



HAL
open science

Towards a Framework for the Classification of Digital Twins and their Applications

Guillaume Pronost, Frédérique Mayer, Brunelle Marche, Mauricio Camargo,
Laurent Dupont

► **To cite this version:**

Guillaume Pronost, Frédérique Mayer, Brunelle Marche, Mauricio Camargo, Laurent Dupont. Towards a Framework for the Classification of Digital Twins and their Applications. 2021 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Jun 2021, Cardiff, France. pp.1-7, 10.1109/ICE/ITMC52061.2021.9570114 . hal-03608145

HAL Id: hal-03608145

<https://hal.science/hal-03608145v1>

Submitted on 21 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Towards a Framework for the Classification of Digital Twins and their Applications

Guillaume Pronost, Frédérique Mayer, Brunelle Marche, Mauricio Camargo, Laurent Dupont

Equipe de Recherche sur les Processus Innovatifs, Université de Lorraine, Nancy, France

guillaume.pronost@univ-lorraine.fr

Abstract— The objective of this paper is to propose a categorization of the objects defined under the term "Digital Twins" in the literature, to reduce the misuse of this term and to facilitate the understanding of the developments in this scientific field. A review of the literature on the categorization and classification of Digital Twins has been carried out. A classification into four distinct categories was made, using a decision tree. These four categories of objects grouped under the term Digital Twin were then explained, presenting their functions as well as their frameworks of use. The classification criteria used for the realization of this study focus only on the existing links between the physical and virtual parts of the Digital Twins, from which will derive their functions. This document represents one of the first attempts to classify Digital Twins, and the first to propose a tool to facilitate the reading of articles on this subject, in the form of a decision tree.

Keywords— *Digital Twin, Framework, Digital Shadow, Classification*

I. INTRODUCTION

In today's highly competitive markets, digitalization of manufacturing companies and Industry 4.0 initiatives are seen as an opportunity to achieve higher levels of productivity. However, these technologies lead to an increasing complexity of systems, and require a better comprehension from the users to take advantage of the opportunities they offer.

One of these emerging technologies is the named "Digital Twin" (DT) [1] enabling the observation and even automatic control of production elements through synchronization between the physical world and the virtual world [2].

In recent years, interest in DTs has been growing, and their uses are being explored in various phases of the life cycle from the early design [3], [4] to the use [5] and disposal phase, but also in very different sectors such as production [6], [7], medicine [8], maintenance [9], ...

Despite the numerous publications on the subject, the nature, definition and use of Digital Twins are still a matter of debate. Due to the variety of terms that exist for DTs, it is difficult to realize a literature review to classify them without missing some of these documents due to a lack of knowledge of the terms used. Moreover, it is currently challenging to find criteria for grouping DTs because of their multiple definitions, from different fields, contexts, and applications, without using a previously existing reading grid. To the best of our knowledge there is not a well-defined method to classify digital objects, therefore it is necessary to develop a reading grid to approach the review of the literature on DTs.

With the support of existing articles covering the classification of DTs, this document presents a first attempt at classifying and defining DTs. This paper aims to provide a tool for classifying "Digital Twins" in the literature, in view of the necessity of this classification in the continuity of this work. Indeed, this classification will be used to subsequently carry out a systematic literature review on Digital Twins and their use for demonstration, within the framework of the realization of a co-design demonstrator.

The remainder of the paper is organized as follows: in Section II, a review of the literature on DTs and their definitions is presented. Section III introduces the classification approach carried out in this work. Section IV presents the study findings. Finally, in section V, conclusions and perspectives for future research are presented.

II. EXISTING THEORIES AND PREVIOUS WORK

A. *Origins of the Digital Twin concept*

The origins of the twinning concept, and one of its most famous examples, can be found in the Apollo program conducted by NASA between 1961 and 1972, and more precisely during the Apollo 13 mission. In their book retracing the history of Apollo 13 [10], Jeffrey Kluger and James Lovell, former commander of the mission, described that NASA engineers constructed a physical replica of the spacecraft, in order to train astronauts to face different flight issues in a simulated environment before the mission, and to eventually figure out solutions if an issue occurred during the flight.

After two days of flight, an oxygen tank on the spacecraft exploded, depriving at the same time the spacecraft of most of its batteries. Using the mirrored physical model and the simulated environment, NASA was able to model, test and find a solution before instructing the astronauts on how to apply this solution onto the spacecraft. This allowed the three astronauts to make it back to earth alive.

This system forms the basis of a future digital twin as being a physical object providing information to its virtual counterpart, representing the current state of the real system, and then carries out simulations before sending a control command back to the real system.

