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Typology as a Deployment Tool for Digital Twins: Application to Maintenance in Industry

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The digital twin is recognized as a key technology for the digital transition in the industry. Nevertheless, even if the digital twin is relatively a new concept, this term has been overused in the last years, and this without any unanimous definitions, models, or standards. Moreover, the main issue to be tackled when developing digital twins, is defining an architecture capable of efficiently connecting data and models. However, there is few generic architectures proposed in the literature, without any consensus. The aim here is to define a digital twin generic architecture suitable for all applications, and technology independent. This architecture is based on a typology composed of 10 criteria characterizing various aspects of the digital twin and its interactions with its physical, virtual and human environment. This architecture is part of a 5-step deployment methodology based on a 5C decomposition. At the end of the paper, we address as validation some specific test cases in the literature relating to maintenance applications .

Keywords: Digital Twin, Architecture, Maintenance, Smart Manufacturing.

1. Introduction

The digital twin is a relatively new technology, that is increasingly spreading in several fields, may it be the industry, healthcare, transportation, energy, building, etc. However, it is used as a fad because of the lack of a shared vision. We have noticed that sometimes it is even difficult to differentiate between a digital shadow and a true digital twin, as many tools developed on the basis of digital technologies are labelled as digital twins, without having clear classification criteria, defined models and architecture, and ultimately any deployment methodology. What is meant here by architecture is a formalization that defines the components of the TD and their nature, as well as their integration and organization, and the relationships between them.

As far as our exploration of the literature has brought us, few works deal with the standardization of digital twin concepts, the

formalization of its maturity process, or even the development of generic descriptive models or architectures. This lack of common vision around the development of this technology represents a real glass ceiling regarding its maturity and sustainability in the long term.

It is indeed at the level of this impasse that we position our work, and through this paper we propose building blocks for a descriptive typology, the first step in the development of our generic deployment methodology.

In the sequel, the paper is organized as follows: Firstly, we present an analysis of works dealing with the digital twin (DT) and its overuse. Secondly, we highlight the lack of standards at this level, hence the relevance of our contribution. In the following section, we present our generic methodology for DT deployment, before addressing a section dedicated to the typology of the digital twin. Thereafter, we test the robustness of our typology by applying it to

different works from the literature that focus on concrete applications of digital twins for maintenance. Finally, we end this paper by a conclusion and perspectives section.

1.1 Overexploitation of the Digital Twin

The digital twin is a dynamic virtual representation of an object, a process, or a service, which follows its operation throughout its lifecycle and reports on the different events, changes or actions that may occur over time. If the technology has seen the light of day in the aerospace industry in the 1960s, the actual term Digital Twin has been first defined in 2002 by Mickael Grieves. Over the years, digital twin has made its appearance in various fields such as industry, transportation, building, energy, etc. This has led to an increasing interest from companies and several scientific communities, and a rapid growth of this technology, but also to a certain anarchy in its development. Moreover, since the digital twin is a springboard for digital transformation, many companies overuse it in their race to business digitalization, and in most cases with an almost non-existent or very poorly defined architecture.

We can see in Fig. 1 that digital twin was at the top of the Gartner Hype Cycle for IT in 2019 (Gartner 2019), capitalizing on the trend surrounding this theme. However, this has fostered the anarchy of initiatives centered on this technology. As a result, we are now at the bottom of the curve in a "disillusionment" zone, where the implementation of robust models and architecture, as well as standardization and convention processes, would accelerate the transition to a period of technological maturity.

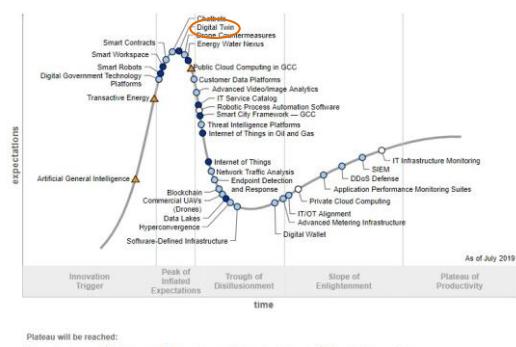


Fig. 1. Gartner's hype cycle (Gartner 2019)

During the hype phase, many DTs were developed in several fields, which required some investment in the use of proprietary software and close collaboration with business experts.

