IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 29, 2021, accepted September 17, 2021, date of publication September 22, 2021,
date of current version September 30, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3115055

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

SEBASTIAN RICHARD NEWRZELLA[1,2], **DAVID W. FRANKLIN**[1,3], **AND SULTAN HAIDER**[2]
[1]Department of Sport and Health Sciences, Technical University of Munich, 80992 Munich, Germany
[2]Innovation Think Tank, Siemens Healthcare GmbH, 91058 Erlangen, Germany
[3]Munich School of Robotics and Machine Intelligence, Technical University of Munich, 80992 Munich, Germany

Corresponding author: Sebastian Richard Newrzella (sebastian.newrzella@siemens-healthineers.com)

This work was supported by Innovation Think Tank, Siemens Healthcare GmbH, Germany.

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

The associate editor coordinating the review of this manuscript and approving it for publication was Shih-Wei Lin.

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].

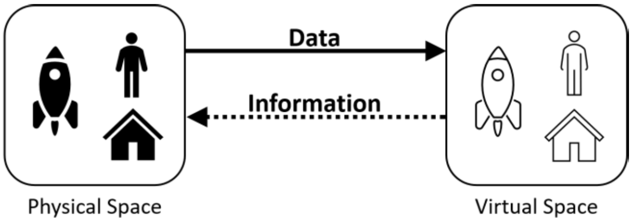

FIGURE 1. Digital Twin concept based on Grieves (2015) [16].

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).

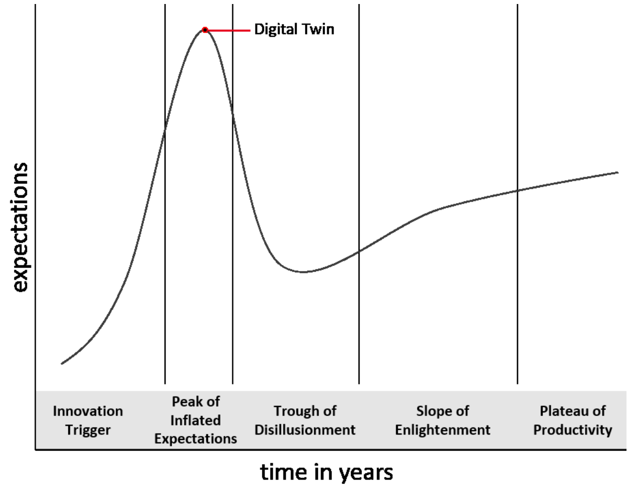

FIGURE 2. Gartner Hype Cycle and the Digital Twin concept, based on Campos-Ferreira *et al.* (2019) [47].

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

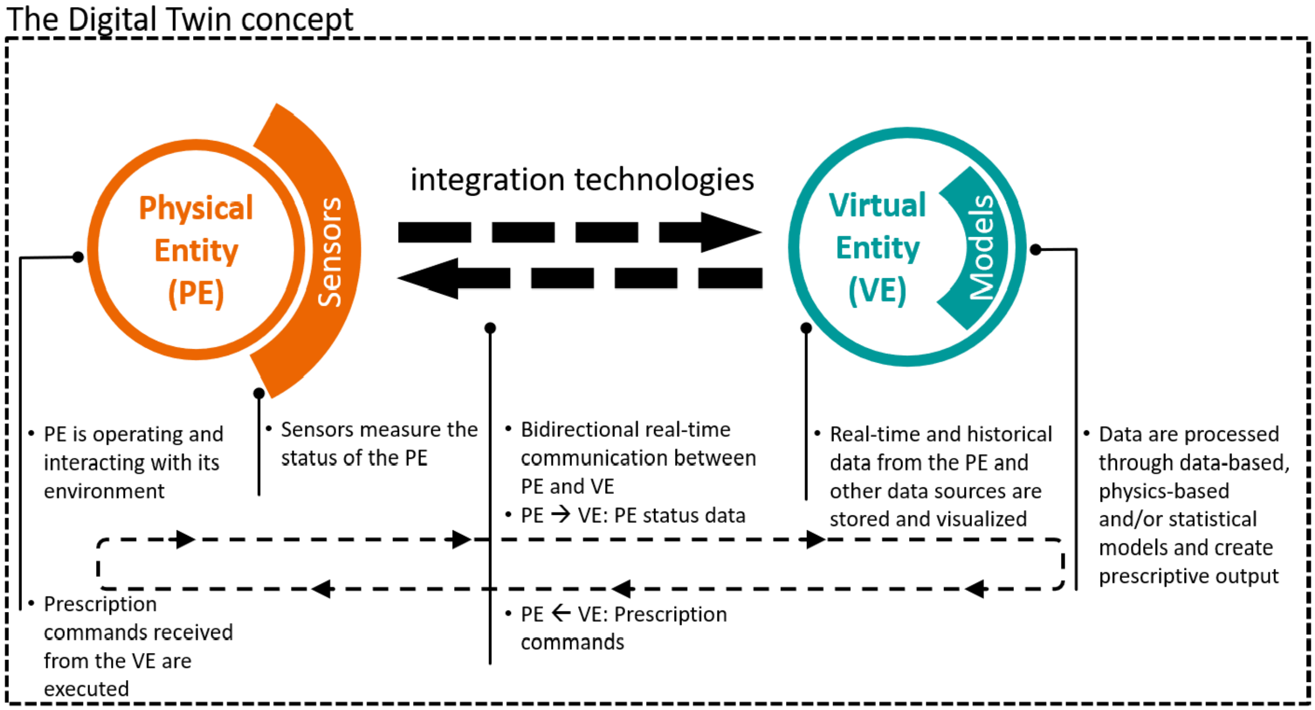

FIGURE 3. The Digital Twin concept.

