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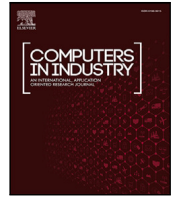
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A Digital Twin use cases classification and definition framework based on Industrial feedback

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ABSTRACT

The Digital Twin paradigm is a very promising technology that can be applied to various fields and applications. However, it lacks a unifying framework for classifying and defining use cases. The goal of this paper is to address the identified gap. Using a field study and a bottom-up approach, it aims to categorize the various uses of the industrial Digital Twin to help formalize the concept and rationalize its adoption by a range of industrial sectors. The study is based on an iterative process of collecting use cases from a wide variety of verticals, applying grounded theory principles. The usage scenarios were extracted, synthesized, grouped and abstracted to develop an actionable use cases classification framework. This article presents the resulting taxonomy and illustrates it by detailing real industrial use cases, including their value proposition and application areas. This collection, classification and analysis of use cases led to a study of the common aspects proposed in academic and industrial definitions of the Digital Twin. The goal was to combine and generalize these aspects into a pragmatic and unifying definition, on which the Alliance for Industry of the Future (AIF) committee has converged. The main contributions of this work include proposing, from a joint industrial and academic perspective, (i) the first domain-independent and industry-focused systematic collection of Digital Twin use cases, (ii) a comprehensive framework for analyzing and classifying Digital Twin use cases and their requirements, and (iii) a consensual general definition of the industrial Digital Twin to contribute to the structuring and standardization of this very active ecosystem.

1. Introduction

Following pioneers such as NASA (Glaessgen and Stargel, 2012), the *Digital Twin* concept has been deployed and continues to expand in the manufacturing industry and many other domains like smart building, smart city, smart mobility, transport and logistics, road and rail networks, port and airport, energy, utilities, and waste management. The concept of *Digital Twin* is also emerging in the field of science and technology, e.g., the *Digital Twin* of the care pathway in health, human heart in medicine, ocean in biology, and networks in telecommunications.

A *Digital Twin* maintains a continuously up-to-date digital representation of the physical world entities of interest, as a basis for holistic

insights for optimal decision-making. *Digital Twins* use historical and live data to represent the past and present, to simulate or even predict possible futures. Typical applications of *Digital Twins* range from basic scanning and visualization (e.g., virtual and augmented reality), to more advanced usages such as simulation, prediction or orchestration, management, and control (Aheleroff et al., 2021).

In manufacturing, the *Digital Twins* have been focusing both on the product and the production process. The former concentrates on the product's life cycle, from concept generation to recycling or disposal (Tao et al., 2018a; Jagusch et al., 2021), while the latter studies the key technologies that can optimize manufacturing (Tao and Zhang, 2017). The usage of *Digital Twin* is closely related to traceability of

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products to save money and time. One of the main objectives is also to give real-time information on the performance of manufacturing resources, to anticipate issues via knowledge-based algorithms. In addition, the capacity to perform real-time simulations is of great interest, with *Digital Twin* being used to test products and systems. Apart from these Industry 4.0 considerations, the *Digital Twin* is also seen as an enabling technology that facilitates human-centricity, sustainability, and resilience in line with Industry 5.0 goals (Xu et al., 2021; Aheleroff et al., 2022).

According to Deloitte (Parrott and Warshaw, 2017), *Digital Twins* can profoundly enhance an enterprise's ability to make proactive, data-driven decisions, increase efficiency, and avoid potential issues. They can also make it possible to "experiment with the future" by exploring what-if scenarios safely and economically. Gartner positioned the *Digital Twin* as a "transformational" technology, expected to reach maturity in 5 to 10 years from 2018 (Halpern, 2022; Walker, 2018). Current technology penetration is attributed to 1%–5% of businesses and organizations that stand to benefit (Velosa and Middleton, 2022). The proliferation of use cases is expected due to the increasing adoption of this technology and its potential applications in all industrial sectors.

However, although the research and number of publications on *Digital Twins* are rapidly increasing, the concept is not yet unanimously understood in the same way (Perno et al., 2022). There exist many definitions of *Digital Twin* in the literature, which have been identified and discussed in a range of papers and surveys, but there is currently no universally agreed-upon definition. One explanation could be that the *Digital Twin* is a term that was widely used by industry before it was standardized or well-defined by the community.

When several different industries use the same term, which is not formally defined, they tend to appropriate it according to their needs. Slowly, as the term becomes popular, everyone starts using it for marketing purposes as well. In the process, these stakeholders begin to expand the definition of the term to include their product.

The variety of definitions results in discrepancies between *Digital Twins* projects and slows down the penetration of the technology. Barriers to the successful implementation and adoption of *Digital Twins* include not only the lack of consensus in the definition, but also explicit purpose, defined scope of application, the multiplicity of capabilities referred to as *Digital Twin* (Boyes and Watson, 2022), cost, and complexity of development, among other obstacles. As stated by Sharma et al. (2022): "Having a formal definition would help clarify the concept and progress towards a universally accepted definition". This way, industrial practitioners and academics will understand exactly what is meant when this key term is used so misinterpretation is avoided (Fuller et al., 2020).

The objective of this article is to formalize the usages and the concept of *Digital Twin* with the aim of rationalizing its adoption by a range of industrial sectors. It reflects the work done by the *Digital Twin* Technical Committee (Comité Technique Jumeau Numérique, CT-JN) of the French Alliance for Industry of the Future — Alliance Industrie du Futur (AIF¹), gathering a wide variety of industry verticals. This article presents the result of this qualitative study.

The CT-JN has adopted a bottom-up approach to fill the gap between practice and theory. A range of operational use cases have been collected in the different industrial domains represented in the consortium. The usage scenarios have then been synthesized, grouped, and abstracted to articulate an actionable framework.

The resulting taxonomy emphasizes the potential of various use cases to simplify the design of new instances, serving as a guide for requirements specification and existing building blocks reuse.

In order to contribute to the formalization of a domain-independent *Digital Twin* concept, the common attributes proposed in academic and industrial definitions, and how these characteristics map the identified

use case types, have been analyzed. This enabled the combination and generalization of these attributes into a pragmatic definition, on which the AIF committee has converged.