This indicates that it was mainly large companies that embarked on this innovation at the beginning and that the DT was not enough well formalized. It should also be noted, that in many cases the DTs were designed to meet a specific demand, where the lack of adaptability and modularity made it difficult to upgrade the digital twin when the physical asset evolves or a part of it may be changed. This, because of the lack of standard models or formalized methods.

1.2 Lack of standards

In (Aheleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. 2021), an approach for digital twin definition was proposed by putting forward an inclusion relation between different concepts. And according to which the digital twin is encompassed by the hybrid twin, which is itself encompassed by the cognitive twin. In this paper, the authors have also proposed a digital twin architecture using the RAMI 4.0 model described in 4 levels of integration: first as a "model"; then as a "digital shadow"; next as a "digital twin"; and finally, as a "digital twin predictive" (DTP) in its last level. But in most of the papers, the DT architecture is not addressed or poorly defined. However, there is no formalism that clearly defines a standard for building a digital twin that can meet different needs. We can also mention the recently introduced 23247 ISO standard that "*defines a framework to support the creation of digital twins of observable manufacturing elements*" (Standard ISO/DIS 23247 2021).

As mentioned earlier, most of the existing digital twins have been developed for a specific application and for a limited use which requires a very important technological expertise. This makes them a very complicated tool to implement for SMEs or companies with low digital maturity. However, all companies, no matter how limited their development is, may benefit from this new technology to initiate a digital transition that allows them to remain competitive.

Therefore, to make this technology accessible to all, including low digital maturity companies,

we propose the development of a generic deployment methodology based on a 5C decomposition, and where the first level stipulates the development of a generic architecture based in the first place on a digital twin typology.

2. Deployment method

As seen before, digital twin is a dynamic representation of an object, a process or a service. It is used for applications in industry, such as: factory construction, training, scheduling and organization, production control or maintenance. To set up this dynamic representation, we need data and models. Sensors and IoT are used to capture data (physical system parameters, events, environmental sensing, etc.) and combine it with different models (such as geometric, behavioral, physical). Therefore, the digital twin is then characterized by a continuous digital thread between real and virtual spaces, at an adapted synchronization rate that can be close to real time or not (ISO 23247). Hence, thanks to a simple Digital Twin, one can perform basic applications, and then with its evolution throughout the maturity levels (Fig. 4), it can be used for more advanced usages to conceptualize, analyze, simulate, compare, optimize, collaborate, and provide decision support.

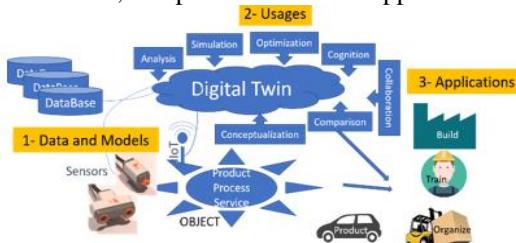


Fig. 2. Generic definition of DT (Traoré, M. K. 2021)

Ultimately, the DT has the ability to manage relevant, reliable and secure data with appropriate accuracy, as well as to increment, enrich and also validate models both online and offline, and this, according to its maturity level. Moreover, the DT may have partial or total control of the physical object via a formalized decision loop, hence the need to clearly formalize the allocation of decision making between the DT and the human agent. Since advanced DT are now provided with cognitive

capabilities based on artificial intelligence algorithms for decision support.

Basically, this shows us that the digital twin must be apprehended according to several levels of abstraction, starting with the criteria and needs (strategic/tactical/operational), the interactions with the human agent, as well as the technical characteristics.