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.

<table>
<tr><th>Life-cycle Phase</th><th>Design</th><th>Building</th><th>Operation</th><th>Maintenance</th><th>Optimization</th></tr>
<tr><td>Rosen et al. [91]</td><td>Digital Product Twin</td><td>Digital Production Twin</td><td>Digital Performance Twin</td><td></td><td>Digital Performance Twin</td></tr>
<tr><td>Trauer et al. [75]</td><td>Engineering Twin</td><td>Production Twin</td><td>Operation Twin</td><td></td><td></td></tr>
<tr><td>Siemens [92]</td><td>Digital Twin of the Product</td><td>Digital Twin of Production</td><td colspan="3">Digital Twin of Performance</td></tr>
<tr><td><i>Tharma et al.</i> [93]</td><td><i>Digital Model</i></td><td><i>Production Twin</i></td><td></td><td><i>Service Twin</i></td><td></td></tr>
</table>

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.

Sophistication/ 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.

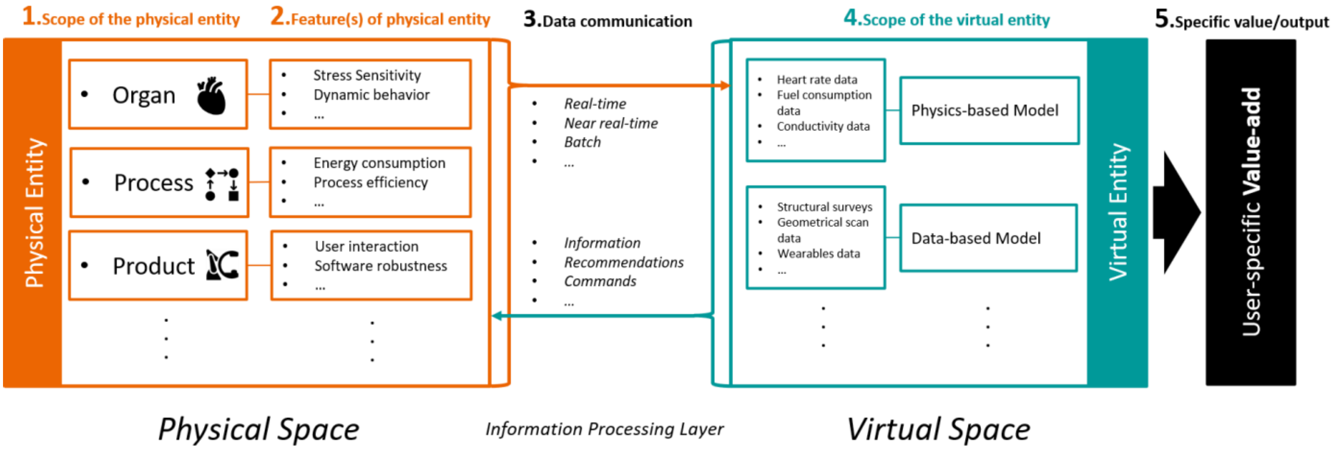

FIGURE 4. Five aspects of Digital Twin applications, allocated to the three Digital Twin parts introduced by Grieves (2015) [16].

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.

REFERENCES

[1] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, ''Digital twin in industry: State-of-the-art,'' *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019, doi: 10.1109/TII.2018.2873186.

[2] Gartner. (Accessed: Feb. 6, 2021). *Gartner Survey Reveals Digital Twins Are Entering Mainstream Use*. Accessed: 2019. [Online]. Available: https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital-twins-are-entering-mai

[3] G. Steindl, M. Stagl, L. Kasper, W. Kastner, and R. Hofmann, ''Generic digital twin architecture for industrial energy systems,'' *Appl. Sci.*, vol. 10, no. 24, p. 8903, Dec. 2020, doi: 10.3390/app10248903.

[4] M. Zborowski, ''Finding meaning, application for the much-discussed 'digital twin,''' *J. Petroleum Technol.*, vol. 70, no. 6, pp. 26–32, Jun. 2018, doi: 10.2118/0618-0026-jpt.

[5] M. Dietz and G. Pernul, ''Digital twin: Empowering enterprises towards a system-of-systems approach,'' *Bus. Inf. Syst. Eng.*, vol. 62, no. 2, pp. 179–184, Apr. 2020, doi: 10.1007/s12599-019-00624-0.