The main contributions of this article include proposing, from a joint industrial and academic perspective:

1. the first domain-independent and industry-focused systematic collection of use cases of the *Digital Twin* technology,
2. a comprehensive framework for analyzing and classifying the industrial *Digital Twin* use cases and their requirements, for strengthening the adoption process,
3. a consensual general definition of the industrial *Digital Twin* (a.k.a *AIF definition*) which fits a lot of industrial perspectives, to contribute to the structuring and standardization of this very active ecosystem.

This article is organized as follows. Section 2 presents the related works in terms of literature reviews of *Digital Twin* usage typologies. Section 3 introduces the methodology adopted by the AIF CT-JN and Section 4 summarizes the Scoping results. Section 5 presents a classification of *Digital Twin* use case types extracted from a large range of industrial interviews and feedback. In Section 6, several illustrative use cases are presented and analyzed with this classification framework. Section 7 develops the common characteristics raised in the *Digital Twin* definitions and the *AIF definition*, resulting from the combined literature and field research analysis.

2. Related work

The concept of *Digital Twin* in scientific literature can be traced back to the work of NASA (Glaessgen and Stargel, 2012), where they define it as an integrated multi-physics, multi-scale, probabilistic simulation of a complex system that uses the best available models and data to mirror the life of its corresponding twin. Since then, hundreds of research articles have been published over the years focusing on different aspects of the *Digital Twin* paradigm and presenting a range of applications and benefits (Botín-Sanabria et al., 2022). *Digital Twin* use cases are found in many areas, mainly in smart cities, manufacturing, and healthcare as noted by Fuller et al. (2020), but also in transport, autonomous mobility, energy, smart buildings, smart homes, business management, etc. In the following, we restrict our focus on general literature reviews of *Digital Twin* use cases and try to reason on their classification criteria.

Lasse Lueth (Lueth, 2020) classified *Digital Twin* use cases along 3 dominant dimensions: (i) *the high-level categories of usage* (named here **criteria 1**); (ii) *the hierarchical level (criteria 2)* of the physical entity the *Digital Twin* is applied to (from component to multi-systems); (iii) *the lifecycle phase (criteria 3)* in which the *Digital Twin* is used (from design to decommission). Seven most common usages are identified: *digitize, visualize, simulate, emulate, extract model, orchestrate, predict*, which makes 252 potential use cases defined by combining the seven most common uses, six hierarchical levels, and six phases listed. These theoretical use cases are represented along these 3 dimensions within a cube model. The report gives some illustrative examples, others can be found in related works as detailed below.

According to Negri et al. (2017), the main uses of *Digital Twins* can be classified in three *high-level categories of usage (criteria 1)*: (i) to support health analyses for improved maintenance and planning, (ii) digital mirroring, and (iii) to support decision-making.

A framework to review how *Digital Twin* technologies are integrated into the smart manufacturing system design (SMSD) is proposed in Leng et al. (2021). This framework is based on Function-Structure-Behavior-Control-Intelligence-Performance (FSBCIP) aspects which correspond to the major steps of the SMS (smart manufacturing system) design process. These steps can be enhanced by the *Digital Twin* technologies thanks to five corresponding model types. The authors propose a classification of 33 *Digital Twin* use cases in SMS design based on the level in the manufacturing system: (1) machine tool/center, (2) manufacturing

¹ AIF: <http://www.industrie-dufutur.org/>

units, (3) workshop, (4) factory, (5) distributed system. This classification is very specialized to the smart manufacturing domain and is based on a detailed categorization of the *hierarchical level* (**criteria 2**) with 5 levels.

Melesse et al. (2020) focus on a systematic review of the state of the art related to the role of *Digital Twins* in the areas of production, predictive maintenance, and after-sale services. This review examines the use cases based on their *life cycle stage* (**criteria 3**).

Al-Sehrawy et al. (2021) propose an interesting multi-dimensional classification framework of *Digital Twin* use cases for urban planning and city infrastructure management. They take into account key features such as application area (which is similar to **criteria 1**), federation or system of systems (similar to **criteria 2**), life cycle stage (**criteria 3**) but also other dimensions such as actors, output spatial scale and resolution, layering, and output temporality. The *user or actor type* appears as an important generic dimension (**criteria 4**) for use case classification while the last three other dimensions seem very specific to the urban domain or related to the implementation of the *Digital Twin*. They are less significant for a conceptual and general taxonomy related to industry applications.

The *industrial domain* (smart building, manufacturing, transportation, energy...) (**criteria 5**), is often an implicit criterion for *Digital Twin* use cases categorization (Attaran and Celik, 2023).

Similarly, Lo et al. (2021) investigate the usage of *Digital Twin* in New Product Design, and provide a classification based on *industrial domains* (**criteria 5**), such as Manufacturing, Building, Smart City, Aerospace, Automotive, Energy, Medical and Healthcare, ICT and Education. In each of them, they observe specific uses of the *Digital Twin* technology. For example, in Aerospace, *Digital Twin* is used for diagnostics and prognostics of aircraft health, virtual testing or simulation, while in Automotive, it is used for vehicle health monitoring and prognosis, digital testing and verification (e.g., crash test), driver intention prediction and automatic driving monitoring. This “use” criterion is a refinement of *high-level categories of usage* (**criteria 1**), mapped to the New Product Design across industrial domains. Concerning the *phases* (**criteria 3**), the results of their review show that the production phase is the most important one with 63% of the cases, design 16.1%, logistics 9.4%, use 5.9% and end of life 4.9%. An interesting result is also that *Digital Twin* benefits from the succession of product generations. In the early days of a product, there is not much data about its use for example, but as it is sold and monitored the database increases, making the *Digital Twin*-based decisions stronger.

In Pystina et al. (2022), Pystina et al. classify existing *Digital Twin* applications by physical twin types *hierarchical levels* (**criteria 2**) for *Digital Twin* classification based on the existing use cases in manufacturing. They have chosen other criteria such as approaches and architectures, features, deployment strategies, structure approaches, and intelligence. We note here that the implementation aspects, used as classification criteria, are tightly mixed with conceptual ones, which blurs the distinction between *why* and *how*.