It took 30 years to regain the use of this concept, reintroduced in 2002 by Michael Grieves at the University of Michigan during a training course on Product Lifecycle Management or PLM, and presented as a "Conceptual Ideal for PLM" [2], [11].

This model was then referred as "Mirrored Space Model" in Dr Grieves work, until the term of "Digital Twin" was introduced by NASA [12] and globally accepted, as presented in the next section.

The late appearance of DTs, both in research and in industry, can be explained by the technologies required for their implementation, particularly in the context of current complex systems. Indeed, DTs require access to a large amount information resulting from multiple distinct and simultaneous data streams, and sufficient computing power to process it in an adequate amount of time. These requirements could not be met before the emergence of Industry 4.0 and the development of fields such as Big Data or the Internet of Things (IoT) [1], [13]. Technological advances in these field allow the acquisition and processing of large amounts of data, providing access to valuable information.

B. Global definition and its limits

The first formal definition of a DT can be attributed to Glaessgen et Stargel [12], in which the authors define the roadmap of the use of DTs in aeronautical and aerospace applications for the US Air Force and NASA.

The need to use a DT is justified by the authors for several reasons. Indeed, due to the evolution of technologies and the rapid complexification of systems and failures modes, it has become necessary to massively realize experiments on a digital counterpart of a system, by simulation, due to practical and economical constraints of the experiments. Also, it is necessary to develop new approaches for verification and validation of the models used. This verification implies the need for emulation. Finally, the modern high performances systems used in aeronautical and aerospace require a real-time management of their complex materials, structures, and subsystems.

To meet these criteria, the authors define the nature and the composition of a DT : "If various best-physics (i.e., the most accurate, physically realistic and robust) models can be integrated with one another and with on-board sensor suites, they will form a basis for certification of vehicles by simulation and for real-time, continuous health management of those vehicles during their missions. They will form the foundation of a Digital Twin." [12]

Thus, they introduce the widely used definition of a DT : "an integrated multiphysics, multiscale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc... to mirror the life of its corresponding twin." [12]

A representation of this definition of a DT is presented Figure 1.

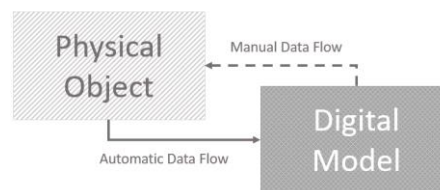


Figure 1: Representation of a Digital Twin, based on [12]

Numerous works have largely contributed to the evolution of the original concept of DT from this definition. As a review of the literature on the subject shows, one of the consequences is the profusion of new definitions that vary according to the approaches used and/or the fields of application targeted [14]. It should be noted, however, that some of these definitions have moved away from the original definition, as well as the confusion that the lack of consensus between these definitions has generated on the meaning given to the term DT.

The following section will present different definitions from the literature, to confront their differences in the nature of the DT defined and its domain of use.

C. Definitions from the literature

As presented before, even though the definition produced by NASA [12] is the most common definition in the literature, there are many other definitions of the DT, generally adapted to each field of application [15].

DTs are often defined in the literature as a set of three parts [16], [17], presented in [18] :

- A model of an object
- An evolving set of data relating to the object
- A means of dynamically updating or adjusting the model in accordance with the data

Despite this, in some applications, the physical object is not even considered, and the DT is defined as a virtual entity, with no apparent link to a real object or system [1]. Even John Vickers, NASA's leading manufacturing expert and manager of NASA's National Center for Advanced Manufacturing said that "the ultimate vision for the digital twin is to create, test and build our equipment in a virtual environment". This raises the question of the necessity of a physical counterpart in the definition of a DT.

In addition, a majority of the articles defining the DT do not mention the existence of communication, exchange of information between the physical object and the virtual model [19].

This imprecision of the different definitions, and the existing contradictions between some of them, can pose a comprehension problem when reading an article or scientific document mentioning the term "Digital Twin". It seems necessary

to dispose of a formalism of the DTs, to be able to sort, organize, and distinguish them easily. This work will be presented thereafter in this paper.

III. METHODS

A. Presented study, research questions and hypothesis

As we remark in the first section of this paper, the multiplicity of different definitions of DT leads to imprecision and confusion about what is described when the term is used. The objective of this paper is not to propose a general definition of DTs to try to encompass most of the existing contradictory definitions into a general definition, as this would raise paradoxes and result in an imprecise definition.

Thus, in this paper, another approach has been realized : to classify the digital twins into a series of categories. Indeed, establishing a classification enables to distinguish the current heterogeneous group of Digital Twins into a series of more precise categories, and to be able to propose for each of these categories a precise definition of the nature of these Digital Twins and their applications.