[6] K. Josifovska, E. Yigitbas, and G. Engels, ''Reference framework for digital twins within cyber-physical systems,'' in *Proc. IEEE/ACM 5th Int. Workshop Softw. Eng. Smart Cyber-Phys. Syst. (SEsCPS)*, May 2019, pp. 25–31, doi: 10.1109/SEsCPS.2019.00012.

[7] J. Autiosalo, J. Vepsalainen, R. Viitala, and K. Tammi, ''A feature-based framework for structuring industrial digital twins,'' *IEEE Access*, vol. 8, pp. 1193–1208, 2020, doi: 10.1109/ACCESS.2019.2950507.

[8] T. Lechler, J. Fuchs, M. Sjarov, M. Brossog, A. Selmaier, F. Faltus, T. Donhauser, and J. Franke, ''Introduction of a comprehensive structure model for the digital twin in manufacturing,'' in *Proc. 25th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2020, pp. 1773–1780, doi: 10.1109/etfa46521.2020.9212030.

[9] M. Sjarov, T. Lechler, J. Fuchs, M. Brossog, A. Selmaier, F. Faltus, T. Donhauser, and J. Franke, ''The digital twin concept in industry—A review and systematization,'' in *Proc. 25th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2020, pp. 1789–1796, doi: 10.1109/etfa46521.2020.9212089.

[10] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, ''Characterising the digital twin: A systematic literature review,'' *CIRP J. Manuf. Sci. Technol.*, vol. 29, pp. 36–52, May 2020, doi: 10.1016/j.cirpj.2020.02.002.

[11] R. Minerva, G. M. Lee, and N. Crespi, ''Digital twin in the IoT context: A survey on technical features, scenarios, and architectural models,'' *Proc. IEEE*, vol. 108, no. 10, pp. 1785–1824, Oct. 2020, doi: 10.1109/JPROC.2020.2998530.

[12] E. H. Glaessgen and D. S. Stargel, ''The digital twin paradigm for future NASA and U.S. Air force vehicles,'' in *Proc. Collect. Tech. Pap. AIAA/ASME/ASCE/ AHS/ASC Struct. Struct. Dyn. Mater. Conf.*, 2012, pp. 1–14, doi: 10.2514/6.2012-1818.

[13] S. Boschert and R. Rosen, ''Digital twin—The simulation aspect,'' in *Mechatronic Futures*, P. Hehenberger and D. Bradley, Eds. Cham, Switzerland: Springer, 2016, pp. 59–74.

[14] B. R. Barricelli, E. Casiraghi, and D. Fogli, ''A survey on digital twin: Definitions, characteristics, applications, and design implications,'' *IEEE Access*, vol. 7, pp. 167653–167671, 2019, doi: 10.1109/ACCESS.2019.2953499.

[15] D. Gelernter, *Mirror Worlds: Or the Day Software Puts the Universe in a ShoeBox... How it Will Happen and What it Will Mean*, vol. 53, no. 4. Oxford, U.K.: Oxford Univ. Press, 1992.

[16] M. Grieves. (Mar. 2015). *Digital Twin?: Manufacturing Excellence through Virtual Factory Replication*. White Paper. [Online]. Available: https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication

[17] R. S. Piascik, J. Vickers, D. Lowry, S. Scotti, J. Steward, and A. Calomino. (2010). *DRAFT Materials, Structures, Mechanical Systems and Manufacturing Roadmap—Technology Area 12*. [Online]. Available: http://www.nasa.gov/pdf/501625main_TA12-MSMSM-DRAFT-Nov2010-A.pdf

[18] M. Gholami Mayani, M. Svendsen, and S. I. Oedegaard, ''Drilling digital twin success stories the last 10 years,'' *SPE Norway One Day Seminar*, vol. 2018, pp. 290–302, Apr. 2018.

[19] B. Korth, C. Schwede, and M. Zajac, ''Simulation-ready digital twin for realtime management of logistics systems,'' in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2018, pp. 4194–4201, doi: 10.1109/BigData.2018.8622160.

[20] A. Rasheed, O. San, and T. Kvamsdal, ''Digital twin: Values, challenges and enablers,'' 2019, *arXiv:1910.01719*. [Online]. Available: http://arxiv.org/abs/1910.01719

[21] S. Sinha, Y. Park, K. R. Gustafson, J. J. Ploegert, and E. Paulson, ''HVAC device registration in a distributed building management system,'' U.S. 2017 02 84 691 A1, Oct. 5, 2017.

[22] S. Yang, R. He, Z. Zhang, Y. Cao, X. Gao, and X. Liu, ''CHAIN: Cyber hierarchy and interactional network enabling digital solution for battery full-lifespan management,'' *Matter*, vol. 3, no. 1, pp. 27–41, Jul. 2020, doi: 10.1016/j.matt.2020.04.015.

[23] M. Abramovici, J. C. Göbel, and P. Savarino, "Reconfiguration of smart products during their use phase based on virtual product twins," *CIRP Ann.*, vol. 66, no. 1, pp. 165–168, 2017, doi: 10.1016/j.cirp.2017.04.042.