Shao (2021) present recent standardization efforts of *Digital Twin* definition and use cases classification. In particular, International Organization for Standardization (ISO)/Draft International Standard (DIS) 23247, *Digital Twin Framework for Manufacturing*, is introduced. ISO 23247-1 provides general principles and requirements for developing *Digital Twins* in manufacturing. It defines terminologies used by the standards. For example, physical systems are defined as Observable Manufacturing Elements (OMEs), which need to be modeled using available standards and technologies based on the use case's specific scope and context. Synchronization between a *Digital Twin* and its OME enables the *Digital Twin* to be kept current with its OME using communication protocols at a rate defined by the application. This framework is not open and is specialized to manufacturing. Shao (2021) explore in-depth scenarios of three digital-twin use cases in manufacturing and present the procedures of implementing such use cases according to the ISO/DIS 23247 framework.

The methodologies adopted by the researchers to categorize *Digital Twin* use cases vary, most of them being literature reviews. Al-Sehrawy et al. develop an original and inspiring framework mixing theory and practice (Al-Sehrawy et al., 2021). It is divided into three parts: (a) terminology standardization to avoid any confusion or ambiguities; (b) detailed documentation of *Digital Twin* user interactions to uncover the ‘know-how’; and (c) a multi-dimensional classification system to better define and specify any *Digital Twin* use case. Their work is specialized for urban planning and city infrastructure management but can be easily adapted to other fields of applications.

In summary, researchers and practitioners have articulated a range of *Digital Twin* use cases in all industrial sectors. It can be observed that the literature proposes a heterogeneous set of criteria, from general to very technical, to classify industrial *Digital Twin* use cases. The key general criteria that come out are: **criteria 1: high-level categories of usage**; **criteria 2: the physical twin hierarchical level**; **criteria 3: the phase of life cycle**; **criteria 4: the actors**; **criteria 5: the industrial domain**. However, there is no open and unifying framework that gathers all these criteria to aid in the process of categorizing the various use cases across the different industrial sectors. This is the goal of our proposal to consolidate this.

3. Methodology

Under the umbrella of the AIF, about 15 members from French industries, research institutions, and universities came together to address common challenges and drive collective progress in *Digital Twins* for a wide variety of industry verticals. For formalizing the concept and usage of *Digital Twin*, the CT-JN has followed a bottom-up approach and qualitative methodology, which led to a classification framework for the *Digital Twin* use case types and a pragmatic definition that could embrace the various implementations and usages.

A structured and inclusive process has been adopted to encourage open dialogue, knowledge sharing, and problem-solving. The committee identified key industry issues for working with *Digital Twin* technologies across multiple industry domains. One of the key issues was the top-down approach to defining *Digital Twins*, where the definition of the term “*Digital Twin*” could not represent the common understanding of the underlying concepts for different industry partners. The technical committee opted for a qualitative research methodology with a bottom-up approach and grounded theory (Chun Tie et al., 2019) as the guiding framework. The qualitative approach allows for exploring the topic comprehensively, while the bottom-up approach lets themes and patterns emerge directly from the data. Grounded theory ensures that conclusions are based on empirical evidence rather than preconceived notions.

As illustrated in Fig. 1, the process began with an initial scoping phase (step 1) in which the committee defined the objectives, scope, and desired outcomes of the effort as detailed in Section 4. Then, the CT-JN conducted an integrative review of the existing literature related to *Digital Twins*. This helped to gain insight into different perspectives and approaches while identifying commonalities and differences. The results of this review are synthesized in Section 7.1.

Next, the CT-JN collected the use cases of *Digital Twins* in a variety of industry sectors (step 2). All this data on definitions and use cases was organized and referenced according to its sources. The committee then engaged in a series of structured discussions, workshops, and brainstorming sessions, to compare the theoretical definitions with actual industrial implementations from different domains (step 3).

In this process, the challenges and opportunities associated with *Digital Twins* were explored from multiple perspectives, i.e., product, process, resource, user, and application goals. This analysis helped to classify the industrial use cases based on the aspects extracted (step 4) as described in Section 5 and illustrated in Section 6.

The features that emerged from these categorizations motivated the CT-JN to formulate a draft definition that could represent the

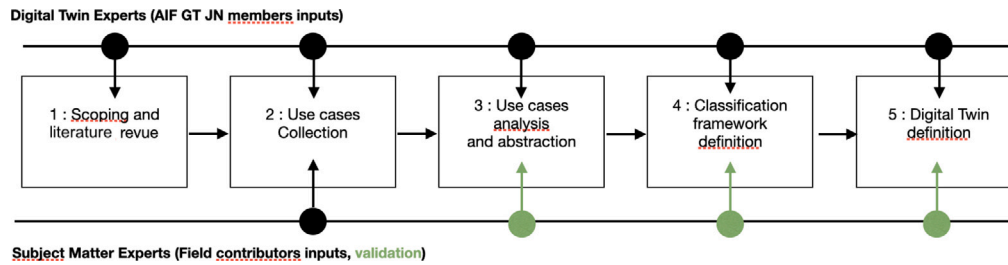


Fig. 1. Overview of the adopted methodology. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

common understanding of the key characteristics of a *Digital Twin* (step 5) as developed in Section 7. This definition underwent iterative refinement and validation within the committee to ensure that it captured the essential characteristics and principles of *Digital Twins* while accommodating diverse perspectives.

Finally, the standard definition of *Digital Twin* was finalized taking into account the input and consensus of all participants. The goal of the resulting definition is to serve as a common reference point for organizations and professionals working with *Digital Twins*, enabling clearer communication, interoperability, and alignment in the field.

To increase the rigor and credibility of the process, the *CT-JN* occasionally sought feedback from relevant stakeholders outside the core group (green arrows in Fig. 1). This external input helped validate the proposed classification and definition, ensuring their relevance and applicability across industries and contexts.

It is important to note, however, that the chosen methodology has its limitations. One limitation of an integrative literature review is that it may not be exhaustive, potentially resulting in missing conference articles and gaps in the available literature.

