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Virtual Representations of Physical Assets – a literature study about Digital Twins from the perspective of application in aviation's retrofit

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Abstract

The concept of a virtual representation of a physical asset can be traced back to the sixties and is currently widely found under the term Digital Twin. Today, increasingly more implementations of this concept in a variety of applications occur, each with individual boundary conditions and views. Aviation and, especially its retrofit, face the need for such representations but also, its very own circumstances. After giving a brief introduction to the world of aviation, its cabin-retrofit and the need for a good virtual representation of aircraft, the history of the concept of Digital Twins is presented. A literature study results in an overview of current definitions, and research domains but also occurring challenges. The results are contrasted with the perspective of aviation's cabin-retrofit and an assessment of the definitions and terminology is given.

Keywords: Virtual Representation, Digital Twin; Literature Study; Aviation; Retrofit;

1. Introduction

Aircraft are one of the longest-living products with lifespans of up to 30 years of nearly non-stop operation. To ensure the required high safety standards as well as keeping up with wear and tear of the cabin, aircraft are being regularly maintained intensively, which often includes a nearly complete dismantling and re-assembling of parts of the aircraft and its cabin. During the so-called cabin-retrofit, occurring approximately every five to seven years, big parts of the aircraft's cabin are removed and replaced by a newly designed interior [1]. During this retrofit, this new cabin has to fit seamlessly into the aircraft's body; its airframe. Thus, the design of the cabin and planning of the overall retrofit-process relies on exact information [2]. Usually, the retrofit is performed by specialized organizations and not the original manufacturer, owner, or operator of the aircraft. With this additional stakeholder, data availability becomes a challenge. Currently, if directly available at all, the information required to plan and perform the retrofit is most-often only available in form of a range of documents. These can originate e.g., from previous maintenance measures or are general information based on the type of aircraft. Specific, detailed, and holistic information regarding geometrics is rare. It requires elaborate work to extract it from several documents and revisions. Easily accessible representations of the aircraft including details regarding the installed components, and geometric information are simply not available. As a result, the designed cabin often does not fit properly into the airframe, which however is only determined once the aircraft is already dismantled or even later during the attempted installation of the new interior. This regularly requires time-consuming adaptions of the new cabin and, thus, a longer time for the aircraft to be out of service. Knowing exact geometric information, or at least what exact components are installed at which position would reduce these conflicts, streamline the complete retrofit-process as well as reduce costs and missed revenues resulting from the longer time spent on the ground and not operating. [3]

Besides these financial benefits for the aircraft's operator, a digitally available up-to-date representation of specific aircraft would ease the overall retrofit planning process, as it would provide the engineer more easily with more accurate

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information during the phase of the cabin design. Because the aircraft is still operating and flying around the world while the new cabin is being designed, physical access to the specific assets is limited. Hence, a virtual representation is essential. If accurate enough, this virtual representation would also allow for a virtual preemptive clash analysis of the cabin and airframe [4]. Such up-to-date virtual representations of a physical asset can currently be found in the literature using the fitting term Digital Twin, albeit often focusing on sensorial or state-describing information, rather than geometric or product-descriptive. With approaches to transfer the concept of Digital Twins to this scenario currently being developed and partly already presented [2, 5], this paper will present a literature study of the general history and concept of Digital Twins from the perspective of aviation and especially its retrofit.

2. Literature Review

The previously described virtual representations of physical assets, in general, can be plentifully found in recent publications. A brief literature review revealed many approaches to such commonly named Digital Twins, albeit, with quite different applications and boundary conditions. Additionally, a variety of comprehensions of the terminology of Digital Twins, Shadows, and Models has been found. Hence, a systematic review of those approaches and concepts stands to reason and will be presented subsequently.