[24] M. Nitti, V. Pilloni, G. Colistra, and L. Atzori, "The virtual object as a major element of the Internet of Things: A survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1228–1240, 2nd Quart., 2015, doi: 10.1109/COMST.2015.2498304.

[25] L. Cheng, T. Yu, X. Zhang, L. Yin, and K. Qu, "Cyberphysical-social systems based smart energy robotic dispatcher and its knowledge automation: Framework, techniques and challenges," in *Proc. CSEE*, 2018, pp. 25–40. [Online]. Available: http://en.cnki.com.cn/Article_en/CJFDTotal-ZGDC201801003.htm

[26] J. Ríos, J. C. Hernández, M. Oliva, and F. Mas, "Product avatar as digital counterpart of a physical individual product: Literature review and implications in an aircraft," in *Proc. Adv. Transdisciplinary Eng.*, vol. 5, 2015, pp. 657–666. [Online]. Available: https://d1wqtxts1xzle7.cloudfront.net/41780302/Transdisciplinary_Lifecycle_Analysis_of_20160130-8718-g81gs8.pdf?1454172162=&response-content-disposition=inline%3B+filename%3DTransdisciplinary_Lifecycle_Analysis_of.pdf&Expires=1597571182&Signature=GHv6gZLP

[27] C. V. Kropas-Hughes, "USAF digital thread initiative," NDIA Model. Simul. Committee, 2014, pp. 1–15.

[28] K. Främling, T. Ala-Risku, M. Kärkkäinen, and J. Holmström, "Agent-based model for managing composite product information," *Comput. Ind.*, vol. 57, no. 1, pp. 72–81, 2006, doi: 10.1016/j.compind.2005.04.004.

[29] K. Främling, J. Holmström, T. Ala-Risku, and M. Kärkkäinen, "Product agents for handling information about physical objects," *Rep. Lab. Inf. Process. Sci. B*, vol. 153, no. 3, pp. 1–20, 2003. [Online]. Available: http://www.cs.hut.fi/Publications/Reports/B153.pdf

[30] C. El Kaed, I. Khan, H. Hossayni, and P. Nappey, "SQenIoT: Semantic query engine for industrial Internet-of-Things gateways," in *Proc. IEEE 3rd World Forum Internet Things (WF-IoT)*, Dec. 2016, pp. 204–209, doi: 10.1109/WF-IoT.2016.7845468.

[31] K. A. Hribernik, L. Rabe, K. D. Thoben, and J. Schumacher, "The product avatar as a product-instance-centric information management concept," *Int. J. Prod. Lifecycle Manag.*, vol. 1, no. 4, pp. 367–379, 2006, doi: 10.1504/IJPLM.2006.011055.

[32] T. Wuest, K. Hribernik, and K.-D. Thoben, "Accessing servitisation potential of PLM data by applying the product avatar concept," *Prod. Planning Control*, vol. 26, nos. 14–15, pp. 1198–1218, Nov. 2015, doi: 10.1080/09537287.2015.1033494.

[33] K. Hribernik, T. Wuest, and K.-D. Thoben, "Towards product avatars representing middle-of-life information for improving design, development and manufacturing processes," in *Proc. Digit. Product Process Develop. Syst., IFIP TC Int. Conf.*, 2013, pp. 85–96.

[34] M. Liu, S. Fang, H. Dong, and C. Xu, "Review of digital twin about concepts, technologies, and industrial applications," *J. Manuf. Syst.*, vol. 58, pp. 1–16, Oct. 2019, doi: 10.1016/j.jmsy.2020.06.017.

[35] J. Autiosalo, "Platform for industrial internet and digital twin focused education, research, and innovation: Ilmatar the overhead crane," in *Proc. IEEE 4th World Forum Internet Things (WF-IoT)*, Feb. 2018, pp. 241–244, doi: 10.1109/WF-IoT.2018.8355217.

[36] S. H. Khajavi, N. H. Motlagh, A. Jaribion, L. C. Werner, and J. Holmström, "Digital twin: Vision, benefits, boundaries, and creation for buildings," *IEEE Access*, vol. 7, pp. 147406–147419, 2019, doi: 10.1109/ACCESS.2019.2946515.

[37] R. Sacks, I. Brilakis, E. Pikas, H. S. Xie, and M. Girolami, "Construction with digital twin information systems," *Data-Centric Eng.*, vol. 1, p. e14, 2020, doi: 10.1017/dce.2020.16.

[38] R. Alonso, M. Borras, R. H. E. M. Koppelaar, A. Lodigiani, E. Loscos, and E. Yöntem, "SPHERE: BIM digital twin platform," *Proceedings*, vol. 20, no. 1, p. 9, Jul. 2019, doi: 10.3390/proceedings2019020009.