4. Scoping results

In the first step of the research, the objectives, scope, and desired outcomes of the effort were defined. This scoping identified the following topics:

1. How can a Digital Twin be differentiated from previous modeling approaches?
2. Is there a definition that can distinguish a Digital Twin from a non-Digital Twin?
3. What is the best way to describe a Digital Twin use case?
4. Can the variety of deployed use cases be classified?

In order to address these questions, the *CT-JN* decided to conduct a comprehensive review of the existing literature and research papers related to *Digital Twin* definitions. Since the *Digital Twin* concept has been studied, used, and defined within a wide range of disciplines, it soon became apparent that a full systematic review was not possible. An integrative review approach (Snyder, 2019) combined with a field study was preferred for developing a pragmatic framework that can distinguish a *Digital Twin* from a non-Digital Twin.

4.1. Integrative literature review

The literature review focused on the problem description and content of interest, leading to the following research questions:

- RQ1: How have the *Digital Twins* been defined in different fields over the years?
- RQ2: What are the key characteristics of the existing definitions of *Digital Twins*?
- RQ3: Which characteristics can differentiate *Digital Twins* from other modeling approaches?

In order to ensure that the literature review corresponds to our joint academic and industrial perspective, searches were conducted on multidisciplinary databases (Scopus, Google Scholar, IEEE Digital Library) over the last ten years. An exploration of frequently cited references from reviewed studies as well as “grey” literature on the topic, such as industrial white papers or analyst reports, oriented the survey. Section 7.1 presents the analysis and results of this literature review.

4.2. Use cases collection, analysis and classification

To optimally perform the field study, based on a use case collection, it was decided to:

1. Limit the scope to the industrial use cases, including both the products & processes.
2. Characterize this scope using a list of industrial sectors defined in a European Commission document titled ‘Classification of products by activity in the European Community’ (European Commission, 2023).
3. Establish a uniform structure for the collection of use cases.

The following information from the different industrial representatives was collected for each use case:

- What is being modeled/twinned by the *Digital Twin*?
- Who uses it?
- What is it composed of?
- What is the added value?
- Why is it developed?
- What KPIs does it improve?
- Real-life implementations and demonstrator examples

5. Digital twin use cases classification

In this section, we present the field study that led to a *Digital Twin* use cases classification framework proposal.

5.1. Use cases data collection and analysis

Following the approach defined in step 1, about fifty (50) interviews have been conducted in a dozen industrial sectors between 2021–2022.

Twenty-three (23) industrial use case types have been extracted from the analysis of these interviews. The first outcome is the revelation that the *Digital Twin* technology is considered as relevant and often already applied in all the selected industrial sectors. Secondly, we observe that many similar usage scenarios are present in different industrial sectors. Consequently, the economic sector does not seem to be an important discriminating criterion for *Digital Twin* use case categorization. This contrasts with the way the *Digital Twin* use cases are often classified and analyzed in the literature (criteria 5 in Section 2).

5.2. Use case characteristics extraction

A use case is a methodology generally used in system analysis to identify, clarify, and organize system requirements (Jacobson, 1987). According to this methodology, every *Digital Twin* use case contains three essential parts:

- The *actor(s)*: The *Digital Twin* user(s) – this can be a single person or a group of people interacting with the *Digital Twin*.
- The *goal*: The final successful outcome that completes the *Digital Twin*'s operations.
- The *system*: The *Digital Twin*'s components and steps taken to reach the end goal, including the necessary functional requirements and their anticipated behaviors.

We explain below how we apply this methodology to classify and document each *Digital Twin* use case collected via our interviews.

5.2.1. The actor

The users or *actors* leveraging a *Digital Twin* are generally the human beings that need to interact with the physical entity during a given phase of its life cycle. They leverage *Digital Twin* to simplify, accelerate, or improve their assigned tasks. In the collected use cases, these actors belong, for example, to the following classes: designers, operators, engineers, managers, etc.

5.2.2. The goal

The *goal* corresponds to the purpose or the function the actor needs to accomplish. This function depends not only on the actor but also on the physical entity and the life cycle phase when the task has to be performed. For the same phase, several actors and applications have been identified. This means that the *Digital Twin* can be mutualized by different functional entities in the same enterprise or between partners. They can collaborate and enrich their knowledge via the same *Digital Twin*.

5.2.3. The system

The third part of the use case, the system, is defined by the different elements of a *Digital Twin*. These are identified in the collected use cases and leveraged as use case classification attributes as follows:

Physical entity type. Our field study shows that, in an industrial environment, the nature of the **real-world entity**, represented by the *Digital Twin*, can be further specified as:

- a product,
- an industrial process, which can itself be subdivided into:
 - procurement process of materials and components needed for production;
 - production process;
 - finished product distribution process.
- a resource needed for production:
 - a specific industrial equipment in the workstation environment: robot in the assembly line, CNC machine on the production floor;
 - a factory considered as a whole (building, production lines, equipment);
 - a human operator in his working environment. We can note that this human-centricity is an important aspect of industry 5.0.

We observe that this segmentation is a critical aspect, in line with the **criteria 2: hierarchical level of the physical entity** outlined in Section 2 (Al-Sehrawy et al., 2021; Tao et al., 2018a; Shao, 2021). It is also interesting to note that, according to the interviews and analysts (Parrott and Warsaw, 2017), not all physical objects are good

candidates for the twinning process. High-value capital assets, intricate processes, or expensive product innovation are those which could reap the greatest advantage from *Digital Twins*.

Applications and tools. Within the *Digital Twin* system, the **applications and tools** correspond to the function that needs to be accomplished by the actor to achieve their goal. The applications define the type of digital tools to be associated with the *Digital Twin*. The functions can be to visualize, simulate, emulate, model, analyze, predict, etc. They are associated with **criteria 1: high-level categories of usage**. Depending on the application, the required tool will be a simulator, a data analyzer, a decision-support tool, etc.

Data and models types. **Data and models**, integrated into the *Digital Twin* system, are necessary to enable the users to perform the function with the corresponding tool. For example, historical data will be needed to make predictive analysis in maintenance during operations, or a 3D model and dynamic simulation will be necessary to help the product designer evaluate the usability of the future device. In our study, data and models types appeared as a key attribute of a use case, not clearly identified in the use case classification literature.