Is it possible to establish a systematic methodology to classify Digital Twins?

The objective of this paper will be to attempt to answer this question, by determining relevant classification criteria and then presenting the result of this classification.

It is difficult to realize a literature review to classify DTs without missing some of these documents due to a lack of knowledge of the terms used. Moreover, it is currently difficult to find criteria for grouping DTs with multiple definitions, from different fields, contexts, and applications, without using a previously existing reading grid. It is therefore of paramount importance to investigate previous research works about DT classifications.

B. Applied research methods

The research presented in this paper follows a systematic approach method, aiming to identify papers that presented a classification or an organization of DTs.

The bibliographic database used for sourcing the articles was Web of Science. To keep the number of articles reasonable and to ensure the quality of the sources, the search was restricted to peer-reviewed journal articles. Web of Science was queried in February 2021 using the terms : ((Digital Twin OR Digital Shadow OR Digital Model) AND (catalog* OR categor* OR classif* OR assignment OR denominat* OR organiz* OR allot* OR systemiz*)). The search for papers was restricted to the keywords, abstract and title of the articles after 2012, as it was the first apparition of the term "Digital Twin" in this context of research. For the search term, 157 articles were retrieved. After removing duplicates, initial screening was done based on the titles, keywords and abstract and 4 articles were selected, presenting a taxonomy or a classification of DTs. To ensure that no relevant articles were missed, references in the 4 articles were cross-checked, retrieving 1 additional relevant article.

Figure 2 describes the research methodology.

After having identified the different items presenting DT categorizations, an attempt will then be made to group together the items presenting the same categorization or sorting criteria, to observe the existing classification methods. This will then enable this work to draw inspiration from these methods to establish a new more general classification of the DTs.

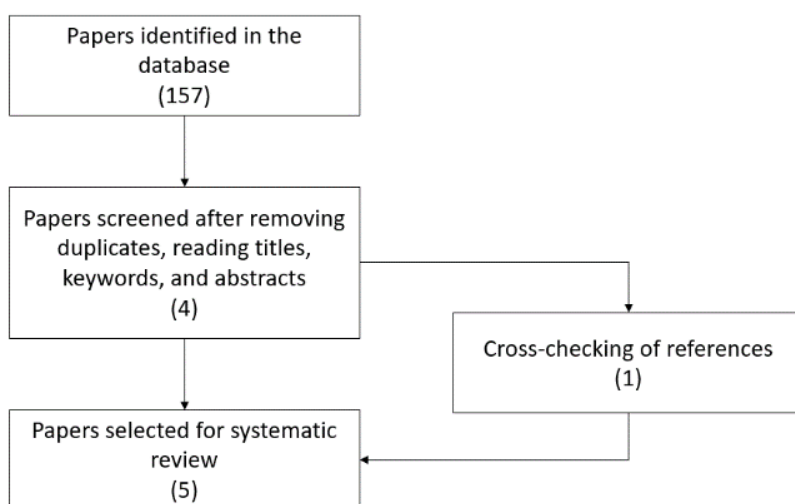


Figure 2: Systematic literature review methodology

IV. FINDINGS

This section presents the implementation of the work proposed in the previous section. The documents resulting from the bibliographical research were analyzed to identify their classification methods, making it possible to propose a new set of

criteria for classifying DTs. Using these criteria, a methodological guide is produced and presented in the form of a decision tree. The different categories of DT, determined using this tool, are then defined, and presented.

As the objective of this paper is to establish a systematic classification of DTs, regardless of its domain of use or its application, the classification criteria chosen for this classification will not concern the application but only the technical composition of the Digital Twin.

A. Existing classifications in the literature

The classifications present in the documents extracted from the literature review can be divided into two categories, depending on the angle of consideration for that classification. Thus, some of the authors proposed to classify the DTs according to their maturity, their degree of evolution, from a simple numerical model to an "intelligent" system able to evolve in its environment thanks to the learning machine. Another part of the authors was interested in the relationship between the virtual and physical parts of the twin.

These different existing classifications are presented in this section.

1) Maturity level

Madni et al. [17] states that "today any digital version of a system, component, or asset is called a digital twin". Due to this situation, other questions arise, such as the necessity of a physical counterpart before the digital twin is created, and the necessity for the physical system to report information automatically to the virtual system.

