



**White paper**

**The Digital Twin Concept:  
History, Definitions, the Challenge of Broad  
Applicability, and the Innovation Think Tank  
Digital Twin Applications Description Model**

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# The Digital Twin Concept: History, Definitions, the Challenge of Broad Applicability, and the Innovation Think Tank Digital Twin Applications Description Model

Sebastian Newrzella<sup>1,2</sup>, David Franklin<sup>1,3</sup>, Sultan Haider<sup>2</sup>

<sup>1</sup>Department of Sport and Health Sciences, Technical University of Munich, 80992 Munich, Germany

<sup>2</sup>Innovation Think Tank, Siemens Healthcare GmbH, 91058 Erlangen, Germany

<sup>3</sup>Munich School of Robotics and Machine Intelligence, Technical University of Munich, 80992 Munich, Germany

## Abstract

Digital Twin is a young concept that promises a variety of valuable benefits across industries. In this White Paper we give an introduction into the history of the Digital Twin concept and how broad applicability results in confusion and mismanaged expectations. We give an overview of Digital Twin definitions, different viewpoints, and how the concept relates to other technologies. We discuss the challenge to describe and cluster Digital Twin applications by presenting related Digital Twin terms and models. From this unsolved need we derive and propose the Innovation Think Tank Digital Twin Applications Description model consisting of five intuitive dimensions by which to describe Digital Twin applications.

**Keywords:** Digital Twin, applications, cross-industry, model, innovation, healthcare

## I. INTRODUCTION

Digitalization is trending across industries with accompanying terms such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), and the Digital Twin concept [1]. The Digital Twin concept consists of a physical and virtual entity and connections between them (see **Figure 1**). The virtual entity evolves with its physical counterpart through real-time connection and provides additional value to stakeholders [1]. The Digital Twin concept has been entering mainstream use by rising interest in industry and academia [2]. Gartner surveyed 599 companies in 2018 and found 62% of companies using IoT to be in the process of or planning to implement the

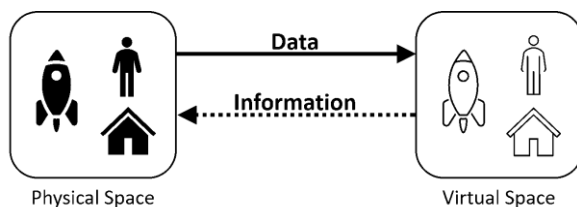
Digital Twin concept, and 13% of those companies already using the Digital Twin concept [3]. The International Data Corporation (IDC) forecasted in 2018 that companies investing in Digital Twin applications would see 30% improvements in manufacturing cycle times of critical processes [4]. Research and Markets in 2017 forecast the Digital Twin market to be worth USD 15.66 Billion by 2023, at a CAGR of 37.87% [5].

The Digital Twin concept can be applied across industries such as Healthcare, Manufacturing, Aviation, Construction, Oil and Gas Industry, and Transportation [6]–[8]. The concept has been defined more and less application domain specific in numerous review articles [6], [9]–[13]. Its loose definition and broad applicability pose a challenge to the young field of Digital Twin. Practitioners are often confused by the term “Digital Twin” as it does not specify the application [14]. Digital Twin applications exist in various shapes and forms and differ considerably in size, scope, and capabilities, which makes the applications sometimes difficult to understand [15]. This challenge was mentioned by several researchers [16]–[22].

In this White Paper we give an overview of the work of Newrzella et al. (2021) [1] by describing the history and definitions of the Digital Twin concept, discussing Digital Twin terms and models, and finally describing the Innovation Think Tank Digital Twin Applications Description model that supports description and communication of Digital Twin applications across industries.

## II. HISTORY OF DIGITAL TWIN

The idea of twinning a physical entity was first prominently described in 1970 when NASA built a second and identical space shuttle within the Apollo program [23], [24]. The “Twin” was kept on earth for simulation of incidences, while its counterpart was in space. This helped to find a solution to exploded oxygen tanks of the Apollo 13 mission. Astronauts were able to develop an air purifier with only the tools available to them on space, as simulated on the grounded twin. The book “Mirror Worlds” by David Gelernter, published in 1992, describes the idea of the Digital Twin concept applied to every aspect of daily life [25]. The informal introduction of the Digital Twin concept is attributed to Michael Grieves in late 2002, when he presents it in his presentation “Conceptual Ideal for PLM” (product life-cycle management) at the University of Michigan [26]. **Figure 1** shows a schematic of the Digital Twin concept, as envisioned by Grieves in 2002 and again described in his White Paper in 2016.

