototype's physical entity consists of the telescopic arm of the radiography model shown in Figure 18.

Figure 18: Illustration from Domínguez (2021) [120]. *The radiography model's ceiling-mounted telescopic arm.*

The GUI (Figure 19) presents the current vertical position of the model's telescopic arm (bottom left), the positions over time (bottom right), and a histogram visualization of the cable sections under bending stress (top left). A rule-based algorithm determines the need for maintenance based on the cable sections' bending cycles and presents its conclusion to the service technician on the GUI in the top right.



No need for maintenance

Figure 19: Illustration from Schoueri (2021) [114]. *Power BI dashboard of the Digital Twin application of the radiography model's ceiling-mounted telescopic arm (decision & user interfacing element).*

This proof-of-concept served as a decision proposition to showcase the potential applicability of the Digital Twin application and convince corporate decision makers of the need and feasibility to further develop the application into a series product. When writing this dissertation, the use case is undergoing a business case calculation and analysis of real device data.

5 Discussion

This chapter discusses the Digital Twin framework proposed in this dissertation. A summary of the key elements of this dissertation's framework is followed by a discussion of the contributions of the framework and its constituents. The practical implications for Digital Twin developers applying the Digital Twin framework are described, the framework's limitations are discussed, and future steps are outlined.

5.1 Summary

This dissertation aimed to consolidate the Digital Twin concept by proposing a cross-industry framework that supports deriving, designing, and describing Digital Twin applications. This was achieved through three contributions: (1) a methodology for deriving and evaluating Digital Twin use cases (2.2), (2) a reference architecture model for designing and visualizing Digital Twin applications (2.3), and (3) a model supporting the effective description of Digital Twin applications (2.1).

5.2 Contributions

Holistic Digital Twin development cycles ([88], [110]) guide developers through the overall process of Digital Twin application development but fail to provide concrete methods for the execution of the specific steps or stages. Methods and models have been proposed to address this research gap and improve existing approaches. Research often focuses on the development, verification, and validation stage, with a focus on the manufacturing domain [14], [82], [121]–[123]. This dissertation's framework aims to facilitate the early stages of the Digital Twin development cycle (see chapter 1.4), focusing on cross-industry applications. The individual parts of this dissertation's framework have already been discussed and compared to similar approaches in detail in the respective scientific publications (see chapter 2). Their main contributions are summarized here.

So far, no other methodology for deriving and evaluating Digital Twin use cases (2.2) independent of the application domain exists. Methods from other fields were combined to address Digital Twin applications' versatile and data-centric character across industries. This approach allows an early prioritization of Digital Twin use cases for design and development, considering stakeholder value, effort, and scalability aspects.

An analysis of Digital Twin applications and architectures across industries identified three major dimensions along which Digital Twin architectures are commonly designed: Functionality, dependability, and life cycle. To the author's knowledge, combining these three aspects into one cross-industry Digital Twin reference architecture model (2.3) has not yet been proposed elsewhere. The reference architecture model allows a flexible combination of functional elements on application-specific dependability levels and along individual life cycle stages of the physical entity.

The Digital Twin application description model (2.1) is guided by the three main elements of the Digital Twin concept introduced by Grieves in 2002 [9] and allows the description and classification of Digital Twin applications across industries. This design and the description following the logical chain from the physical entity to the virtual entity to the value-receiving stakeholder enable an easy understanding of the essential elements of Digital Twin applications, which other models fall short of.

The overall framework stands out through its continuous guiding of the early stages in the Digital Twin development cycle, namely the imagine and identify stages of Parrott and Warshaw (2017) [88], the envision and design stages of Moyne et al. (2020) [110], and the plan, analyze, and design stages of the SDLC. The framework has been specifically developed to enable application across industries, providing concrete methods and examples for its application.

5.3 Practical implications

The framework guides developers at the early stages of the Digital Twin development cycle to find the most cost-effective and scalable use cases, designing them accordingly, considering functionality, dependability, and life cycle aspects, and convincing stakeholders of its setup and value-add through clear communication. This early strategic orientation reduces the long-term effort and costs of the overall development of Digital Twin applications. This helps smaller firms develop Digital Twin applications, as the uncertainty in effort and value estimation affects smaller firms more than bigger corporations, which already have a disadvantage in Digital Twin development, as described by Tao and Qi (2019) [107]. Furthermore, the framework's cross-industry character enables industries with few Digital Twin applications and best practices to learn from more dominant industries in Digital Twin research, such as the manufacturing industry, that are applying the framework. The cross-industry examples in the individual publications support this aspect and encourage a cross-industry exchange of ideas and best practices.