To answer these questions, the authors defined a classification of DTs in 4 levels:

- Pre-Digital Twin: A virtual prototype created before its physical counterpart. Its purpose is to optimize the system and mitigate technical issues or risks before the physical system is produced
- Digital Twin: This corresponds to the "classic" version of a DT, where a virtual model receives data (status data, objective-related data) from the physical system. The Digital Twin updates its model according to the data received. The interaction between the virtual and physical systems is bidirectional, which allow the Digital Twin to use the acquired data and the models from the virtual system to optimize the performance of the physical counterpart.
- Adaptative Digital Twin: In addition to the properties of the Digital Twin, it presents the ability to learn (machine learning algorithm) the users' preferences and priorities, and to reinvest them by producing an interface sensitive to these criteria.
- Intelligent Digital Twin: An intelligent Digital Twin presents all the functionalities of an Adaptative Digital Twin, providing not only internal adaptive capabilities, but also considering other entities coexisting in the environment.

2) Integration level

Another angle of classification is to observe the level of data integration between the physical object and its digital counterpart.

Kritzinger et al. [6] proposes a classification of DTs into 3 categories depending on their level of integration :

- Digital Model: A Digital Model is composed of a physical object and a digital counterpart, with no form of data exchanged automatically between one and the other. Thus, a change of state in one of the objects will have no impact on the other. the digital object is a representative model of the physical system.
- Digital Shadow: A Digital Shadow presents a one-way automated data flow from the physical object to its digital counterpart. A change in the state of the physical object will be communicated to the virtual object, but not the other way around. The digital object can serve as an observer of the state of the physical system.
- Digital Twin: In a Digital Twin, the data flow between the physical and digital objects is automated in both directions, allowing the digital object to act as a "controlling instance" for the physical counterpart.

This classification is also taken up by Uhlenkamp et al. [20], who describe these three degrees of integration as "manual", "semi-automated" and "automated" respectively, while Van Der Valk et al. [21] considers two distinct aspects from which the different degrees of integration presented above derive: unidirectional or bidirectional communication between the physical and virtual parts, and the presence of synchronization of the two parts.

In addition to these three categories presented previously, Tekinerdogan et al. [22] proposes a fourth category of DT, having an automated communication from the virtual to the physical object, and a manual communication from the physical to the virtual: the Digital Generator. It is in fact a way for the author to describe that the real object is created automatically, without human assistance, from the virtual object.

B. Determination of the classification criteria and creation of a reading grid

1) Determination of the classification criteria

By bringing together the different classifications from literature, presented in the last subsection, a list of classification criteria can be established to categorize DTs. These different criteria are:

1. Presence of a physical system: the digital model studied may or may not have a physical counterpart of which it serves as a representation.

2. Automatic model update: data collected on the physical system can automatically feed the digital model. Otherwise, the model will only be updated with information from the physical system manually, by user decision.
3. Control of the physical system: information from the execution of the digital model can be automatically fed to the physical system as a command from the physical system. Otherwise, there will be no automated communication from the digital model to its physical counterpart.
4. Adaptation to user preferences: the adaptive user interface is sensitive to the preferences and priorities of the operator.
5. Awareness of the surrounding environment: the DT can have a learning capacity to discern objects and models encountered in the operational environment.

2) Assumptions made for the classification

Several hypotheses have been made in the framework of this study, to identify the classification criteria relevant to this work, as well as the relationships between these criteria.

It will be considered in this study that there can only be communication between the physical object and the virtual object if both exist at the same time, i.e., if a physical object is present. This implies that criteria 2 and 3 established previously are dependent on criterion 1, the presence or not of a physical part.

Furthermore, it will also be considered here that one cannot have automatic control from the virtual object to the physical object without having automatic communication from the physical object to the virtual object. Indeed, without knowledge of the state of the physical system, it is not possible to control it.

A contradiction could appear in the fact that Tekinerdogan et al. [22] consider the existence of a Digital Generator, presenting a single automated link from the virtual object to the physical object, but this representation is only made to designate the fact that the physical object is created automatically from the virtual object already existing.

Finally, as research on DTs is quite recent, interest is mainly focused on the first three functions mentioned above, and the functions of "Adaptation to user preferences" and "Awareness of the surrounding environment" are not really considered for the moment, as the development of their prerequisites is still in progress.

These last two functions will therefore not be considered in the rest of this study.

3) Realization of a decision tree for classifying Digital Twins

Based on these classification criteria, a decision tree, presented Figure 3 has been created, to be able to determine when reading a scientific document dealing with "Digital Twins" the sub-category to which the mentioned DT belongs.