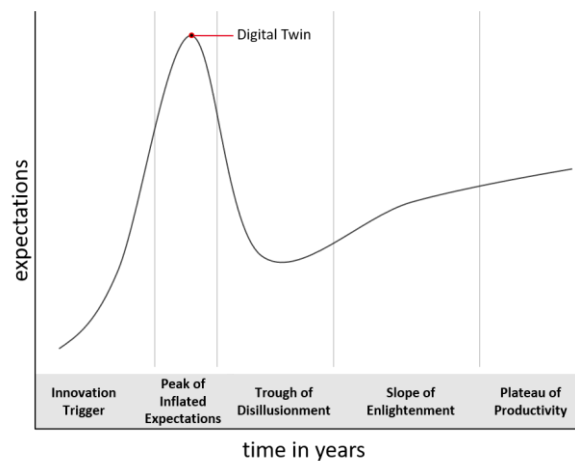


**Figure 1:** Illustration from Newrzella et al. (2021) [1], based on Grieves (2016) [26]: Schematic of the Digital Twin concept.

Grieves’ previous NASA colleague John Vickers minted the term “Digital Twin” in the 2010 NASA roadmap [14], [27]. The technology was not capable of supporting the Digital Twin concept as intended at its introduction in 2002 but the following decade saw technology developments making the Digital Twin concept technically feasible [28]. From its first introduction in the product-centric manufacturing and aviation industry, applications of the Digital Twin concept quickly spread across industries. With the rising popularity of the concept, other terms emerged, but ultimately only the term “Digital Twin”

prevailed. The concept offers a variety of benefits such as real-time performance analysis and control, prediction of potential outcomes, personalized diagnoses and suggestions, and support in designing and manufacturing better products.

While researchers and analysts see a bright future for the Digital Twin concept, challenges to its success exist. Campos-Ferreira et al. (2019) [29] for example mention mismanaged expectations (see Figure 2). Zborowski (2018) [14] and other researchers [16]–[22] highlight the confusing aspect of the Digital Twin concept which means something else to everyone using it.



**Figure 2:** Illustration from Newrzella et al. (2021) [1]: The Digital Twin concept within the Gartner Hype Cycle, based on Campos-Ferreira et al. (2019) [29].

The Digital Twin concept is still rather young, technology enablers have matured just recently and use cases and applications are being developed across industries. The broad applicability of the concept entails the risk of mismanaged expectations. This challenge can be addressed by universal definitions, descriptions, and frameworks.

## III. DEFINITIONS OF DIGITAL TWIN

There is no consensus on the definition of the Digital Twin concept. Plenty of review articles have analyzed existing definitions [6], [9]–[13]. Definitions often depend on the field of

application and the use case. The multidisciplinary character of the Digital Twin concept shows itself in the different focuses of definition between the fields of Engineering and IT. Definitions and applications in Engineering focus on modeling, while in IT, information management plays the primary role [18]. A popular definition comes from NASA in 2010 calling the Digital Twin concept a multi-physics, multi-scale simulation of an asset, incorporating high-fidelity modeling and simulation and situational awareness in real-time [27]. The International Academy for Production Engineering CIRP defines a “Digital Twin” 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” [11].

With the Digital Twin concept developing and getting more and more widely applied, definitions adapt, but three main parts of the concept seem to be ubiquitous. Michael Grieves described them in 2002 [30] and 2016 [26] 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. Three characteristics can be attributed to these main parts, real-time capability, evolution, and functionality [24], [31], [32]. Real-time capability addresses the direct connection between the physical and the virtual entity, which enables the evolution of the virtual entity along with the physical entity. The virtual entity therefore always holds the current knowledge about the physical entity, which it uses to create additional functionality in the form of decision propositions through modeling and simulation for example. Combining these aspects, Newrzella et al. (2021) [1] propose the following cross-industry definition of the Digital Twin concept. “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.”