To define a deployment method, we started from the 5C Cyber Physical System (CPS) implementation architecture (Lee, J., Bagheri, B., & Kao, H. A. 2015). It proposes a 5-level CPS pyramid and offers a step-by-step guide for developing and deploying a CPS for manufacturing applications. At the top of the pyramid, we find the Configuration level, followed by the Cognitive one. These two layers are technology independent (see Fig. 3), therefore, a generic development approach can be considered at an early stage. We propose for the first level, the setting up of a typology for a "Generic architecture", while for the cognitive level it will be a "Decision architecture" using a CWA (Cognitive Work Analysis) method (See Fig. 3). The third part concerns the cyber, conversion, and connection aspects, which will then allow us to set up a more specific architecture for the digital twin to be developed and implies iterative refinement including technological choices

For this paper, we will focus on the first level of the pyramid (Configuration), and more precisely in establishing a generic architecture of the digital twin. For this purpose, we present a typology of the digital twin as a first building block. The latter is necessary to identify the characteristics of the DT to be developed according to the real needs of the application. This typology offers the designer a basis for the development of an initial sketch to contain the decision architecture and the specific technical architecture in the dedicated development steps.

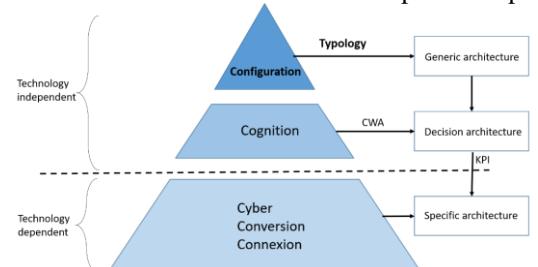


Fig. 3. 5C CPS Architecture (Julien & Martin 2022)

3. Typology

As outlined before, to put in place our generic architecture, we first need to define a typology for digital twin (Julien, N., & Martin, E. 2022). This latter is composed of 10 criteria, that define as comprehensively as possible the DT and its interactions.

3.1. DT Entity

The ISO/DIS 23247 standard defines the entity as “thing (physical or non-physical) having a distinct existence” together with the observable manufacturing element (OME) as an “*item that as an observable physical presence or operation in manufacturing*”. OMEs include equipment, material, personnel, process, facility, environment, product and supporting document. However, as our typology is not restricted to manufacturing applications, we choose to qualify this object as DT entity.

3.2. Type

There are 3 different types of DT, as defined by Grieves in (Grieves, M., & Vickers, J. 2017) : DT Prototype; DT Instance; DT aggregate. The prototype describes the prototypical artifact who is mainly used in the design phase. The instance describes the individual object related to the production phase. The aggregate is composed of all DT instances for the same entity used in exploitation or maintenance phase.

3.3. Level

A DT level is defined with 4 different levels:

- Component, elementary level, a part of equipment or system
- Equipment, composed of components, a part of system or system of systems
- System, composed of equipment, can be a part of system of system
- System of system, composed of systems

3.4. Maturity

To distinguish between the digital shadow, the digital mirror, and the digital twin, we have classified the digital representation by its maturity as shown in Fig 4. The digital mirror is a set of mathematical models representing the object and its behavior like 3D simulation with no direct communication between physical and digital entity.

The digital shadow represents all the numerical activity of the DT entity and provides its dynamic footprint. In the final step, both physical and virtual entity are merged in Cyber-Physical System (CPS). There is first a communication between physical object to the DT but also with a partial or total control feedback from the DT to the object, this is a control DT. It can evolve if adding predictive ability in Cognitive DT. Then, with more decision and control it becomes Collaborative DT.

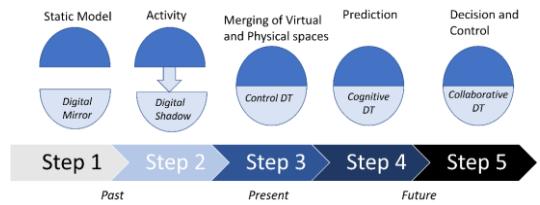


Fig. 4. Numerical maturity (Julien & Martin 2021)

3.5. Topology

It qualifies the connection between the observable manufacturing asset and the digital twin. From (Schroeder, G. N., Steinmetz, C., Rodrigues, R. N., Rettberg, A., & Pereira, C. E. 2021), we have defined 4 topologies which are:

- Disconnected, there is no direct connection between the DT and its entity, the information comes from external components or users.
- Connected, the DT is directly connected to its entity
- Embedded, the DT is included in its entity, the communication may be facilitated but the computational capabilities will be limited.
- Combined, the DT is composed of two or more of the topologies described above.