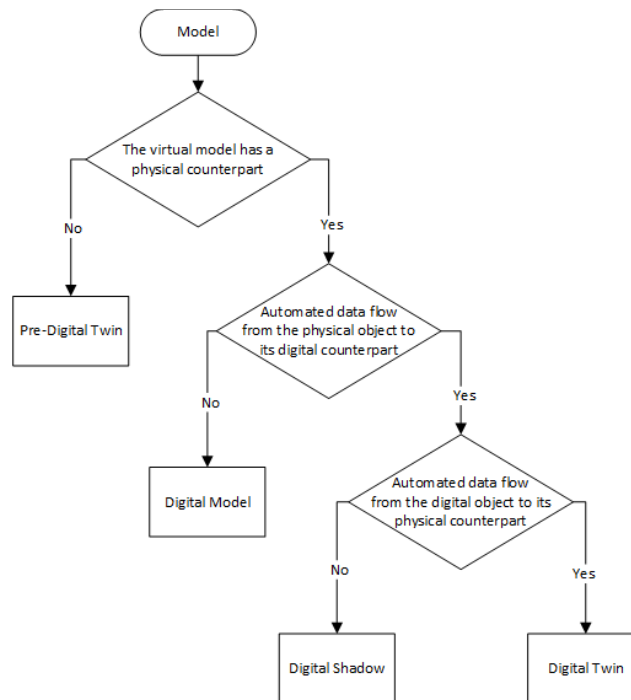


Figure 3: Decision tree of the Digital Twins subcategories

C. Unified classification of the Digital Twin

As presented Figure 3, the classification of DTs contains four sub-categories: Pre-Digital Twin, Digital Model, Digital Shadow, and Digital Twin. This section will describe the nature of each of these subcategories and present their functions and areas of use.

1) Pre-Digital Twin

A Pre-Digital Twin consists of a virtual model alone, since in its case there is no physical counterpart. This model is thus supposed to represent a system or part of a physical system not yet realized. In the absence of real data measured at the input of a real system, the execution of this model can therefore only be carried out using theoretical data at the input of the model.

A representation of a Pre-Digital Twin is given Figure 4.

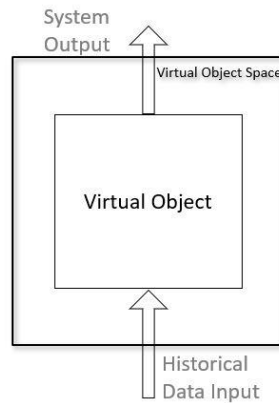


Figure 4: Representation of a Pre-Digital Twin

The objective of executing this model is to carry out series of tests with an objective of optimization, which implies that an important factor for a simulation is its speed of execution. Simulations can be designed for fast execution, at the expense of the level of detail and therefore the accuracy of the model [23].

Pre-Digital Twin is traditionally created during the upstream design phase of a system [4], [24]. It is mainly used to validate or invalidate design decisions and for potential risks or technical issues before the real system is built.

Conducting this experiment on a virtual model has several advantages. Indeed, series of tests on real systems can be very costly, especially if the prototype used is intended to be damaged or destroyed during the test. Moreover, the conditions under which the tests are carried out on physical prototypes can also prove costly or difficult to set up, or to reproduce precisely between several tests [12]. Finally, some tests can be dangerous, due to the nature of the test itself or the products and systems used in the test.

The advantage of the Pre-Digital Twin lies in the low cost of its use, since once the model has been created, the only cost of experimentation is the cost of executing the model. A drawback of executing this model is that, since it is only a theoretical model of a system, fed with theoretical values corresponding to supposed operating ranges of the future real system, its response can deviate from the real response of the physical system.

2) Digital Model

A Digital Model is a digital representation of a physical object that "does not use any form of automated data exchange between the physical object and the digital object" [6]. Unlike the Pre-Digital Twin, its physical counterpart exists.

Measured data at the input and output of the real system can therefore be used to feed the digital object at the input and check the accuracy of its output response against that of the real system.

A representation of a Digital Model is given Figure 5.

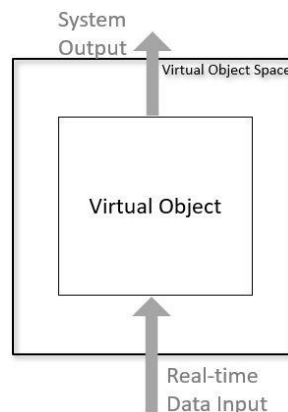


Figure 5: Representation of a Digital Model

The Digital Model makes it possible to compare the virtual model with the real object it represents, to ensure its accuracy. Therefore, Digital Models are used in applications when a high-fidelity model is required.

It is generally used in various simulation applications such as organizational optimization, for example for a machine park [25]. It is also used for the training or education of personnel in real conditions, without the need to manipulate the physical system

[26]. This allows the trainees a better immersion than a simple theoretical training, without the need to manipulate the real system, which is advantageous for maintenance situations taking place in dangerous systems or systems that are too expensive to stop for maintenance training.