5.2.4. Life cycle phase

It is generally accepted that, to be profitable, a *Digital Twin* should be used throughout the life cycle of the physical entity. However, from our collected data, we observe that each use case corresponds to a well-identified **phase of the life cycle** of the physical entity of interest. Moreover, the considered phases vary depending on the nature of the physical entity:

1. For a product: design, manufacturing, use and maintenance, refurbishment or recycling phases.
2. For an industrial process: process design, set-up and execution phases.
3. For an industrial equipment type resource: implementation phase in the production environment, use and maintenance in this same environment. The phases of design, manufacture, and recycling of industrial equipment do not give rise to use cases because the equipment can be considered as a product to be designed, manufactured or recycled.
4. For a factory-type resource: design of the factory or industrial installation as a building, construction, use and dismantling.
5. For an operator: it is considered here the context of the execution of an industrial process.

Therefore, the *life cycle phase(s)* has been introduced as a criterion for use case classification, which is consistent with **criteria 3** of Section 2. The types of phases considered are typically design, development, operation, maintenance, and end of life.

It is important to note that the same *Digital Twin* can evolve and be used in several phases by several teams, with different tools, gradually increasing the benefits of the *Digital Twin* technology, which is complex and costly to implement. Moreover, the *Digital Twin* adoption can lead to changes at the enterprise scale, in workflows, revised criteria, and timelines throughout the life cycle of a product or a process.

5.3. Classification criteria selection

Each collected use case type has been formally described by a brief description, the expected outcomes, the list of industries that can benefit from it and formulated according to the classification framework with the following set of criteria:

1. The **goal** of the use case
2. The **actors** that are involved in the use case
3. The **real-world entity**, the physical object, represented by the *Digital Twin*

Table 1
Digital Twin use cases classification characteristics.

| Characteristics | Value examples |
|--------------------------|---|
| 1-Goal | design, visualize, improve, trace, train, optimize, troubleshoot, manage, etc. |
| 2-Actors involved | designer, operators, engineers, managers, etc. |
| 3-Real-world entity | a product to be produced, an industrial process, a resource needed for production, etc. |
| 4-Life cycle phase | design, manufacturing, set-up, execution, use, maintenance, refurbishment, recycling, dismantling, etc. |
| 5-Applications and tools | simulator, data analysis, predictive maintenance, etc. |
| 6-Models and data | fabrication data, life data, multi-physic models, AI models, etc. |

4. The **life cycle phase** of the represented entity that interests the use case
5. The **applications and tools** to deliver the value of the *Digital Twin*
6. The **models and data** needed to run tools and applications

This set of criteria, summarized in Table 1, extracted from field data and cross-domain discussions, overlaps and enriches the key dimensions that come out from the literature review in Section 2. In our case, “models and data” has been added and “industrial domain” removed. This specifies more clearly the use case and its requirements. This framework can serve as a guide to classify any existing use case or to create a new one.

The list of use cases collected by the AIF community and their detailed description, or UC collection, can be found in Scart et al. (2023). The real-world entity has been encoded to ease the indexing of the use case collection. The following notation convention has been adopted:

- PDT: corresponds to a use case centered on a Product.
- PCP: corresponds to a use case related to Production Process.
- PCA: corresponds to a use case related to Procurement Process.
- PCD: corresponds to a use case related to Distribution Process.
- EQT: corresponds to a use case related to an operational Equipment or a complex machine or infrastructure.
- USN: corresponds to a use case related to a whole Factory or Plant.
- OPR: corresponds to a use case related to a user or Operator.

The Fig. 2 represents the UC collection as an illustration of different possible applications of the *Digital Twin* in the industry. Although it may be non-exhaustive, all the use cases listed during the interviews with the industrial community can be mapped on it. As can be seen, a ‘green leaf’ is associated with areas where environmental impact reductions are most likely to be achievable.

6. Illustrative examples

In this part, three use cases have been selected from the UC collection to illustrate different usages and attributes of the *Digital Twin* for design, operations, and equipment.

6.1. Predictive maintenance of a system: EQT-03

One of the hot topics in industry relates to the predictive maintenance of equipment. The use case type, EQT-03, investigates possibilities in this area. For example, the *Digital Twin* of equipment (or a sub-part) can predict the occurrence of breakdowns, provide maintenance recommendations and, if the predictive model allows it, assist

Table 2
Use Case and *Digital Twin* characteristics for Use Case 1, EQT-03.

| Use Case characteristics | |
|--|--|
| Characteristics | Values |
| Use case name | EQT-03 |
| Goal | Predictive maintenance of a system |
| Actors | Designer, operators, engineers, managers |
| Real-world entity | In-service system or product |
| Life cycle phase | Use and maintenance |
| Applications and tools | Decision support system for maintenance service |
| Models and data | Fabrication data, in-service data, failure physical or statistical models |
| Associated <i>Digital Twin</i> characteristics | |
| Digital entity | Realistic model of the current state, physical and/or probabilistic simulations |
| Purpose | Predict damage and failure of the system or a part of it and propose maintenance actions/decisions |
| Synchronization | The frequency of data acquisition depends on the possible damages and failures dynamics |
| Data | Relevant data from sensors selected based on the knowledge of maintenance history on such system/product |
| Fidelity | Depends on the type of damages and failures that have to be predicted |

in troubleshooting. To do so, a predictive model is built beforehand based on observed failures and historical equipment usage data or on a physical model of the system, its damage, and failure mechanisms. This model is then fed using the data collected on the system to predict its future state and make decisions if needed.

The objective is to maintain a high production level by reducing the number of breakdowns that can affect the throughput of the production system and impact the mean time to failure. It may also reduce equipment unavailability as maintenance is only carried out when necessary and not according to a pre-determined schedule. Thanks to the *Digital Twin*, it becomes possible to understand the causes of breakdowns if proper tools are embedded.

Major users are equipment experts, data scientists, maintenance managers, or operators. The perimeter of actors may vary, as users can be customers or the manufacturer of the equipment. Based on the acquired data on full traceability of product components and their status (e.g., Product Lifecycle Management), the *Digital Twin* also eases upgrading, reusing, recycling, or dismantling the equipment, similarly to use case PDT-05 detailed below (see Table 2).

