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Digital twin: concept, key features, and core characteristics

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Abstract. Digital twins are defined in different ways across the literature, particularly with regard to the characteristics required for a digital system to qualify as a digital twin. This study compares existing definitions and identifies the features that recur most consistently across different approaches. The analysis shows that a digital twin is characterized not simply by the existence of a digital representation of a physical object, but by the relationship between the physical and digital entities, the direction of data exchange, the way the digital representation is updated, and the extent to which the two remain synchronized. These findings are considered alongside relevant international standards to clarify the terminology, architectural principles, and information exchange requirements associated with digital twin systems.

Keywords: digital transformation, digital twin, architecture, features, classification.

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Цифровой двойник: понятие, ключевые признаки и основные характеристики

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Аннотация. В современной научной литературе понятие цифрового двойника не имеет единой трактовки. Наиболее существенные различия связаны с тем, какие именно свойства и характеристики позволяют рассматривать цифровую систему как цифровой двойник, а не просто как цифровую модель или виртуальное представление объекта. В работе проведен сравнительный анализ существующих определений цифрового двойника и выделены признаки, наиболее часто встречающиеся в различных научных и нормативных подходах. Показано, что сущность цифрового двойника определяется не только наличием цифрового представления физического объекта, но прежде всего характером связи между физической и цифровой сущностями, организацией обмена данными, механизмами актуализации цифрового представления и степенью их взаимной синхронизации. Полученные результаты сопоставлены с положениями международных стандартов, регламентирующих терминологию, архитектурные принципы и информационное взаимодействие в системах цифровых двойников. Проведенный анализ позволяет уточнить содержание понятия «цифровой двойник» и систематизировать его основные признаки и характеристики.

Ключевые слова: цифровая трансформация, цифровой двойник, архитектура цифрового двойника, признаки цифрового двойника, классификация.

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1. Introduction

Digital transformation has significantly changed the way technical and manufacturing systems are designed, monitored, and managed. As a result, digital models are increasingly used not only to represent physical assets, but also to support their operation throughout the life cycle. Within this context, the concept of the digital twin has gained particular importance. A digital twin is generally understood as a digital representation associated with a specific physical object and updated as the condition of that object changes.

Despite its widespread use, the term digital twin is still interpreted differently across research fields and application domains. The main differences concern the features that are considered essential for a digital system to qualify as a digital twin. In some definitions, the presence of a digital representation of a physical object is treated as the primary requirement. Other approaches place greater emphasis on the exchange of information between the physical and digital entities, the direction and frequency of data transfer, the mechanisms used to update the digital representation, and the degree to which the two states remain consistent over time.

These differences make the boundaries of the concept difficult to define. Systems with similar functions may therefore be described differently depending on the criteria used. This also complicates the comparison of existing approaches and makes it difficult to identify a common set of characteristics that can be applied across different implementations.

A digital twin should therefore be defined through a combination of interrelated features rather than through a single property. The aim of this article is to identify the key features and characteristics of a digital twin that allow it to be distinguished from other digital systems and provide a consistent basis for comparing different interpretations of the concept.

2. Materials and methods

This study adopts a comparative conceptual approach to examine how digital twins are defined and characterized in the literature and in relevant international standards. The analysis draws on publications that address the relationship between physical and digital entities, the structure of digital twin systems, data exchange and synchronization, and the functional capabilities associated with digital twins. The analysis also considers ISO 23247, ISO/IEC 30173, and IEC 63278-1, which provide the terminology, architectural principles, and interoperability requirements established at the standards level.

The selected approaches are examined using the same set of characteristics to allow direct comparison. These include the presence of physical and digital entities, the direction and degree of

automation of data exchange, the mechanisms used to update and synchronize the digital representation, the consistency between physical and digital states, the completeness and fidelity of the representation, and the analytical and functional capabilities of the system. Integration and interoperability are also considered where they form part of the proposed digital twin architecture.

The comparison focuses on two main questions: which characteristics recur across different definitions of the digital twin, and which remain subject to different interpretations. These characteristics are then considered in relation to the international standards to identify areas of convergence and divergence between conceptual approaches and formalized requirements. The comparison therefore provides a common basis for identifying the features most consistently associated with digital twins and for assessing how different authors interpret the concept.

3. Results

The digital twin concept has been developed and refined across a substantial body of research. In [1], a digital twin is described as an interconnected representation of physical and virtual entities that exchange information. The digital entity is associated with a specific physical object and is intended to reflect both its characteristics and changes in its state throughout the life cycle. This coupling supports the analysis of system behavior, the identification of deviations, and the assessment of conditions that may lead to undesirable emergent behavior. In this interpretation, the key distinction between a digital twin and a standalone digital model lies in the presence of an information link to the physical counterpart and in the updating of the digital representation based on data reflecting the object's actual state.