3) Digital Shadow

The Digital Shadow is composed of a physical object, and a virtual model dynamically updated by data from the physical object. This automatic input of data from the physical object ensures that the model is always an up-to-date representation of the real system. A representation of a Digital Shadow is given Figure 6.

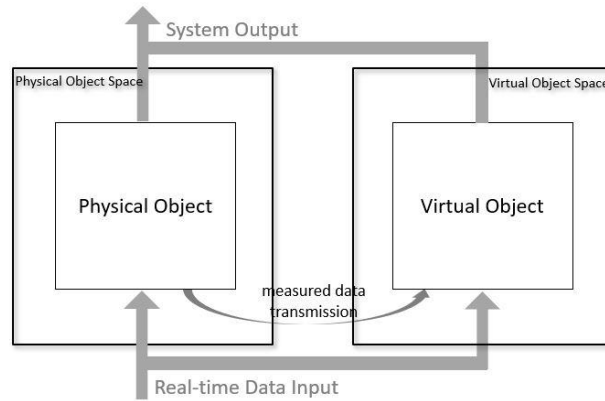


Figure 6: Representation of a Digital Shadow

The Digital Shadow therefore allows the real system to be observed at any time without the need to measure the information to be acquired directly on the real system. This has several uses: first, it allows to observe the functioning of the physical system from a distance, without direct contact with it. Secondly, it is possible, in real time, to obtain additional information on the model which has not been measured on the physical system, but which is the result of feeding the digital model with data from the physical system. This feature therefore allows better observability of the real system.

Applications of Digital Shadow can be found in Industry, notably through real-time visualization of operations [27], [28], as well as predictive maintenance [9], [29], [30], which consists in identifying patterns in the data received from the physical system corresponding to a defect, a technical problem or wear and tear of parts. This allows intervention for repair and maintenance operations before these problems become critical, which can represent a considerable saving in time and money. There are also applications of Digital Shadow in medicine, such as the management of patients and their information for emergencies [8] or the establishment of personalized treatment.

4) Digital Twin

A Digital Twin is composed of a physical and a digital object, which are equipped with networking devices to guarantee a seamless connection and a continuous data exchange either through direct physical communications or through indirect cloud-based connections. [15]

The automatic input to the virtual object allows the dynamic update of the model, which is then executed to produce an optimized command to its physical counterpart for its task.

A representation of a DT is given Figure 7.

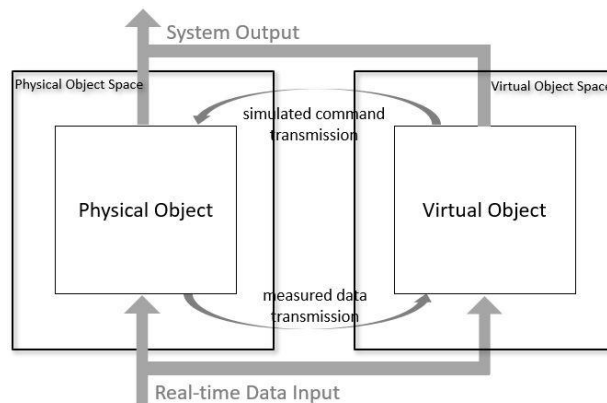


Figure 7: Representation of a Digital Twin

Due to their ability to control their real system, DTs can optimize tasks carried out by the real system. This optimized system control allows numerous applications in many different areas [31]. For example, DTs are used in industry for the optimization of manufacturing operations, allowing a reduction in production time and cost [32], [33], [34]. DTs can also be used in the management of networks [35], [36], such as urban transport networks or energy transport and storage networks.

V. CONCLUSION ON THE CLASSIFICATION OF DIGITAL TWINS

The work presented in this document has allowed the realization of a general classification of Digital Twins, based on the use of multiple existing classifications.

This classification makes it possible to directly identify, using the decision tree presented in Figure 3, the category of "Digital Twin" appearing in a scientific production. But this tool can also be used as a guide for choosing a digital object: depending on the objective, different categories of digital objects can be used or not. By identifying these categories, one can determine the criteria that the objects must fulfil to fulfil its desired role. This tool will be used in the continuation of this work, which will focus on a systematic literature review of DTs. It will make it possible to identify the use of Digital Twins as demonstration tools, and to establish a digital twin of co-design. In particular, an application of this tool will be realized within the framework of the INEDIT (open INnovation Ecosystems for Do It Together process) [37] project.

Some additional classification criteria established in the "Methods" section have been neglected in the realization of this tree and classification. As the DTs develop, it will be necessary to complete this classification considering these criteria, and other possible criteria discovered by then.