Several other technologies and concepts exist and are mentioned around the Digital Twin concept. The term “Digital Thread”, for example, was used interchangeably with “Digital Twin” by the U.S. Air Force in 2013 but was later differentiated 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” [33]. The Internet of Things (IoT) can be described as “the networking capability that allows information to be sent to and received from objects and devices (such as fixtures and kitchen appliances) using the Internet” [34]. IoT sensor data often serves as an input for data from the physical entity and is also described as the enabler of the Digital Twin concept [7]. Cyber-Physical Systems (CPS) are systems connecting the physical world to computing and communication entities using the internet [35], [36]. The virtual entity of the Digital Twin concept enables CPSs to offer services of self-adjustment, self-configuration, and self-optimization [17]. The field of Cybernetics aims to understand and define systems based on the concept of circular feedback [37]. The feedback loop between physical and virtual entity in the Digital Twin concept displayed in **Figure 1** makes the Digital Twin concept to be part of Cybernetics [38].

Numerous definitions of the Digital Twin concept exist. Their character depends on the field of application and the specific use case. This broad applicability makes the concept align well with a variety of other technologies and concepts, but also poses the challenge of properly understanding Digital Twin applications. Several companies and researchers have addressed this challenge by classifying and describing Digital Twin applications.

Table 1: Table from Newrzella et al. (2021) [1]: Digital Twin classification models.

Authors	Purpose	Dimensions
Deuter & Pethig [39]	Description and classification of Digital Twin applications	<ul style="list-style-type: none"> <li>• Hierarchy levels</li> <li>• Life Cycle &amp; Value Stream</li> <li>• Layers</li> </ul>
Stark et al. [40]	Planning the scope and type of a Digital Twin	<ul style="list-style-type: none"> <li>• Integration breadth</li> <li>• Connection mode</li> <li>• Update frequency</li> <li>• Product life cycle</li> <li>• CPS intelligence</li> <li>• Simulation capabilities</li> <li>• Digital model richness</li> <li>• Human interaction</li> </ul>
Enders & Hoßbach [13]	Categorizing Digital Twin applications	<ul style="list-style-type: none"> <li>• Industrial sector</li> <li>• Purpose</li> <li>• Physical reference object</li> <li>• Completeness</li> <li>• Creation time</li> <li>• Connection</li> </ul>
Uhlenkamp et al. [41]	Classifying future Digital Twin applications independent of their domain	<ul style="list-style-type: none"> <li>• Goals</li> <li>• User focus</li> <li>• Life cycle focus</li> <li>• System focus</li> <li>• Data sources</li> <li>• Data integration level</li> <li>• Authenticity</li> </ul>
Agnusdei et al. [42]	Assessment of current and development of new Digital Twin applications	<ul style="list-style-type: none"> <li>• Safety issue</li> <li>• Data acquisition</li> <li>• Data processing</li> </ul>
Lechler et al. [19]	Enabling and facilitating Digital Twin application classifications	<ul style="list-style-type: none"> <li>• Application level</li> <li>• Domain</li> <li>• Timing</li> </ul>
PTC Inc. [43]	Organizing current and developing future Digital Twin applications	<ul style="list-style-type: none"> <li>• Source</li> <li>• Contextualize</li> <li>• Synthesize</li> <li>• Orchestrate</li> <li>• Engage</li> </ul>

#### IV. DIGITAL TWIN TERMS AND MODELS

Models have been proposed in order to classify existing Digital Twin applications, learn from similar applications, and ultimately facilitate the development of new applications [13], [19], [39]–

[43]. These models propose three to eight dimensions by which to successfully classify and describe Digital Twin applications (see Table 1).

Within these and other dimensions researchers and companies propose and use Digital Twin terms to explain certain characteristics of an application. An overview of such terms is given in Table 2, Table 3, Table 4, Table 5, and Table 6. The main dimensions under which the terms are clustered are hierarchical level, life cycle phase, functional use, data type/ data flow, and sophistication/maturity level. The first three dimensions were proposed by an analysis conducted by IoT analytics [44].

The categorization of Digital Twin applications into different hierarchical levels addresses different scopes of the physical entity on which the Digital Twin concept is applied (see Table 2). The different levels range from the informational and component level, where a component is twinned, over product, process, and system level to multi-system level, where a multitude of systems is virtualized and integrated in a Digital Twin application.

Digital Twin applications are located at different life cycle stages of its physical entity. This aspect is considered in many Digital Twin terms, which are visualized in Table 3. The product life cycle is a common reference in the Digital Twin domain, due to the Digital Twin concept’s product-centric history. The life cycle stages often referred to are, therefore, the design, building, operation, maintenance, and optimization stage.