[39] Siemens. (Accessed: Mar. 20, 2021). *Digital Twins—Simulation at Siemens*. Research & Technologies. Accessed: 2020. [Online]. Available: https://new.siemens.com/global/en/company/stories/research-technologies/ digitaltwin/digital-twin.html

[40] GE. (Accessed: Mar. 20, 2021). *Digital Twin—Apply Advanced Analytics and Machine Learning to Reduce Operational Costs and Risks*. GE Digital. Accessed: 2020. [Online]. Available: https://www.ge.com/digital/applications/digital-twin

[41] PTC. (Accessed: Mar. 20, 2021). *PTC Digital Twin Insights—Learn How to Capitalize on the Opportunity Presented by Digital Twin Technology*. Industry Insights. Accessed: 2021. [Online]. Available: https://www.ptc.com/en/industry-insights/digital-twin

[42] K. Panetta. (Accessed: Nov. 23, 2020). *Gartner's Top 10 Strategic Technology Trends for 2017*. Gartner Press Release. Accessed: 2016. [Online]. Available: https://www.gartner.com/smarterwithgartner/gartners-top-10-technology-trends-2017/

[43] K. Panetta. (Accessed: Nov. 23, 2020). *Gartner Top 10 Strategic Technology Trends for 2018*. Gartner Press Release. Accessed: 2017. [Online]. Available: https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2018/

[44] K. Panetta. (Accessed: Jan. 16, 2021). *Gartner Top 10 Strategic Technology Trends for 2019*. Gartner Press Release. Accessed: 2018. [Online]. Available: https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019/

[45] W. Vorhies. (Accessed: Nov. 21, 2020). *Digital Twins, Machine Learning & AI*. TechTarget Data Science Central. Accessed: 2018. [Online]. Available: https://www.datasciencecentral.com/profiles/blogs/digital-twins-machine-learning-ai

[46] M. and M. Research and Markets. (2017). *Digital Twin Market by End User (Aerospace & Defense, Automotive & Transportation, Home & Commercial, Electronics & Electricals/Machine Manufacturing, Energy & Utilities, Healthcare, Retail & Consumer Goods), and Geography—Forecast to 2023*. [Online]. Available: https://www.researchandmarkets.com/research/v9xl4t/digital_twin

[47] A. E. Campos-Ferreira, J. J. de Lozoya-Santos, A. Vargas-Martínez, R. R. Mendoza, and R. Morales-Menéndez, "Digital twin applications: A review," in *Proc. Memorias del Congreso Nacional de Control Automático*, 2019, pp. 1–6. [Online]. Available: http://www.amca.mx/RevistaDigital/cnca2019/files/0111.pdf

[48] Q. Qi, F. Tao, Y. Zuo, and D. Zhao, "Digital twin service towards smart manufacturing," *Proc. CIRP*, vol. 72, no. 1, pp. 237–242, 2018, doi: 10.1016/j.procir.2018.03.103.

[49] R. Stark and T. Damerau, "Digital twin," in *CIRP Encyclopedia of Production Engineering*. Berlin, Germany: Springer, 2019, pp. 1–8.

[50] E. Negri, L. Fumagalli, and M. Macchi, "A review of the roles of digital twin in CPS-based production systems," *Proc. Manuf.*, vol. 11, pp. 939–948, Jan. 2017, doi: 10.1016/J.PROMFG.2017.07.198.

[51] M. R. Enders and N. Hoßbach, "Dimensions of digital twin applications—A literature review," in *Proc. 25th Amer. Conf. Inf. Syst. (AMCIS)*, no. 1, 2019, pp. 1–10.

[52] M. El Jazzar, M. Piskernik, and H. Nassereddine, "Digital twin in construction: An empirical analysis," in *Proc. Work. Intell. Comput. Eng. (EG-ICE)*, Aug. 2020, pp. 501–510.

[53] G. Angjeliu, D. Coronelli, and G. Cardani, "Development of the simulation model for digital twin applications in historical masonry buildings: The integration between numerical and experimental reality," *Comput. Struct.*, vol. 238, Oct. 2020, Art. no. 106282, doi: 10.1016/j.compstruc.2020.106282.

[54] S. Kaewunruen, P. Rungskunroch, and J. Welsh, "A digital-twin evaluation of net zero energy building for existing buildings," *Sustainability*, vol. 11, no. 1, pp. 1–22, 2018, doi: 10.3390/su11010159.

[55] Y. Liu, L. Zhang, Y. Yang, L. Zhou, L. Ren, F. Wang, R. Liu, Z. Pang, and M. J. Deen, "A novel cloud-based framework for the elderly healthcare services using digital twin," *IEEE Access*, vol. 7, pp. 49088–49101, 2019, doi: 10.1109/ACCESS.2019.2909828.

[56] A. Croatti, M. Gabellini, S. Montagna, and A. Ricci, "On the integration of agents and digital twins in healthcare," *J. Med. Syst.*, vol. 44, no. 9, pp. 1–8, Sep. 2020, doi: 10.1007/s10916-020-01623-5.

[57] C. Patrone, M. Lattuada, G. Galli, and R. Revetria, "The role of Internet of Things and digital twin in healthcare digitalization process," in *Proc. Trans. Eng. Technol.*, 2020, pp. 30–37.