The classification carried out is also intended to allow, thereafter, the realization of a literature review of the Digital Twins and in a broader sense of digital objects. This review will then be able to focus in detail on the applications of the different categories of DTs, quickly presented in this document, or on the use of the different types of DTs as demonstration tools.

ACKNOWLEDGMENT

The work reported in this paper has been undertaken and funded as part of the H2020 INEDIT project (Project Grant Agreement N°869952).

REFERENCES

- [1] Q. Qi and F. Tao, "Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison," *IEEE Access*, vol. 6, no. January, pp. 3585–3593, 2018, doi: 10.1109/ACCESS.2018.2793265.
- [2] M. Grieves, "Digital Twin : Manufacturing Excellence through Virtual Factory Replication," *A Whitepaper*, no. November, p. 9, 2014, doi: 10.5281/zenodo.1493930.
- [3] F. Tao and Q. Qi, "New IT driven service-oriented smart manufacturing: Framework and characteristics," *IEEE Trans. Syst. Man, Cybern. Syst.*, vol. 49, no. 1, pp. 81–91, 2019, doi: 10.1109/TSMC.2017.2723764.
- [4] D. E. Jones, C. Snider, L. Kent, and B. Hicks, "Early stage digital twins for early stage engineering design," *Proc. Int. Conf. Eng. Des. ICED*, vol. 2019-Augus, no. August, pp. 2557–2566, 2019, doi: 10.1017/dsi.2019.262.
- [5] W. Polini and A. Corrado, "Digital twin of composite assembly manufacturing process," *Int. J. Prod. Res.*, vol. 58, no. 17, pp. 5238–5252, 2020, doi: 10.1080/00207543.2020.1714091.
- [6] 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.
- [7] C. Cimino, E. Negri, and L. Fumagalli, "Review of digital twin applications in manufacturing," *Comput. Ind.*, vol. 113, p. 103130, 2019, doi: 10.1016/j.compind.2019.103130.
- [8] 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, 2020, doi: 10.1007/s10916-020-01623-5.
- [9] W. Luo, T. Hu, Y. Ye, C. Zhang, and Y. Wei, "A hybrid predictive maintenance approach for CNC machine tool driven by Digital Twin," *Robot. Comput. Integr. Manuf.*, vol. 65, no. April, p. 101974, 2020, doi: 10.1016/j.rcim.2020.101974.
- [10] J. Lovell and J. Kluger, *Lost Moon: The Perilous Voyage of Apollo 13*, Houghton M. 1994.
- [11] M. Grieves, "Origins of the Digital Twin Concept," *Rev. Obstet. y Ginecol. Venez.*, vol. 23, no. August, pp. 889–896, 2016, doi: 10.13140/RG.2.2.26367.61609.
- [12] E. H. Glaessgen and D. S. Stargel, "The digital twin paradigm for future NASA and U.S. Air force vehicles," *Collect. Tech. Pap. - AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf.*, pp. 1–14, 2012, doi: 10.2514/6.2012-1818.
- [13] F. Tao, Q. Qi, L. Wang, and A. Y. C. Nee, "Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison," *Engineering*, vol. 5, no. 4, pp. 653–661, 2019, doi: 10.1016/j.eng.2019.01.014.
- [14] C. Boje, A. Guerriero, S. Kubicki, and Y. Rezgui, "Towards a semantic Construction Digital Twin: Directions for future research," *Autom. Constr.*, vol. 114, no. January, p. 103179, 2020, doi: 10.1016/j.autcon.2020.103179.
- [15] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, p. 1, 2019, doi: 10.1109/ACCESS.2019.2953499.
- [16] 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, no. 9–12, pp. 3563–3576, 2018, doi: 10.1007/s00170-017-0233-1.
- [17] A. Madni, C. Madni, and S. Lucero, "Leveraging Digital Twin Technology in Model-Based Systems Engineering," *Systems*, vol. 7, no. 1, p. 7, 2019, doi: 10.3390/systems7010007.
- [18] C. D. Wright and K. Case, "Emulation of modular manufacturing machines using CAD modelling," *Mechatronics*, vol. 4, no. 7, pp. 713–735, 1994, doi: 10.1016/0957-4158(94)90033-7.
- [19] E. Negri, L. Fumagalli, and M. Macchi, "A Review of the Roles of Digital Twin in CPS-based Production Systems," *Procedia Manuf.*, vol. 11, no. June, pp. 939–948, 2017, doi: 10.1016/j.promfg.2017.07.198.
- [20] J. Uhlenkamp, K. A. Hribernik, and S. Wellsandt, "A first systemization of their dimensions," no. October, 2019, doi: 10.1109/ICE.2019.8792579.