3.6. Synchronization

In many publications the digital twin is assumed to be real-time synchronized in real time, but We decided to enlarge this vision by including synchronous and asynchronous communication. Synchronous synchronization can be done in real time, near real time or periodically. Asynchronous synchronization can be event-based, conditional or on-demand.

3.7. Decision loop

We have extended the works in (Traoré, M. K. 2021) by proposing 3 different types. The first type is the open loop, the human receives the information and decides.

The second type is the closed loop, the human just receives information, and the DT is autonomous regarding the decision making. The third type is the mixed loop, the human receives the information but can also decide just like the DT; in this case, the assignment between human and system decision must be clearly formalized.

3.8. Users

According to (Standard ISO/DIS 23247 2021), appropriate interfaces must be provided to different DT users who may be the human, the device, the application or another DT.

3.9. Usages

The digital twin can be used to analyze, to simulate, to optimize, to predict, to compare, to collaborate and to conceptualize; details can be found in (Julien, N., & Martin, E. 2021). Different usages can be combined to respond to the application.

3.10. Applications

Applications consist in the final service delivered by the DT to the users. In (Standard ISO/DIS 23247 2021) the digital twin can be used for real time control, off-line analytics, predictive maintenance, health check, engineering design.

4. Comparison to literature

In their quest to conceptualize and formalize the digital twin, many researchers in the community have tried to propose models that faithfully represent the digital twin. One of the models that seems to be the most robust is the one proposed by (Tao, F., Zhang, M., & Nee, A. Y. C. 2019), namely the five-dimension DT model (Fig. 5). In this representation, five main elements are considered: (1) Physical entity; (2) Virtual entity; (3) Data; (4) Services; and (5) Interactions. This model has demonstrated a very good robustness, both by the adherence of the scientific community and by its confrontation with several real case studies.

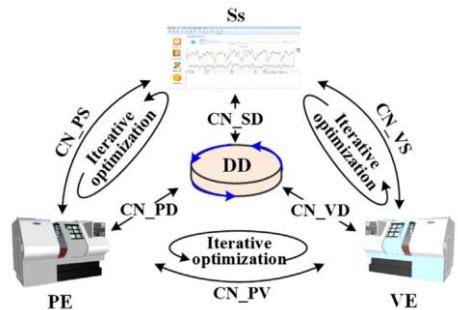


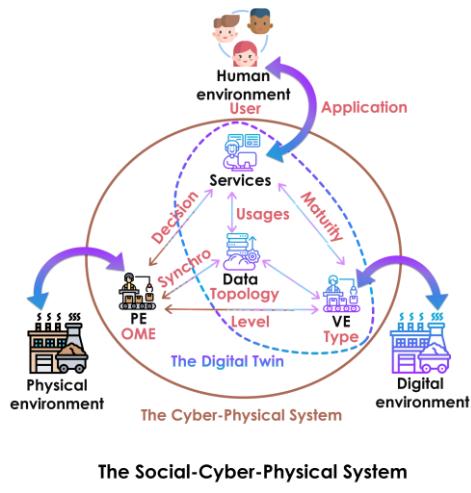
Fig. 5. The 5-Dimensions Digital Twin model (Tao et. al., 2019)

This reinforced our choice to take this model as a reference to add other elements which seems to us essential as for the formal definition of the digital twin, and then to see how far this model and the proposed typology are consistent with each other (Fig. 6). The additional dimensions we have considered are related to the environment in which the digital twin evolves, in other words, to the interactions it can have with its surroundings (physical environment, virtual environment, and human environment).