[58] C. A. Bahón, J. A. O. Ramírez, and L. G. Abril, "Towards a healthcare digital twin," in *Proc. Int. Conf. Catalan Assoc. Artif. Intell.*, 2019, pp. 312–315. [Online]. Available: http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

[59] R. Martinez-Velazquez, R. Gamez, and A. E. Saddik, "Cardio twin: A digital twin of the human heart running on the edge," in *Proc. Med. Meas. Appl. MeMeA Symp.*, 2019, pp. 1–6, doi: 10.1109/MeMeA.2019.8802162.

[60] B. R. Barricelli, E. Casiraghi, J. Gliozzo, A. Petrini, and S. Valtolina, "Human digital twin for fitness management," *IEEE Access*, vol. 8, pp. 26637–26664, 2020, doi: 10.1109/ACCESS.2020.2971576.

[61] D. B. Cameron, A. Waaler, and T. M. Komulainen, "Oil and gas digital twins after twenty years. How can they be made sustainable, maintainable and useful?" in *Proc. 59th Conf. Simulation Modeling (SIMS)*. Oslo, Norway: Oslo Metropolitan Univ., Nov. 2018, pp. 9–16, doi: 10.3384/ecp181539.

[62] S. Sun and T. Zhang, "A 6M digital twin for modeling and simulation in subsurface reservoirs," *Adv. Geo-Energy Res.*, vol. 4, no. 4, pp. 349–351, Dec. 2020, doi: 10.46690/ager.2020.04.01.

[63] T. R. Wanasinghe, L. Wroblewski, B. K. Petersen, R. G. Gosine, L. A. James, O. De Silva, G. K. I. Mann, and P. J. Warrian, "Digital twin for the oil and gas industry: Overview, research trends, opportunities, and challenges," *IEEE Access*, vol. 8, pp. 104175–104197, 2020, doi: 10.1109/ACCESS.2020.2998723.

[64] D. Nadhan, M. G. Mayani, and R. Rommetveit, "Drilling with digital twins," in *Proc. Day 1 Mon*, Aug. 2018, pp. 27–29, doi: 10.2118/191388-ms.

[65] M. Bevilacqua, E. Bottani, F. E. Ciarapica, F. Costantino, L. D. Donato, A. Ferraro, G. Mazzuto, A. Monteriù, G. Nardini, M. Ortenzi, and M. Paroncini, "Digital twin reference model development to prevent operators' risk in process plants," *Sustainability*, vol. 12, no. 3, pp. 1–17, 2020, doi: 10.3390/su12031088.

[66] H. Haße, B. Li, N. Weißenberg, J. Cirullies, and B. Otto, "Digital twin for real-time data processing in logistics," in *Proc. Hambg. Int. Conf. Logist. (HICL)*, Feb. 2020, pp. 4–28. [Online]. Available: http://hdl.handle.net/10419/209367https://creativecommons.org/licenses/by-sa/4.0/www.econstor.eu

[67] A. Carvalho, P. Melo, M. A. Oliveira, and R. Barros, "The 4-corner model as a synchromodal and digital twin enabler in the transportation sector," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2020, pp. 1–8, doi: 10.1109/ICE/ITMC49519.2020.9198592.

[68] T. Defraeye, G. Tagliavini, W. Wu, K. Prawiranto, S. Schudel, M. A. Kerisima, P. Verboven, and A. Bühlmann, "Digital twins probe into food cooling and biochemical quality changes for reducing losses in refrigerated supply chains," *Resour., Conservation Recycling*, vol. 149, pp. 778–794, Oct. 2019, doi: 10.1016/j.resconrec.2019.06.002.

[69] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems*, F.-J. Kahlen, S. Flumerfelt, and A. Alves, Eds. Cham, Switzerland: Springer, 2016, pp. 85–113.

[70] Y. Zheng, S. Yang, and H. Cheng, "An application framework of digital twin and its case study," *J. Ambient Intell. Hum. Comput.*, vol. 10, no. 3, pp. 1141–1153, 2019, doi: 10.1007/s12652-018-0911-3.

[71] F. Tao and M. Zhang, "Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing," *IEEE Access*, vol. 5, pp. 20418–20427, 2017, doi: 10.1109/ACCESS.2017.2756069.

[72] A. J. H. Redelinghuys, A. H. Basson, and K. Kruger, "A six-layer architecture for the digital twin: A manufacturing case study implementation," *J. Intell. Manuf.*, vol. 31, no. 6, pp. 1383–1402, Aug. 2020, doi: 10.1007/s10845-019-01516-6.

[73] F. Tao, M. Zhang, and A. Y. C. Nee, "Five-dimension digital twin modeling and its key technologies," in *Digital Twin Driven Smart Manufacturing*. New York, NY, USA: Academic, 2019, ch. 3, pp. 63–81, doi: 10.1016/b978-0-12-817630-6.00003-5.

[74] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 9–12, pp. 3563–3576, Feb. 2018, doi: 10.1007/s00170-017-0233-1.

[75] J. Trauer, S. Schweigert-Recksiek, C. Engel, K. Spreitzer, and M. Zimmermann, "What is a digital twin?—Definitions and insights from an industrial case study in technical product development," in *Proc. Des. Soc. Des. Conf.*, vol. 1, 2020, pp. 757–766, doi: 10.1017/dsd.2020.15.