The functional use of a Digital Twin application is the focus in Table 4. This classification subdivides applications by the form of value creation or outcome of a Digital Twin application. A digital footprint might just digitize available information, other applications can predict future behaviors.

Table 5 classifies Digital Twin terms into the type or flow of data handled in a Digital Twin application. Artificial test data, historical, and real-time data can be used, the latter uni- or bidirectionally between physical and virtual entity.

Table 2: Table from Newrzella et al. (2021) [1]: Hierarchical Level Digital Twin classification terms.

Hierarchical Level	Informational	Component	Product	Process	System	Multi-System
GE [45]	Asset DT			Process DT	Asset DT	Network DT
Siemens (Zborowski) [14]	Equipment-level Twin			Process Twin	System-level Twin	Plant-level Twin
IBM [46]		Part Twin	Product Twin		System Twin	

Table 3: Table from Newrzella et al. (2021) [1]: Life cycle Phase Digital Twin classification terms.

Life-cycle Phase	Design	Building	Operation	Maintenance	Optimization
Rosen et al. [47]	Digital Product Twin	Digital Production Twin	Digital Performance Twin		Digital Performance Twin
Trauer et al. [48]	Engineering Twin	Production Twin	Operation Twin		
Siemens [49]	Digital Twin of the Product	Digital Twin of Production	Digital Twin of Performance		
Tharma et al. [50]	Digital Model	Production Twin		Service Twin	

Table 4: Table from Newrzella et al. (2021) [1]: Functional Use Digital Twin classification terms.

Functional Use	Digitize	Visualize	Simulate	Emulate	Extract	Orches- trate	Predict
US DoD [51], [52]		Mirror	Simulation				Predict activities or performance
ABB [53]	Design						Prediction
	System integration						
	Diagnostics						
	Advanced Services						

Table 5: Table from Newrzella et al. (2021) [1]: Data Type/ Data Flow Digital Twin classification terms.

Data Type/ Data Flow	Test data (assumptions)	Historical data (manual data flow and/or not continuously updated)	Realtime data	
			Unidirectional automated data flow	Bidirectional automated data flow
Kritzinger et al. [54]		Digital Model	Digital Shadow	Digital Twin
Chakshu et al. [55]	Passive Digital Twin	Semi-active Digital Twin	Active Digital Twin	

Table 6: Table from Newrzella et al. (2021) [1]: 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 [26]	Digital Twin Prototype	Digital Twin Instance			Digital Twin Aggregate
Kucera et al. [56]		Partial Digital Twin	Clone Digital Twin	Augmented Digital Twin	
Madni et al. [57]	Pre-Digital Twin	Digital Twin	Adaptive Digital Twin	Intelligent Digital Twin	
Oracle [58], [59]		Simple Device Model/ Virtual Twin	Industrial Twin		
			Predictive Twin	Twin Projections	
Hagan [52]	Digital System Model	Digital Twin (enabled by Digital Thread)			

The level of information and features generated with the data from a Digital Twin application is the focus in Digital Twin terms displayed in Table 6. Digital Twin terms exist from without a physical entity, to a single and multiple physical entities. Data can come in simple and little form up to complex and much data.

While the benefits and fields of application of the Digital Twin concept seem abundant, the extensive use of the term “Digital Twin” and its loose definition pose a challenge to the acceptance and further development of the concept.

## V. THE INNOVATION THINK TANK DIGITAL TWIN APPLICATIONS DESCRIPTION MODEL

In order to address the need to describe Digital Twin applications and avoid specific Digital Twin terms, Newrzella et al. (2021) [1] propose an intuitive model to describe Digital Twin applications across industries, the Innovation Think Tank Digital Twin applications description model. The model is guided by the three main parts of the Digital Twin concept introduced by Grieves (2015) [60]. The model shown in Figure 3 consists of five dimensions which follow the intuitive flow from the physical entity to the virtual entity to the user.

The first dimension consists of the scope of the physical entity. The subject of the physical entity

has to be clearly defined as for example a distinct product, a concrete building part, a unique manufacturing process, or a specific organ of a human body.

A specific feature of the physical entity is defined in the second dimension. Instead of representing a physical entity in every detail, a Digital Twin application only mirrors certain aspects or features of a physical entity. Such a feature can, for example, be the product’s usage cycle, the energy efficiency rate of the manufacturing process, the wall integrity of the building section, or the stress sensitivity of the human organ of interest.