According to the 5D model, one of the main dimensions is the "Virtual Element", because it is the one that encompasses the various models that mimic the behavior of the physical element (Geometry model; Physics model; Behavior model; Rule model). These two entities (Physical Element and Virtual Element) will interact with each other via data exchanges (Connections), these data (the data element) can be multitemporal, multidimensional, multi-sources and heterogeneous. Thanks to this interaction, the DT can then offer different services (the services elements) to its users.

Firstly, it is important to know that the digital twin can be a collaborative tool, which means that this latter interact with its environment. Therefore, we highlight the presence of three distinct environments of its ecosystem which allows him to be part of a Social Cyber-Physical System. Secondly, we believe that the "Physical Element" of the 5D model should not be part of the DT model, since this latter is considered to be the "Physical Twin" or the "Physical counterpart" of the Digital Twin. Finally, we complement this model with all the elements of our typology, which fit perfectly into this representation in Fig. 6, illustrating the coherence and complementarity of these two

formalizations. The objective of this, is to ensure that the proposed typology allows the designer to identify any technical specificities (or capabilities) that the DT must possess in order to satisfy the expected needs, while not omitting any of its fundamental elements (the main 5 dimensions of the 5D model).



The Social-Cyber-Physical System

Fig. 6. Extended 5D model

5. Maintenance applications

To validate our typology, we decided to confront it with different works dealing with the digital twin for maintenance.

To do so, we conducted a survey of papers dealing with this subject, and then selected those that best described the digital twins they had developed.

Moreover, for those who presented DT architectures, they were in most cases too dependent on the technology and dedicated to the problem being addressed to our knowledge no generic architecture for the digital twin has been presented.

For this study we have limited the scope to choose only 4 articles that cover several aspects of maintenance and are different enough to validate our architecture (Table 1).

The first paper (Centomo, S., Dall’Ora, N., & Fummi, F. 2020) deals with predictive maintenance.

A general approach is based on the EDA (Electronic Design Automation) approach, which allows to set up a maintenance strategy by analyzing the data recovered via different

sensors. The study described in this article is the analysis of vibrations according to the size of the machine.

This health state detection is an important information that will be used to reflect the health state detected in the model allowing to obtain the digital twin of the equipment.

Via this study we have applied our DT typology, as far as the entity concerned is of course the machines. We have here an instance twin, the level of this twin is rather centered on the equipment. At the level of maturity, we have a cognitive system. For the topology level, we have a system that is disconnected because the vibration data is recovered and processed much later for analysis. As for the synchronization, it is not clearly defined but it is assumed that it is the same as the synchronization rate of the sensors.

We are here in an open loop because we only recover the health status of an equipment, and it is up to the human to take a decision. Concerning the users of this twin, we suppose that it could concern the managers, or the operators on the production line. In terms of use, we are sure of the prediction, to make a health diagnosis and to enable predictive maintenance.

The second paper (Barthelmey, A., Lee, E., Hana, R., & Deuse, J. 2019) addresses predictive maintenance in a so-called flexible system. This study presents the effects of flexibility on the predictive maintenance strategy. The application proposed here is based on a reference plant which is put in the form of a flexible hybrid assembly system.

Here we have the digital twin of each component which is stored as an AML file. In this article we have as entity a hybrid assembly system, this digital twin is a prototype.

Concerning the level, we are here in a system, the digital twin takes all the components present in the assembly system.

The maturity of this twin is rather collaborative because the twin includes HMI (Human machine interface) that includes the important elements present in the database to help the maintenance technician to create labels that will describe the problems concerned.

To have a flexible system, this DT must be connected. Regarding the synchronization we have found no information, nevertheless we

assume that it is linked to the same frequency as the sensors present on the assembly system.

Here again we are in an open loop, the twin only sends information back to the human who decides at his turn. The users of this platform will be the maintenance technicians and the manager.

This twin is used for prediction or optimization, the application is health diagnosis of the different components of the system for predictive maintenance.