5.4 Limitations

As showcased in chapter 1.4, this dissertation’s framework supports the early stages in the Digital Twin development cycle. The described industrial use case is currently in a predevelopment stage and further development and system integration are still pending. Therefore, the framework’s ability to transition well into the subsequent development stages has not yet been investigated. Aspects facilitating further development of Digital Twin applications might therefore not be considered sufficiently in the current version of the framework.

The framework was developed from the viewpoint of a product developer in the field of engineering. Therefore, the methods and models considered during the development come from engineering and adjacent fields such as innovation. These methods are already well known within the engineering product development field, which is why their adapted integration in the Digital Twin framework facilitates the understanding, acceptability, and ultimately adoptability of the framework in the Digital Twin development process in this field. This aspect supports the Digital Twin development efforts in engineering but fails to address the same initiative in other fields.

The methodology and models proposed in this dissertation’s framework were developed iteratively by considering industrial best practices while working on innovation projects at the Siemens Healthineers Innovation Think Tank Mechatronic Products location. This approach is driven by practitioners’ likelihood of adoption of the framework but lacks an objective evaluation of alternative solutions. An alternative development approach could have been to define goals for each identified challenge. A goal could have been, for example, a development methodology that supports developers in finding the Digital Twin use cases that generate the highest value add for the customer at the lowest required effort. For each goal, uncorrelated criteria would have to be created to quantify the attainment of these goals. Criteria could have been, for example, the rate of successful identification of high-value-low-effort use cases and the average resources required for a method’s execution. Various new and existing methods and models that could address the goals could be scouted and evaluated along the set criteria. This evaluation could be done theoretically or better by applying the methods and models to the same industrial example and measuring their performance. The criteria would be weighed depending on their importance. The methods and models leaving the evaluation with the highest rating could be considered the most suitable for addressing the goal and would therefore be considered in the proposed solution to the challenge.

The framework was not developed with the preceding approach, but its efficiency compared to alternative approaches could still be evaluated after the framework’s development. The effectiveness of the framework and its methodologies and models was validated on development examples from the Siemens Healthineers Innovation Think Tank and case studies from existing Digital Twin research. This validation shows that the framework achieves its intended purpose. Nevertheless, an evaluation based on efficiency metrics compared to common alternative approaches is still pending. Therefore, testing the framework and its constituents to whether they are better than alternative approaches is still an open task. Potential testing approaches are discussed in the “Outlook” section.

The framework’s cross-industry applicability has been validated on two industrial innovation projects in the field of medical mechatronics and theoretical case studies from other fields. The framework has been formed by the experiences from the two industrial projects but industrial validation in other fields is still an open task. The framework might, therefore, have been improved for application in an engineering innovation field, but it might still show weaknesses in other fields that could have been discovered when applying the framework to industrial projects in those fields.

5.5 Outlook

In this section, future directions for research resulting from this dissertation are presented. Some directions arose from ongoing implementation projects, others from discussed limitations.

The industrial use case presented in this dissertation is further developed. The framework will show strengths and weaknesses in the following development stages, which can be analyzed and used to improve this dissertation’s framework further. Existing development, verification, and validation methodologies [14], [82], [123] can be applied, and the framework can be extended to support further steps in the Digital Twin development cycle.

As discussed in the limitations section, industrial use case validation from outside the medical mechatronics field has not been conducted yet. Future work can apply this framework to industrial projects in other fields and analyze the framework’s effectiveness and its acceptability with practitioners from this field. The framework can be further improved with every industrial validation to strengthen its cross-industry character.

The framework and its constituents have not yet been quantitatively compared to alternative methodologies and models. This evaluation can be the subject of future work. The methodology and models included in this dissertation’s framework can be tested as follows.

The methodology for deriving and evaluating Digital Twin use cases (2.2) is often replaced by expert gut feeling and business case assessment of single use cases. An efficiency evaluation could compare both approaches based on their ability to work out valuable Digital Twin use cases and develop them into scalable applications. A comparison of long-term effort and value-add between both approaches could identify the more efficient one, as conducted by Newrzella (2019) [124] in the field of Machine Learning in a manufacturing environment.

The cross-industry Digital Twin reference architecture model (2.3) is often replaced by alternative architectures or models from other fields. The purpose of all architectures is to include as many aspects necessary for developing Digital Twin applications as possible while keeping the complexity considerably low for ease of understanding. An analysis of Digital Twin application development projects in different industries could compare applications using the proposed Digital Twin reference architecture model with applications using alternative architectures. Developers could be questioned about the ability of the architectures to address their development needs, the architectures’ perceived complexity, and ease of understanding.