[76] U.S. Air Force. (2013). *United States Air Force Global Science and Technology Vision*. Global Horizons Final Report. [Online]. Available: https://www.hsdl.org/?view&did=741377

[77] C. Leiva, "Demystifying the digital thread and digital twin concepts," *IndustryWeek*, vol. 2015, p. 50061, Jun. 2016. [Online]. Available: https://info.ibaset.com/hubfs/Demystifying_the_Digital_Thread_and_Digital_Twin.pdf

[78] Merriam-Webster.com Dictionary. (Accessed: Jan. 4, 2021). *Internet of Things*. Merriam-Webster. Accessed: 2001. [Online]. Available: https://www.merriam-webster.com/dictionary/Internet Things

[79] M. Farsi, A. Daneshkhah, A. Hosseinian-Far, and H. Jahankhani, *Internet of Things Digital Twin Technologies and Smart Cities*. Cham, Switzerland: Springer, 2020, doi: 10.1007/978-3-030-18732-3.

[80] L. Wang, M. Törngren, and M. Onori, "Current status and advancement of cyber-physical systems in manufacturing," *J. Manuf. Syst.*, vol. 37, pp. 517–527, Oct. 2015, doi: 10.1016/j.jmsy.2015.04.008.

[81] N. Jazdi, "Cyber physical systems in the context of industry 4.0," in *Proc. IEEE Int. Conf. Autom., Qual. Test., Robot.*, May 2014, pp. 1–4, doi: 10.1109/AQTR.2014.6857843.

[82] W. R. Ashby, *An Introduction to Cybernetics*. New York, NY, USA: Wiley, 1957.

[83] A. Deuter and F. Pethig, "The digital twin theory," *Ind. 4.0 Manag.*, vol. 36, pp. 27–30, Feb. 2019, doi: 10.30844/I40M_19-1_S27-30.

[84] K. Lenk, U. Meyerholt, P. Wengelowski, K. Lenk, U. Meyerholt, and P. Wengelowski, "Umsetzungsstrategie industrie 4.0," in *Proc. Wissen Manag. Staat und Verwaltung*, Apr. 2014, pp. 163–172, doi: 10.5771/9783845267913-163.

[85] R. Stark, C. Fresemann, and K. Lindow, "Development and operation of digital twins for technical systems and services," *CIRP Ann.*, vol. 68, no. 1, pp. 129–132, 2019, doi: 10.1016/j.cirp.2019.04.024.

[86] J.-F. Uhlenkamp, K. Hribernik, S. Wellsandt, and K.-D. Thoben, "Digital twin applications: A first systemization of their dimensions," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2019, pp. 1–8, doi: 10.1109/ICE.2019.8792579.

[87] G. P. Agnusdei, V. Elia, and M. G. Gnoni, "A classification proposal of digital twin applications in the safety domain," *Comput. Ind. Eng.*, vol. 154, Apr. 2021, Art. no. 107137, doi: 10.1016/j.cie.2021.107137.

[88] S. Dertien, J. Lang, and D. Immerman, "Digital twin: A primer for industrial enterprises," PTC, Boston, MA, USA, Tech. Rep. 13361-Digital_Twin_APIE-0519, 2019.

[89] P. Scully. (Accessed: Nov. 28, 2020). *How the World's 250 Digital Twins Compare? Same, Same But Different*. IoT Analytics. Accessed: 2020. [Online]. Available: https://iot-analytics.com/how-the-worlds-250-digital-twins-compare/

[90] R. Kienzler. (Accessed: Jan. 28, 2021). *Digital Twins and the Internet of Things*. IBM Developer. Accessed: 2019. [Online]. Available: https://developer.ibm.com/articles/digital-twins-and-the-internet-of-things/

[91] R. Rosen, S. Boschert, and A. Sohr, "Next generation digital twin," *Atp Mag.*, vol. 60, no. 10, p. 86, 2018, doi: 10.17560/atp.v60i10.2371.

[92] Siemens. (Accessed: Mar. 21, 2021). *Digitalization in Industry: Twins With Potential*. Industry. Accessed: 2020. [Online]. Available: https://new.siemens.com /global/en/company/stories/industry/the-digital-twin.html

[93] R. Tharma, R. Winter, and M. Eigner, "An approach for the implementation of the digital twin in the automotive wiring harness field," in *Proc. 15th Int. Design Conf. (DESIGN)*, 2018, pp. 3023–3032, doi: 10.21278/idc.2018.0188.

[94] T. D. West and M. Blackburn, "Is digital thread/digital twin affordable? A systemic assessment of the cost of DoD's latest Manhattan project," *Proc. Comput. Sci.*, vol. 114, pp. 47–56, Jan. 2017, doi: 10.1016/j.procs.2017.09.003.

[95] G. Hagan. (2015). *Glossary of Defense Acquisition Acronyms & Terms*. [Online]. Available: https://www.dau.edu/tools/Documents/Glossary_16th_ed.pdf

[96] ABB. (2020). *Digital Twin Applications*. Distributed Control Systems. [Online]. Available: https://new.abb.com/control-systems/features/digital-twin-applications

[97] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1016–1022, 2018, doi: 10.1016/j.ifacol.2018.08.474.