2.1. Procedure

The term Digital Twins has been experiencing a trend in recent years with nearly 2000 publications listed on Scopus in the year 2020 and over 2500 in 2021 respectively. With that many publications spanning areas of applications ranging from manufacturing facilities [6] to power grids [7], a systematic review with regards to the presented scenario is conducted to gain an overview of current approaches and challenges. A single query for the two keywords “digital” and “twin” using the online database Scopus led to 8.056 results as of January 2022. The results were reduced to 4.227 entries by enforcing the explicit reference of the keyword “digital twin” or its plural “digital twins”. As the scope of the presented application lies solidly within the field of engineering, filtering for this subarea results in a further reduction to now 2.810 entries. A manual clustering is done, further narrowing down the results to a selection that can be analyzed in a reasonable amount of time. Thereto a visualization of the used author keywords is generated using the software VOSviewer [8], resulting in a visual overview of the keywords used together with “digital twin(s)”. The more often specific keywords are used together, the nearer they are visualized to each other. Additionally, VOSviewer colourized 5 clusters of correlating keywords. By manually inspecting this visualization, these 5 clusters were named “networking”, “modeling”, “production”, “digitalization” and “optimization” and will be used for further breaking down the number of the results. As with this clustering, the number of 2.810 entries is still too high to analyze each of them in a realistic amount of time, a further reduction was made by filtering in each of the clusters for the top 10 highest cited as well as for the top 10 according to the Scopus relevance. By doing so, not only the highest cited publications, which are usually older and have had more time to be cited but also more recent ones were considered. With two times ten entries for each of the five clusters, the remaining publications were reduced to 100. As some publications are categorized into multiple clusters or within the two filters “highest cited” and “highest relevance” the last filter is used to remove any duplicate entries leading to the final number of 82 publications. Each of these 82 publications is now analyzed regarding factors like the type of publication, the presented understanding of the term Digital Twin, and the field of application as well as described challenges. The filtering approach is visualized in Figure 1.

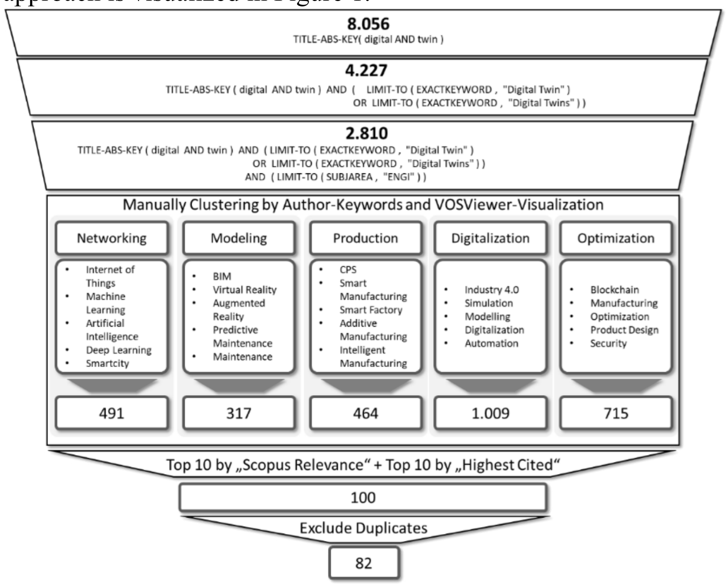

Fig. 1. Overview of the filtering process of the systematic literature review

2.2. History and Common Definitions

The origin of the idea of Digital Twins can be traced back to the 1960s and the famous Apollo 11 and 13 mission. Although not technically matching today’s definitions, the quickly adaptable simulators on earth, that could be reconfigured to match the current state of the real asset more than 40.000 miles away based on the transmitted data can be seen as the very first instance of the general concept [9]. The first scientific research referring to a pendant similar to today’s concept was published in 1997 by HERNANDEZ ET AL. [10] and in more detail by GRIEVES ET AL. in 2002 before it was finally labelled *Digital Twin* in NASAs 2020 technology roadmap (c.f. Fig. 2). [11,12,13]