Digital Twin applications are commonly described based on the outstanding characteristics of an individual Digital Twin application to highlight certain features. Classification models determine a set number of characteristics. These models and the Digital Twin application description model (2.1) aim to facilitate the understanding and classification of Digital Twin applications across industries. The better and quicker someone understands the general idea of a Digital Twin application and can compare it to other applications using a certain model, the better that model is suited for description and classification. Interviewees could be confronted with different models’ Digital Twin application descriptions, and the interviewees’ ability to understand and classify Digital Twin applications could be evaluated. This would identify the most suitable model for cross-industry Digital Twin application description.

Concluding the discussion section, it can be said that the overall framework supports deriving, designing, and describing Digital Twin applications. The main contributions of the framework, when compared to similar approaches, lay in its flexible cross-industry character. This structured approach allows developers in different domains to strategically plan their Digital Twin portfolio by reducing uncertainty in value and effort estimation, designing for scalability, dependability, and life cycle aspects, and getting stakeholders on board. Limitations in partial bias and efficiency comparison of the framework’s constituents were discussed, and future steps were outlined.

6 Conclusion

This dissertation aims to consolidate the Digital Twin concept by proposing a cross-industry framework that assists developers in deriving, designing, and describing Digital Twin applications. This was accomplished through the three constituents of the framework: (1) a methodology for deriving and prioritizing Digital Twin use cases, (2) a reference architecture model for designing and visualizing Digital Twin applications, and (3) a model for effectively describing Digital Twin applications. Within this dissertation, the Digital Twin concept was introduced through its history, definitions, fields of application, and business values. The research development and outlook were outlined, and the concept's challenges as this dissertation's motivation, the resulting aims, and the included scientific publications were described. The framework was allocated in related research, and its development methods were outlined. Early in the Digital Twin development cycle, the framework provides a strategic orientation to developers by reducing uncertainty and increasing the likelihood of sustainable Digital Twin applications. The methodology and models included in the framework were derived from an engineering background and, therefore, the framework might be biased towards Digital Twin applications in that domain. Furthermore, a comparison of the framework with alternative methods and models has not yet been conducted, which should be addressed in future work. Nevertheless, the framework's flexible cross-industry character intends to enable more streamlined Digital Twin application development across industries. To better understand the framework's impact, future work could investigate the measurable effect of its application.

Abbreviations

AR	Augmented Reality
CAGR	Compound Annual Growth Rate
CPS	Cyber-Physical System
DT	Digital Twin
GE	General Electric
GUI	Graphical User Interface
IoT	Internet of Things
NASA	National Aeronautics and Space Administration
PLM	Product Lifecycle Management
PTC	Parametric Technology Corporation
ROS	Robot Operating System
SDLC	Systems Development Life Cycle
UCMEA	Use Case Mode and Effects Analysis
USB	Universal Serial Bus
VR	Virtual Reality

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Appendices

A List of supervised theses

Raúl David Domínguez Sánchez, “Integration of a Fully Autonomous Ceiling-Mounted X-Ray Device”, Bachelor Thesis, *Zittau/Görlitz University of Applied Sciences*, 15.01.2021

Luís Roberto de Souza Queiroz Schoueri, “Enhancement of an X-Ray Device’s Automated Guided Module Using a Digital Twin”, Master Thesis, *Technical University Darmstadt*, 19.07.2021

Harvis Daniel Castellanos Barroeta, “Future Radiography Room: Use-Case Scenarios and Proof-of-Principle Prototype”, Bachelor Thesis, *University of Applied Sciences Würzburg-Schweinfurt*, 22.01.2022

Julius Carl Schwarz, “Patient Table Autonomy – Use Case Development and Proof-of-Concept”, Bachelor Thesis, *Pforzheim University of Applied Sciences*, 01.05.2022

Lisbet Doris Casavilca Ortega, “Potential Business Plan for digital and sensorial product upgrades in Siemens Healthineers by Innovation Think Tank”, Master Thesis, *University of Barcelona*, 22.06.2022

Begüm Dirik, “Robotic Add-ons for Radiography-Fluoroscopy-Urology (RFU): Use Case Scenario Development and Proof-of-Concept”, Bachelor Thesis, *University of Applied Sciences Würzburg-Schweinfurt*, 11.09.2022

Stefanie Wagner, “Analysis of Medical Devices using Optical Sensors for Human-Machine Interaction: Use Case Scenario Development and Proof-of-Concept using Innovation Think Tank Methodology”, Bachelor Thesis, *Mannheim University of Applied Sciences*, 30.09.2022

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