The third paper (Xu, Y., Sun, Y., Liu, X., & Zheng, Y. 2019) deals with failure diagnostics using deep transfer learning. This paper presents a method of failure diagnosis assisted by DT using deep transfer learning, these diagnostics are performed during the development and maintenance phase.

This study is performed on a physical workshop which is then digitized via a model for the digital twin. So, for the entity part we have a workshop, the digital twin is an instance. Compared to the level, we are more towards the system. This twin is a cognitive twin that must be connected in real time with the physical workshop. Concerning the synchronization, we take the same as the frequency of the PLC.

We are always on an open decision loop because the digital twin does not act alone and only reports to the human. Maintenance engineers will interact with this DT. For the

uses, we are still with prediction as well as diagnosis with the aim of setting up a diagnosis of the health state for the workshop.

Finally, the last paper (Mi, S., Feng, Y., Zheng, H., Wang, Y., Gao, Y., & Tan, J. 2021) deals with predictive maintenance with the integration of decision making driven by the digital twin. The digital twin is integrated here to improve the accuracy of the diagnosis, the prediction of defects as well as to support the development of a more reliable maintenance plan. The OME part here is quite generic, this part concerns the site environment (workshop, production line, etc.). We are here in a system rather aggregated; the twin is part of a system which groups several systems. The level is then rather a system. This twin is cognitive and must be continuously connected with the production environment of the factory to function.

Concerning the synchronization, it will have to respect the frequency of the sensors or the PLC (Programmable Logic Controller) which could be present in a production line. Regarding the decision loop, we are in a mixed loop, the twin takes some minor decisions, especially regarding the maintenance plan, but the human also decides in this system. The users will rather be maintenance engineers. The uses of this twin are mainly prediction, and it is used in a case of organization and optimization of the maintenance plan.

Table 1. Typology validation

Papers Typology criteria	<i>"The Design of a Digital-Twin for Predictive Maintenance"</i> (Centomo et al., 2020)	<i>"Dynamic digital twin for predictive maintenance in flexible production systems"</i> (Barthelmeij et al., 2019)	<i>"A digital-twin-assisted fault diagnosis using deep transfer learning"</i> (Xu et al., 2019)	<i>"Prediction maintenance integrated decision-making approach supported by digital twin-driven cooperative awareness and interconnection framework"</i> (Mi et al., 2021)
Entity	Machines	Hybrid assembly system	Physical shop floor	Site environment/maintenance resource
Type	Instance	Prototype	Instance	Aggregate
Level	Equipment	System	System	System
Maturity	Cognitive	Collaborative	Cognitive	Cognitive
Topology	Connected	Connected	Connected	Connected
Synchronization	Periodic	Near real time	Near real time	Near real time
Decision loop	Open	Open	Open	Mixed loop
User	Manager/operator	Maintenance technician	Maintenance engineer	Manager/Maintenance engineer
Usage	Analysis/Cognition	Cognition/Collaboration	Cognition/Analysis	Analysis/Cognition

Application	Health diagnosis & predictive maintenance	Diagnosis/Maintenance	Health diagnosis	Organization of the maintenance plan
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6. Conclusion

Throughout this work, we are interested in the first step of our strategy for the development of a generic deployment methodology for the digital twin.

We first presented a typology for the digital twin, through which we aspire to set up an exhaustive generic architecture of all non-technology dependent features. Afterwards, we contrasted the latter with the 5D model of the DT to see if it is generic enough and comprehensive. In the second part, we conducted a literature review to identify papers dealing with the digital twin for maintenance. Subsequently, we also exposed our typology to these use cases to validate its robustness. It has demonstrated a very good adequacy and a certain coherence with respect to the studied cases, while waiting to validate it with other works dealing with other concerns.

Future work on the Cognition part with the deployment of CWA (Cognitive Work Analysis) and the study of the data level architecture (respectively part 2 and 3 of our 5C CPS architecture) will allow us to refine and develop our generic methodology to provide a formalized DT deployment methodology.

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