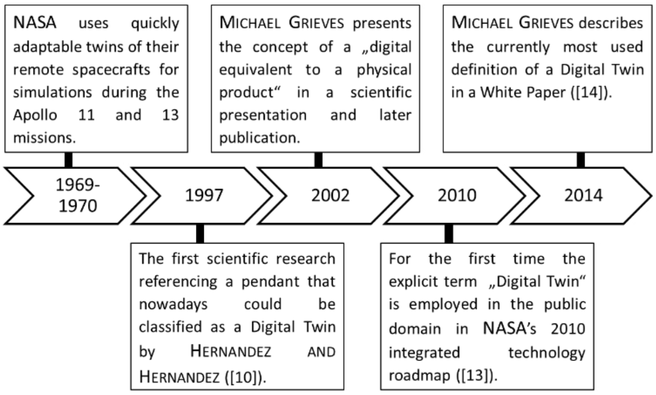

Fig. 2. Brief history of Digital Twins, based on information from [9,11,12]

In 2017 GRIEVES ET AL. define a Digital Twin as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometric level. At its optimum, any information that could be obtained from inspecting a physically […] product can be obtained from its Digital Twin". [15]
While GRIEVES ET AL. explicitly include potential manufactured products, other definitions clearly distinguish more strictly. WRIGHT ET AL. state, that "a digital twin without a physical twin is a model" [16]. These diverse interpretations between Digital Models, Shadows, and Twins were also identified by KRITZINGER ET AL. as an "incomplete understanding of [the] concept [Digital Twin]" [17]. Hence, they integrated levels of integration to distinguish between Digital Models, Digital Shadows, and Digital Twins. While focusing on manufacturing they classify by differentiating whether the data flow from the physical asset to the digital object and vice versa is realized manually or automatically [17]. This concept as visualized in Figure 3 is often referenced when establishing Digital Twins in today's research papers, especially within the scope of manufacturing.

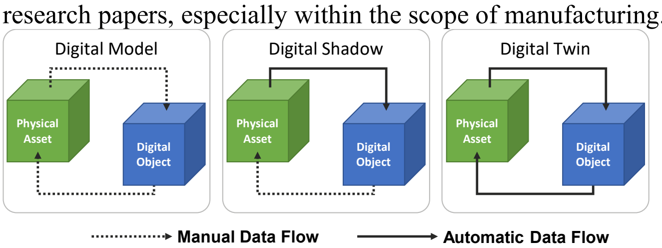

Fig. 3. Digital Model, Shadow, and Twin, based [17]

In that scope, the concept has evolved thus far, that with the ISO 23247 – Digital Twin framework for manufacturing [18] in 2021 an ISO-Standard was released, defining a Digital Twin as a "digital representation of an observable manufacturing element with synchronization between the element and its digital representation" [18] with a digital representation being defined as a "data element representing a set of properties of an observable manufacturing element" [18]. Despite this focus on manufacturing, the framework greatly depicts some core elements and their connections necessary to implement Digital Twins, which can be adapted to other applications.

2.3. Current Research Domains

Analyzing the Scopus pool of publications the first finding is the distribution of publications across different research domains referencing Digital Twins. With 30 of the 82 publications remaining after the steps described in Section 2.1, the most commonly occurring domain is manufacturing, showing the progress that has been made in that scope and the determining factors of manufacturing facilities. Many of these publications are more focused on implementing Digital Twins of the manufacturing facility and less on Digital Twins of the manufactured asset. Digital Twins being a digitally driven topic, the second biggest group within the 82 publications is the domain of information and communication with 17 publications. Next comes the domain of civil engineering with 9 papers, followed by maintenance with 6, and finally product development or mechanical engineering with 5 occurrences. The high relative number of papers within the domain of manufacturing correlates with the many occurring references to KRITZINGER ET AL. With these diverse areas of application and focuses there are different definitions to be found. Despite them being generally compatible, some aspects or views of Digital Twins differ vastly within the publications. While the very idea of a *virtual representation of a physical asset* can be seen as the common ground, whether a Twin always needs to be holistic or if it can be focused on a few relevant aspects of the physical asset differs. Even multiple Twins, each focusing on individual aspects of the very same physical asset, might stand to reason.