- [21] H. van der Valk, H. Haße, F. Möller, M. Arbter, J.-L. Henning, and B. Otto, "A Taxonomy of Digital Twins," *26th Am. Conf. Inf. Syst.*, no. August, pp. 1–10, 2020.
- [22] B. Tekinerdogan and C. Verdouw, "Systems Architecture Design Pattern Catalog for Developing Digital Twins Systems Architecture Design Pattern Catalog for Developing Digital Twins," no. September, 2020, doi: 10.3390/s20185103.
- [23] I. Mcgregor, "The Relationship between Simulation and Emulation," *Simul. Conf. 2002. Proc. Winter*, pp. 1683–1688, 2002.
- [24] B. Schleich, N. Anwer, L. Mathieu, and S. Wartzack, "Shaping the digital twin for design and production engineering," *CIRP Ann. - Manuf. Technol.*, vol. 66, no. 1, pp. 141–144, 2017, doi: 10.1016/j.cirp.2017.04.040.
- [25] E. Lampen, J. Teuber, F. Gaisbauer, T. Bär, T. Pfeiffer, and S. Wachsmuth, "Combining simulation and augmented reality methods for enhanced worker assistance in manual assembly," *Procedia CIRP*, vol. 81, pp. 588–659, 2019, doi: 10.1016/j.procir.2019.03.160.
- [26] È. Pairet, P. Ardón, X. Liu, J. Lopes, H. Hastie, and K. S. Lohan, "A Digital Twin for Human-Robot Interaction," *ACM/IEEE Int. Conf. Human-Robot Interact.*, vol. 2019-March, p. 372, 2019, doi: 10.1109/HRI.2019.8673015.
- [27] W. Li, M. Rentemeister, J. Badeda, D. Jöst, D. Schulte, and D. U. Sauer, "Digital twin for battery systems: Cloud battery management system with online state-of-charge and state-of-health estimation," *J. Energy Storage*, vol. 30, no. July, p. 101557, 2020, doi: 10.1016/j.est.2020.101557.
- [28] X. Li, J. Cao, Z. Liu, and X. Luo, "Sustainable business model based on digital twin platform network: The inspiration from haier's case study in China," *Sustain.*, vol. 12, no. 3, pp. 1–26, 2020, doi: 10.3390/su12030936.
- [29] M. Milton, C. O. De La, H. L. Ginn, and A. Benigni, "Controller-Embeddable Probabilistic Real-Time Digital Twins for Power Electronic Converter Diagnostics," *IEEE Trans. Power Electron.*, vol. 35, no. 9, pp. 9852–9866, 2020, doi: 10.1109/TPEL.2020.2971775.
- [30] D. Shanguan, L. Chen, and J. Ding, "A digital twin-based approach for the fault diagnosis and health monitoring of a complex satellite system," *Symmetry (Basel)*, vol. 12, no. 8, 2020, doi: 10.3390/SYM12081307.
- [31] R. Wagner, B. Schleich, B. Haefner, A. Kuhnle, S. Wartzack, and G. Lanza, "Challenges and potentials of digital twins and industry 4.0 in product design and production for high performance products," *Procedia CIRP*, vol. 84, no. January, pp. 88–93, 2019, doi: 10.1016/j.procir.2019.04.219.
- [32] R. S. Tabar, K. Warmefjord, R. Soderberg, and L. Lindkvist, "Efficient spot welding sequence optimization in a geometry assurance digital twin," *J. Mech. Des. Trans. ASME*, vol. 142, no. 10, 2020, doi: 10.1115/1.4046436.
- [33] C. Liu, P. Jiang, and W. Jiang, "Web-based digital twin modeling and remote control of cyber-physical production systems," *Robot. Comput. Integr. Manuf.*, vol. 64, no. January 2019, p. 101956, 2020, doi: 10.1016/j.rcim.2020.101956.
- [34] L. Monostori *et al.*, "Cyber-physical systems in manufacturing," *CIRP Ann.*, vol. 65, no. 2, pp. 621–641, 2016, doi: 10.1016/j.cirp.2016.06.005.
- [35] T. Greif, N. Stein, and C. M. Flath, "Peeking into the void: Digital twins for construction site logistics," *Comput. Ind.*, vol. 121, p. 103264, 2020, doi: 10.1016/j.compind.2020.103264.
- [36] K. T. Park, J. Lee, H. J. Kim, and S. Do Noh, "Digital twin-based cyber physical production system architectural framework for personalized production," *Int. J. Adv. Manuf. Technol.*, vol. 106, no. 5–6, pp. 1787–1810, 2020, doi: 10.1007/s00170-019-04653-7.
- [37] "INEDIT Project website." [Online]. Available: <https://www.inedit-project.eu/>.