The form of data communication describes the interaction between physical and virtual entity. The frequency of data exchange between the two and to outside data sources is considered. This dimension is closely linked to the scope of the virtual entity.

The scope of the virtual entity mentions the data being processed in the virtual entity as well as the models using the data. This data can come from the physical entity or any other data source with direct or indirect information about the physical entity. The data can be analyzed in, for example, physics-based, data-based, and statistical models. The output of this analysis results in an outcome that creates a value-add for users.

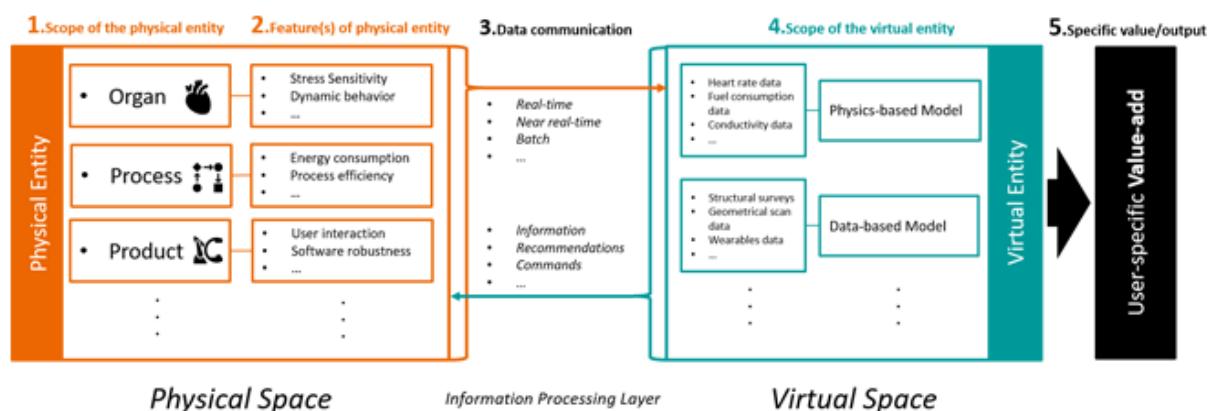


Figure 3: Illustration from Newrzella et al. (2021) [1]: Innovation Think Tank Digital Twin applications description model, based on the main Digital Twin parts introduced by Grieves (2015) [60]



The fifth dimension describes this user-specific value add such as design suggestions for product designers, process scheduling for the production manager, a building's risk assessment for maintenance engineers, or a stroke warning of a patient and notification of the nearest emergency unit.

The model proposed describes the main elements of any Digital Twin application in an intuitive way and highlights the value created for its users.

## VI. CONCLUSION

In this White Paper we gave an overview of the work of Newrzella et al. (2021) [1] by describing the history and definitions of the Digital Twin concept and showcasing its importance in research and the corporate field. We discussed the cross-industry applicability and the resulting challenge of describing applications and managing expectations. Addressing this research gap, we presented the Innovation Think Tank Digital Twin Applications Description model. The model can be applied to intuitively describe Digital Twin applications of different complexities across different industries. This helps to communicate ideas effectively and manage expectations during the entire Digital Twin development cycle.

The Innovation Think Tank (ITT) supports Digital Twin projects along the Digital Twin development cycle by following the Innovation Think Tank methodology proposed by Haider (2021) [61]. From defining Digital Twin use cases through inquiring stakeholder voices and pain points from global hospital visits and ITT Certification Programs to designing and visualizing Digital Twin architectures, prototyping of Digital Twin applications and validation with customers. Feel free to approach us to discuss and shape your Digital Twin endeavors with us.

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## Authors

**Sebastian Newrzella**

Doctoral Employee  
Product Management  
Former ITT Coordinator  
Siemens Healthineers  
Kemnath, Germany

**Prof. Dr. David Franklin**

Neuromuscular Diagnostics  
Sport and Health Sciences  
Technical University of Munich  
Munich, Germany

**Prof. Sultan Haider**

Founder and Global Head  
Innovation Think Tank  
Siemens Healthineers  
Erlangen, Germany

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**Siemens Healthineers Headquarters**

Siemens Healthcare GmbH  
Henkestr. 127  
Erlangen 91052, Germany

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Henri-Dunant-Str. 50, 91058 Erlangen, Germany  
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<https://www.siemens-healthineers.com>  
<https://www.siemens-healthineers.com/careers/innovation-think-tank>