Similar to manufacturing, within the product development community there is a common understanding, as prominently published by the German Scientific Society for Product Development (WiGEP), describing Digital Twins originating from product development (see Figure 4). Here the Digital Shadow is the dataset of the physical asset that describes its actual state and is combined with the Digital Master, which originates from the phase of product creation. [19]

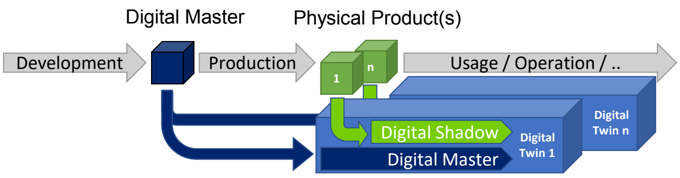

Fig. 4. Digital Twin originating from product development, based on [19]

Product development is faced with a different set of circumstances, as the physical asset is not a spatial accessible production facility with sensors and controls already in place. Instead, there is a multitude of individually produced products that each needs to be paired with its very own virtual representation. Once produced, these products will leave the factory. With that usually comes a loss of direct access to the asset from the producer, hence, limiting the data flow of information about the actual state from the physical to the virtual space. As this seems to be a generic challenge during the implementation of Digital Twins in product development, the following Section will take a deeper dive into the challenges occurring in the scope of product development. Complementary to the presented results of this Section, an overview from the viewpoint of the industry using Digital Twins was composed by WILKING ET AL. [20], showing the wide range of applications and definitions.

2.4. Identified Challenges in Product Development

After the publications were analyzed without focusing on a specific domain, a more detailed analysis was performed. It focuses on the domain of product development, as that most perfectly fits the depicted scenario in Section 1. The original dataset includes 33 publications referring to product development. To extend the dataset it is joined by 18 publications from the online library of the Design Society resulting from searching for "twin" in the years 2014 to 2021. This set of 51 publications was further analyzed regarding the current state of implementations and especially described solutions and challenges. It can be seen, that *data handling* is one of the leading challenges regarding Digital Twins with 13 of 32 papers of the Scopus pool and 12 of the 18 publications of the Design Society pool listing it. Within this category lie challenges regarding the acquisition and respective individual data formats as well as the challenges to efficiently process, manage, store, and connect the information. Another occurring challenge is *Model Quality*, describing the process of how the data was acquired and its effects on accuracy and reliability. Factors like *real-time sensitivity*, how fast changes in the physical or virtual domain are reflected in the other, or *physical reality*, how well the relevant physics of the surrounding environment is reflected in the virtual space, are challenging when needed. Also, concerns about the *safety and security* of information are crucial but more relevant for implementation. An overview of publications referring to at least one of these top 5 challenges is shown in Figure 5.

Author	Data Handling	Realtime Sensitivity	Model Quality	Physical Reality	Data Safety & Security
[21]	X	X	X		
[22]	X		X		
[23]	X	X	X	X	
[24]	X		X		
[25]	X	X	X		
[26]		X			
[27]	X				
[28]	X				
[29]			X		
[30]	X			X	X
[31]	X				X
[32]			X		
[33]	X				
[34]			X		X
[35]	X		X		
[36]					X
[37]	X				
[38]		X		X	
[39]			X	X	
[40]	X		X		X

Author	Data Handling	Realtime Sensitivity	Model Quality	Physical Reality	Data Safety & Security
[20]	X		X		
[41]	X				
[42]	X		X		X
[43]	X		X	X	
[44]	X				
[45]	X		X	X	
[46]	X		X		
[47]	X				
[48]		X	X	X	
[49]			X		
[50]	X		X	X	
[51]	X			X	

Fig. 5. Publications referring to challenges when realizing Digital Twins as found in the pool of product development-specific publications from Scopus (left) and the Design Society database (right)

These challenges occur with a wide range of targeted applications and depict the state of implementation of Digital Twins within the product development community.

2.5. Result Summarization

The literature review showed the origin and elementary steps of the evolution of the concept of Digital Twins. It was shown, that in the past years, manufacturing was one of the leading domains that were able to implement the concept and likewise advanced the definitions and general research. Anyhow, in other domains like product development approaches to implement the idea of Digital Twins in their specific set of circumstances have been rising as well. Yet, they are facing a range of challenges ranging from the spatial displacement between the physical asset and virtual representation to different aspects of handling the needed and occurring data. With these different focuses come different descriptions and definitions. However, the very essence of implementing a virtual representation of a physical asset stays mostly the same.