[98] N. K. Chakshu, J. Carson, I. Sazonov, and P. Nithiarasu, "A semi-active human digital twin model for detecting severity of carotid stenoses from head vibration—A coupled computational mechanics and computer vision method," *Int. J. Numer. Method. Biomed. Eng.*, vol. 35, no. 5, pp. 1–17, 2019, doi: 10.1002/cnm.3180.

[99] R. Kucera, M. Aanenson, and M. Benson. (Jan. 2016). *The Augmented Digital Twin: Combining Physical and Virtual Data to Unlock the Value of IoT*. [Online]. Available: http://www.gartner.com/newsroom/id/3165317

[100] A. Madni, C. Madni, and S. Lucero, "Leveraging digital twin technology in model-based systems engineering," *Systems*, vol. 7, no. 1, p. 7, Jan. 2019, doi: 10.3390/systems7010007.

[101] Oracle. (Accessed: Mar. 21, 2021). *About the IoT Digital Twin Framework*. Internet of Things Cloud Service. Accessed: 2021. [Online]. Available: https://docs.oracle.com/en/cloud/paas/iot-cloud/iotgs/iot-digital-twin-framework.html

[102] Oracle. (Accessed: Mar. 21, 2021). *About the Oracle IoT Digital Twin Implementation*. Internet of Things Cloud Service. Accessed: 2021. [Online]. Available: https://docs.oracle.com/en/cloud/paas/iot-cloud/iotgs/oracle-iot-digital-twin-implementation.html

[103] A. Coraddu, L. Oneto, F. Baldi, F. Cipollini, M. Atlar, and S. Savio, "Data-driven ship digital twin for estimating the speed loss caused by the marine fouling," *Ocean Eng.*, vol. 186, Aug. 2019, Art. no. 106063, doi: 10.1016/j.oceaneng.2019.05.045.

[104] R. Klostermeier, S. Haag, and A. Benlian, "Digital twins—An explorative case study of business models," *HMD Prax. der Wirtschaftsinformatik*, vol. 55, no. 2, pp. 297–311, 2018, doi: 10.1365/s40702-018-0406-x.

[105] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020, doi: 10.1109/ACCESS.2020.2998358.

[106] R. Söderberg, K. Wärmefjord, J. Madrid, S. Lorin, A. Forslund, and L. Lindkvist, "An information and simulation framework for increased quality in welded components," *CIRP Ann.*, vol. 67, no. 1, pp. 165–168, 2018, doi: 10.1016/j.cirp.2018.04.118.

SEBASTIAN RICHARD NEWRZELLA received the B.Sc. degree in mechanical and process engineering, the B.Sc. degree in business engineering, and the M.Sc. degree in mechanical and process engineering from the Technical University of Darmstadt, in 2014, 2017, and 2019, respectively. He is currently pursuing the Ph.D. degree with the Technical University of Munich, in collaboration with Siemens Healthcare GmbH, Germany.

He served his civilian service in Masatepe, Nicaragua, from 2010 to 2011, where he taught English and German. From 2013 to 2014, he experimentally investigated wet surfaces as a Scientific Assistant with the Center of Smart Interfaces, Technical University of Darmstadt. From 2015 to 2016, he studied and did research on ultrasound transducers at Nagaoka University of Technology, Niigata, Japan. Within his master's thesis he used machine learning to analyze patterns in the production of magnetic resonance imaging (MRI) magnets at Siemens Healthcare Ltd., Oxford, U.K. From 2016 to 2018, he mentored international master's students by giving workshops and offering individual study counseling. In his industrial internship at Philips Medical Systems, Hamburg, Germany, in 2018, he assisted with the introduction of new X-ray devices into production by, among other things, optimizing the production layout and production processes. He joined Siemens Healthineers Innovation Think Tank as a Master's Thesis Fellow, in 2019. After completing his master's degree, he started working as a Doctoral Employee with Siemens Healthineers Innovation Think Tank Mechatronic Products, Kemnath, Germany, where he focuses on innovation projects in the fields of digital twin, machine learning, robotics, and virtual reality.

DAVID W. FRANKLIN received the B.Sc. and M.Sc. degrees in human physiology from the Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Canada, and the Ph.D. degree in neuroscience from the Department of Biomedical Physiology and Kinesiology, Simon Fraser University, in 2005.

He worked as a Researcher with the Computational Neuroscience Laboratory, Institute for Advanced Telecommunications Research, Kyoto, Japan, from 1999 to 2006. He then spent three years as a Postdoctoral Research Associate with the Department of Engineering, University of Cambridge, U.K. In 2010, he was awarded the Wellcome Trust Fellowship and became a Research Fellow with the University of Cambridge. In 2016, he moved to Munich and became an Associate Professor of neuromuscular diagnostics with the Technical University of Munich. 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 56 activity locations (Innovation Labs and 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. ITT labs all together have filed over 1600 inventions and patents and have worked on over 2500 technology, strategy, and product definition projects worldwide.

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.

• • •