6.2. Design and product quality improvement of a production line: PCP-01 and PCP-05

Two *Digital Twins* of the same system – a production line – are presented to illustrate the fact that multiple *Digital Twins* of the same system can be developed depending on the targeted usage.

In the first investigated “production line” use case, named PCP-01, the purpose is to improve the design of the production line. This is made possible by using simulations based on current and historical production lines’ data and according to the anticipated demand. A rule-based model can also be added to help decision-making. The *Digital Twin* enables the design improvement of future production lines or the evolution of existing ones to new products. Hence, the *Digital Twin* benefits manufacturers and solution providers, considering the successful retrieval of operating data from their customers (equipment and line models, processes, production data, maintenance data, etc.) (see Table 3).

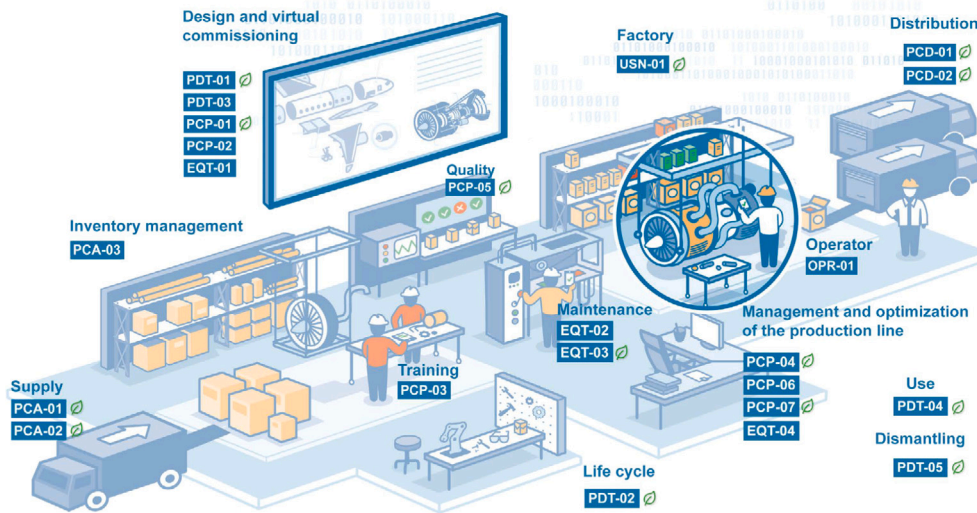


Fig. 2. Overview of the *Digital Twin* Use Cases classification in Industry. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3

Use Case and *Digital Twin* characteristics for Use Case 2, PCP-01.

| Use Case characteristics | |
|--|---|
| Characteristics | Values |
| Use case name | PCP-01 |
| Goal | Design of a production line |
| Actors | Designer, engineers |
| Physical entity | Production line |
| Life cycle phase | Design and in service (if it is an agile or reconfigurable production line) |
| Applications and tools | Design tools to improve the productivity of the line |
| Models and data | Historical data-based modeling for flux optimization, flux model including production line steps modeling |
| Associated <i>Digital Twin</i> characteristics | |
| Digital entity | Flux model of the production line |
| Purpose | Optimization of the production line design |
| Synchronization | Depends on the type of product on the line, can be at the end of each production batch |
| Data | Flux and quality data |
| Fidelity | Depends on the targeted level of optimization in the production line |

The *Digital Twin* may also support decision-making for relocating production, building new factories or production lines, or reorganizing the supply chain according to cost, quality, and environmental impact criteria. In this use case type, the main users of the *Digital Twin* can be a production line designer or an industrialization manager. Such applications may find profitable echoes in several sectors such as the automotive or aviation industries, energy production, pharmaceutical industries, etc.

The second use case, named PCP-05, focuses on the improvement of product quality based on production history. The use case aims at presenting possible improvements to the quality of products based on previously acquired data, including reporting of quality issues. This data can be used to run scenarios on operations, to provide predictions and recommendations during production, and to simulate alternative operations (see Table 4).

In such contexts, *Digital Twin* can be used to identify and understand (if explanatory tools are embedded) the root cause of past incidents

Table 4

Use Case and *Digital Twin* characteristics for Use Case 3, PCP-05.

| Use Case characteristics | |
|--|--|
| Characteristics | Values |
| Use case name | PCP-05 |
| Goal | Quality improvement of a production line |
| Actors | Production Manager; Data Scientist; Production line Designer; Product Engineer; Quality Manager |
| Physical entity | Production environment (humidity, UV, particles, temperature, etc.); Production lines; Materials and products being procured/manufactured |
| Life cycle phase | In service |
| Applications and tools | Analysis of production history (incidents); Construction of predictive models; Prediction of quality defects; Production process simulation; Recommendations for measures to prevent manufacturing defects |
| Models and data | Model of the material flow; Production process models (past, present); Configuration of manufacturing operations; Production status data; Product models (past, current) |
| Associated <i>Digital Twin</i> characteristics | |
| Digital entity | 3D model of machine and product |
| Purpose | Improving product quality |
| Lifecycle | In service phase |
| Synchronization | Real-time/asynchronous |
| Data | In: sensors, Out: spindle speed adjustment, etc. |
| Fidelity | Depends on the level of detail required for quality improvement |

by observing previous end-to-end operations. Possible incidents could also be anticipated based on the collected data and the behavior of the system and/or equipment at hand. Finally, the *Digital Twin* allows the improvement of the quality of final products by simulating alternative processes to avoid/reduce the aforementioned incidents and by implementing recommendations in the virtual entity, which can be pushed afterward to the physical one. In this use case, applications and the data layers they rely on can be relevant to a larger number of users, such as data scientists, quality managers, or even product engineers. As interested parties may have different usages of the collected data and the *Digital Twin*, as well as different expertise, it is important to

consider collaborative work in order to maximize the benefits of the developed *Digital Twin*. Targeted industries are similar to PCP-01.

7. Digital twin definition proposal

The real-world use cases gathered by the *CT-JN*, their analysis and classification presented above, helped the *AIF* community to better understand how the *Digital Twin* technology is already used in industry and how it can apply to many more purposes. This process led to a long consultation within the technical committee for converging on a reference definition that can well express how *Digital Twin* technology benefits many domains, in a range of use cases, all along the life cycle of physical entities.