3. The perspective of aviation and its retrofit

From NASA's first idea to HERNANDEZ ET AL.s urban planning and highway design and finally, the many approaches found in manufacturing the distance between digital and physical instances has been reduced, allowing stricter described definitions like the prominent visualization by KRITZINGER ET AL. While the original idea of a Digital Twin is still matching, aviation's special circumstances exacerbate the adaption of said concepts. During the original manufacturing of aircraft or components for them, the described concepts from the perspective of manufacturing might be still applicable. However, during the cabin-retrofit, a new cabin for an already existing aircraft is being developed by a third party and there is only limited access to the original information or the physical asset itself. Thus, the circumstances greatly differ. Additionally, the concept common in product development can also not be easily applied, as the retrofit company is not the designer and producer of the aircraft. The described flow of information from product creation to the usage and concurrently instantiation of the Digital Twin is not feasible with today's structures. Instead, all necessary information needs to be acquired and collected individually after the aircraft already has been produced. [52]
Adding to the system discontinuities and less tangible information is the diversity of the products. While aircraft are generally comparable to a product family structure and quite similar in many aspects, even two once identical airframes deviate from each other after some time because of their individual wear and tear as well as maintenance. Aircraft as the target assets are not spatially attainable but literally distributed across the world and in continuous motion, exacerbating the flow of data from the physical to the virtual space. With the focus of the application in retrofit lying on geometric rather

than sensorial information, this is only amplified. Usually, during regular maintenance events, the current state of the aircraft will be obtained. Likewise, modifications planned in the virtual world using the virtual representation will be transferred to the physical world during the retrofit procedure, thus bringing them back in sync. Regarding the scenario of retrofitting aircraft, a virtual representation of a specific airframe would be classified as a Digital Model or Shadow according to KRITZINGER ET AL. [17] (c.f. Fig. 4). However, regarding the original idea of a "virtual representation of a physical asset" and according to the definition by GRIEVES ET AL. [12] this representation could be classified as a Digital Twin. Establishing an automatic data flow between a produced physical product and its Digital Twin may be possible regarding sensorial information. Yet, in scenarios where the virtual representation of the said product should include geometric information, a continuous automatic data flow of the respective information is not easily feasible with current technology. Continuously acquiring the current geometrics of a complete asset is a big effort and is currently only partly done on occasion. While, thus, the data flow would not be continuous, during the regularly scheduled maintenance activities, changes in the physical asset are implemented in the virtual object. The digital object can be used as a base to plan modifications of the physical asset, that are subsequently implemented. In this setting, the Digital Twin could be described as *a concept, that describes the linkage between aspects of a physical asset and its virtual representation. To keep the virtual representation up to date there has to be a regular flow of information from the physical asset to its virtual counterpart. The virtual instance can be used to plan or simulate changes to the physical asset which will consequently be adapted and performed. This iterative concept can be applied throughout the lifespan of the product*.

4. Summary, discussion, and outlook

The concept of Digital Twins has come a long way. This paper presented a brief introduction to the origins and evolution of the concept of Digital Twins based on a literature study. With new technology came more applications and with that a diversification but also a drift of definitions, and terminology. Over the years different views of the idea of Digital Twins have evolved. Manufacturing was identified as one of the currently leading domains in the evolution and implementation of Digital Twins, also resulting in one of the most known and referenced definitions and illustrations of the concept of Digital Twins. Besides product manufacturing, a closer look was taken into product development and its most common view on the concept. Finally, the results of the literature study are contrasted with the perspective of aviation's cabin-retrofit, and, thus yet another view on the concept. Despite having a similar goal, some aspects of current descriptions and definitions cannot easily be transferred to the application in that setting. An idea for a description of Digital Twins was described, that incorporates the circumstances of aviation's retrofit but also stays true to the core idea of the said concept. In cooperation with a partner from the industry, current research is developing a methodology how to acquire and handle the required data to allow for the implementation of Digital Twins of airframes under the described circumstances and focusing on the geometric information needed for cabin retrofits [2,52].

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