7.1. Digital twin definition elements identification

The first step of this collective conceptualization of the *Digital Twin* paradigm consisted of analyzing the definitions proposed in the literature, according to the research questions identified in Section 4. This enabled us to:

1. Formally identify the common elements and their characteristics
2. Collect the terms used in each category to have a clear characterization of them
3. Map an illustrative sample of existing definitions into this framework

The variety of sources considered generates a range of candidate definitions. Twenty-one definitions have been extracted according to their quality, anteriority, and popularity from the most cited academic and well-known industrial definitions, as well as *Digital Twin* definitions literature reviews (Kritzinger et al., 2018; VanDerHorn and Mahadevan, 2021; Negri et al., 2017; Sjarov et al., 2020; Semeraro et al., 2021; Tao et al., 2018b; Lo et al., 2021; Pystina et al., 2022). Their analysis revealed that despite their many differences, they contain certain core elements that are present in all of them: **a physical entity, a digital entity, a linkage (or coupling) between these two entities**. There are other additional components like lifecycle aspects frequently found in the literature. We have identified seven main discriminating characteristics. Table 5 extracts, from the set of twenty-one selected definitions, the wording employed to characterize these seven elements, so as to exemplify them.

We detail and illustrate them below:

1. **Digital entity:** This element corresponds to the very core definition, the meaning of the concept of a *Digital Twin* as a software entity, typically a *model* (or a set of models) of possibly different nature (e.g., mathematical, mechanical, behavioral, semantic...). This answers to the “what” is a *Digital Twin*. The “what” is completed by the two following core elements: the physical twin and the coupling aspect.
2. **Physical entity:** This is the real-world entity that is twinned and inseparable from the digital entity, typically an object or product, a process, a complete system, or a system of systems.
3. **Purpose:** This important element answers the question “why”. The purpose explains the motivation and goals of the *Digital Twin* and what it is used for.
4. **Lifecycle:** This element specifies that the virtual entity can be used at different phases or should exist throughout the life of the physical entity. Some definitions explicitly refer to specific steps of the lifecycle (e.g., design, operation, maintenance, decommissioning...). This element relates to the “when” the *Digital Twin* is used.

Table 5
Digital Twin definition elements and associated values.

| Characteristics | Values |
|--------------------|--|
| 1- Digital entity | model, digital representation, comprehensive software representation, a computerized model, virtual instance, realistic model of the current state, representation of the operational dynamics, a living model, encapsulated software object or model, set of virtual information constructs, a collection of selected digital artifacts, integrated multi-physics, multi-scale, probabilistic simulation |
| 2- Physical entity | physical counterpart, individual physical object (PO), a potential or actual physical manufactured product, a physical device or system, an individual unique physical asset, or a group of physical assets, an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service), an as-built vehicle or system, aircraft, flying twin, the process and their own behavior, real-world entity or system, unique physical object, process, organization, person |
| 3- Purpose | fully describes, mirror the life, represents and reflects, represents all functional features, mimics the structure, context and behavior, visualized in a variety of ways, can simulate, can forecast the future, predict current and future conditions, informs decisions that realize value, enhance decision making, continually adapts to operational changes, re-engineering of structural life prediction and management |
| 4- Lifecycle | across multiple life cycle phases, entire lifecycle |
| 5- Synchronization | connected, links with the working elements, near real-time synchronization, dynamically updated, mirrors |
| 6- Data | data, the collected online data and information, sensor updates, selected characteristics, properties, conditions, and behaviors, performance, maintenance, and health information, fleet history, models (physical models) |
| 7- Fidelity | ultra high fidelity, high-fidelity, micro atomic level to the macro geometrical level |

5. **Synchronization:** This element denotes the fact that the physical and digital entities are somehow coupled, connected, linked via data flows. In other terms, this highlights that *Digital Twin* is consubstantial to the existence of a physical entity in the real world, and consequently, that a simulator or a model, alone, cannot be considered a *Digital Twin*. The bi-directional coupling can also be specified to distinguish a *Digital Twin* (bi-directional coupling) from a *Digital Shadow* (uni-directional coupling from physical to digital), from a *model* or a *mock-up* (no coupling at all). It makes explicit the type of synchronization required: frequency and the “real-time” nature (to be understood as “bounded in time”, not necessarily as “fast”) of the information updates between the twins. Some articles add that the synchronization is done specifically by means of IoT sensors and actuators (Chen, 2017; Vrabič et al., 2018; Lu et al., 2020)
6. **Data:** This aspect covers the nature, and often the source, of the *data*, which compose the digital entity and typically populate models. This element is part of the “how”.
7. **Fidelity:** This aspect gives information about how detailed or close to “the reality” the virtual representation is. Early definitions were quite vague about this notion and mentioned “high fidelity” without clarifying or quantifying this attribute (not defining either what is meant by “reality”). This lack of precision has been subject to a lot of interpretations and misconceptions. This element relates to the “how”.

Table 6 uses the characteristics mentioned above to compare the selected definitions.

Table 6
Characterization of *Digital Twin* definitions.

| Source | Date | Digital entity | Physical entity | Purpose | Lifecycle | Synchron. | Data | Fidelity |
|--|------|----------------|-----------------|---------|-----------|-----------|------|----------|
| Tuegel et al. (2011) | 2011 | X | X | X | | | | X |
| Glaessgen and Stargel (2012) | 2012 | X | X | X | | | | X |
| Reifsnider and Majumdar (2013) | 2013 | X | X | X | | | | X |
| Rosen et al. (2015) | 2015 | X | X | | | | | |
| Grieves and Vickers (2017) | 2017 | X | X | X | | | | X |
| Chen (2017) | 2017 | X | X | X | | X | | |
| Liu et al. (2018) | 2018 | X | X | X | | | | X |
| Vrabič et al. (2018) | 2018 | X | X | X | X | X | X | X |
| Bolton et al. (2018) | 2018 | X | X | X | X | X | | X |
| Madni et al. (2019) | 2019 | X | X | | X | | | X |
| Stark and Damerau (2019) | 2019 | X | X | | X | | X | |
| Lu et al. (2020) | 2020 | X | X | | | X | | X |
| Minerva and Crespi (2021) | 2020 | X | X | X | X | | X | |
| Autiosalo et al. (2020) | 2020 | X | X | X | | X | | X |
| AIAA. Digital Engineering Integration Committee (2021) | 2021 | X | X | X | X | X | X | |
| Gartner (2021) | 2021 | X | X | X | | | X | |
| Rasheed et al. (2020) | 2021 | X | X | X | | | X | |
| Hribernik et al. (2021) | 2021 | X | X | | | | X | |
| Wang et al. (2021) | 2021 | X | X | X | X | | X | |
| Hartmann and Van der Auweraer (2021) | 2021 | X | X | X | X | | X | |
| Semeraro et al. (2021) | 2021 | X | X | X | X | X | X | |
| Total (21) | | 21 | 21 | 16 | 9 | 7 | 10 | 10 |

7.2. AIF digital twin definition and explanation

After having collected and classified industrial use case types and examined the definitions proposed by academics and industrials, the *CT-JN*, targeting the industry sector, converged on a synthetic definition. This proposal is inspired by the generalization trend observed in the *Digital Twin* community and articulates the different perspectives of the *AIF* industrial and academic communities. This definition integrates and characterizes the seven dimensions extracted from the definitions analyzed above.

A *Digital Twin* is

- **an organized set of digital models (1) representing**
- **a real-world entity (2)**
- **designed to address specific issues and uses (3).**
- **The *Digital Twin* is updated in relation to reality (5),**
- **with a frequency and precision adapted to its issues and uses (7).**
- **The *Digital Twin* is equipped with advanced operating tools including the ability to understand, analyze, predict or optimize (6)**
- **the operation and management of the real entity (4).**

We explain below the different aspects of this definition:

- **an organized set of digital models (characteristic 1):** Digital models span from 2D or 3D geometric models, topological models, physical and mathematical models, functional models, etc. These models are organized and interconnected. *Digital Twins* are intended to be assembled and nested according to the evolution of the expected uses (life cycle aspect) and the targeted scope (systems of systems).
- **a real-world entity (characteristic 2):** The *Digital Twin* must represent an entity that actually exists. It is therefore distinguished from the digital mock-up produced before production,

which is not a *Digital Twin*. On the other hand, a digital mock-up can be part of a *Digital Twin*. Moreover, once the digital mock-up is physically implemented and synchronized with its physical counterpart, it becomes a *Digital Twin*. The entity studied can be, for example, a product, a machine, a process, a service, a whole production plant, etc.

- **designed to address specific issues and uses (characteristic 3):** The *Digital Twin* is not an objective on its own, it is a means to meet specific objectives.
- **updated in relation to reality (characteristic 5):** If the models are not fed with data from the real world, they do not form a *Digital Twin*. A simple simulation or a simple model is therefore not a *Digital Twin* if it is not synchronized with reality. The linkage is not always direct nor automated.
- **frequency and precision (characteristic 7):** The update in relation to reality follows the dynamics of the studied entity and is calibrated to the exact needs of the intended use(s). The update is therefore not necessarily done in strict real time. The precision (granularity and content) must also be chosen according to the right need. The *Digital Twin* can, for example, contain shapes, states, functions, processes, behaviors, attributes, operational data, dynamics, enabling environment, etc. Absolute precision and ultra-high fidelity (from the micro-atomic level to the macro-geometric level) is impossible and not necessary.
- **advanced operating tools to understand, analyze, predict or optimize (characteristic 6):** Advanced operating tools help achieve the intended objectives. A simple database, embedding no tools, is therefore not a *Digital Twin*.
- **the operation and management (characteristic 4):** The *Digital Twin* must have an impact on the physical twin during a given phase of its life cycle.

We observe that the *AIF* definition manages to embrace the seven dimensions of our categorization. These dimensions are characterized

in a way that can encompass the various real-world use cases collected and analyzed in detail in Section 6. In particular, the AIF definition emphasizes the critical role of the purpose and the tools to process data and generate models such as 3D modelers, simulators, etc., which are tightly coupled with the *Digital Twin* models as highlighted by [Boschert and Rosen \(2016\)](#) and our use case analysis (see Section 5).

8. Conclusion

This article synthesizes a field study conducted over two years within the industrial community in France, gathered in the context of the *Alliance for Industry of the Future (AIF)*, to detail, publish, and classify *Digital Twin* use cases across a range of industry verticals. Observing that no cross-domain classification for *Digital Twin* use cases existed in the literature, and adopting a bottom-up approach, the technical committee CT-JN conducted a series of about 50 interviews to collect the “know-how” and viewpoints of practitioners in many different sectors. These data have been analyzed and compared to clarify the terminology and to formalize a template to document each *Digital Twin* use case. These use cases have then been grouped into 23 categories and a classification framework with seven criteria has been proposed. This article details the results of this study, discusses the classification framework, and illustrates it with three use case examples.

Then, we discussed the results of a combined literature review and a long consultation process to establish a general and unifying definition of *Industrial Digital Twin*, in which the various viewpoints can converge. Seven key dimensions that are present in the majority of *Digital Twin* definitions proposed by both the academic and industrial communities have been extracted and defined. These dimensions serve to elaborate a unifying definition. They are formulated in a way that integrates and generalizes the different collected *Digital Twin* use cases.

Establishing a consensual architecture for *Digital Twin*, integrating and connecting the various data, models, and tools components identified in this work as foundational requirements, along with a list of standard technical building blocks to implement and validate them from the use case collection is on our future agenda.

We also plan to analyze and characterize the potential environmental impact of each *Digital Twin* use case type, taking into account the footprint of the *Digital Twin* tool itself. Such analysis should be performed at the early stage of any *Digital Twin* design, to ensure minimal environmental impact of the whole system, including both its physical and digital entities.

CRedit authorship contribution statement

Emmanuelle Abisset-Chavanne: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Methodology, Validation. **Thierry Coupaye:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Investigation, Validation. **Fahad R. Golra:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Validation. **Damien Lamy:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Investigation, Validation. **Ariane Piel:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, Validation, Project administration. **Olivier Scart:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Validation. **Pascale Vicat-Blanc:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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