A similar view is presented in [2], where the digital twin is defined as a high-fidelity integrated model of a specific physical object that is continuously updated using operational data, maintenance history, and information about its current condition. This interpretation introduces the requirement for one-to-one correspondence with a specific physical instance: the digital representation is tied not to an abstract class of objects, but to a particular physical counterpart and evolves as that counterpart changes over time.

In [3], the distinction between a digital model, a digital shadow, and a digital twin is drawn on the basis of the way information is exchanged between the physical and digital entities. The three concepts are differentiated by their level of integration. A digital model has no automated data exchange with the physical object, while a digital shadow receives data automatically from the physical object. A digital twin, by contrast, enables automated bidirectional data exchange. This framework therefore treats the information link between the physical and digital entities as one of the defining features of a digital twin.

Drawing on a systematic review of existing definitions, [4] identifies a set of interrelated characteristics that collectively define a digital twin. These include the physical and virtual entities, their respective states and operating environments, measured parameters, coupling mechanisms, update frequency, the links between the physical and virtual entities, and changes in the state of each entity over time. From this perspective, a digital twin is defined not by any single feature, but by the way these characteristics work together to describe the relationship and information exchange between a physical object and its digital representation.

In [5], a digital twin is described as a virtual representation of a physical object that combines data with computational models to capture and assess the object's current state. A key feature of this representation is that it evolves as new information about the physical object becomes available. A static match between the digital model and its physical counterpart is therefore not sufficient; correspondence between the two must be maintained over time through ongoing updates to the digital state.

In [6], the digital twin is presented as a virtual representation of a real-world object that is kept in sync with the object's actual state. In this view, synchronization is what allows the digital and physical entities to remain aligned over time: changes in the physical object should be reflected in its digital counterpart. A digital twin is therefore defined not only by how completely it represents the object, but also by its ability to remain current as that object changes.

Across the existing literature, digital twins are consistently associated with a core set of features: the presence of both physical and digital entities, an information link between them, correspondence between the digital representation and the state of the physical object, and the ability to update that representation as the object changes. At the same time, definitions vary in the level of completeness they require, in how they treat the direction of data exchange, and in the degree of synchronization expected between the physical and digital entities. As a result, the boundaries of the digital twin concept remain somewhat fluid.

A wide range of approaches has been used to create digital representations of physical objects, which has led to some overlap between the digital twin and related concepts. The literature commonly distinguishes between virtual models, digital models, digital shadows, digital replicas, simulation models, and digital twins. These concepts are generally differentiated by how closely the digital representation reflects the physical object, how information flows between the two, how updates are handled, and how well their states remain aligned over time.

One of the most widely used distinctions is outlined in [3], where digital models, digital shadows, and digital twins are differentiated according to how data move between the physical and digital entities. In a digital model, there is no automated data transfer. A digital shadow receives data

automatically from the physical object, whereas a digital twin allows data to flow automatically in both directions. The distinction therefore depends mainly on the direction of data flow and on how far the exchange between the physical and digital entities is automated.

In [7], a broader framework is proposed for distinguishing digital twins from other forms of digital representation. The framework identifies three essential elements: a physical entity, its virtual counterpart, and a means of exchanging information between the two. From this perspective, a digital twin differs from conventional digital modeling and computer simulation in one important respect: even a highly detailed computational model is not enough on its own. To qualify as a digital twin, the model must remain connected to the corresponding physical object through ongoing information exchange.

In [8], the authors distinguish between the digital twin and the digital shadow. A digital shadow is described as a digital representation that reflects the state of a physical entity using data received from it, while a digital twin involves a more extensive connection between the physical and digital counterparts. From this perspective, keeping a digital representation current does not, by itself, make it a digital twin.

In [9], the terms digital model and digital shadow are used in different ways across the literature. Some studies treat them as closely related to, or even interchangeable with, the digital twin, while others regard them as separate forms of digital representation. This variation makes the boundary of the digital twin concept difficult to define. The distinction therefore depends not only on whether a digital representation exists, but also on the nature of its connection to the physical entity and the extent to which the two remain synchronized over time.

In [10], the digital twin is set apart from related computational concepts by the way its core elements are brought together. A digital twin cannot be reduced to a simulation, an autonomous system, or a standalone optimization model. What defines it is the combination of a digital representation, a direct connection to the physical object, mechanisms for keeping that representation current, and the use of incoming data to maintain alignment between the physical and digital entities over time.

The term digital replica is used less consistently across the literature and does not occupy a clearly defined place within existing classifications. In [11], it is used as part of the definition of a digital twin, referring to a digital representation of a physical entity that captures its state and behavior in a virtual environment throughout its life cycle. In this context, the digital replica is not treated as a separate category, but rather as the representation on which the digital twin is built. In [12], the term is used in a different sense: a digital shadow is described as a digital replica of a physical system whose state is kept aligned with the physical object in real time through one-way data flow, whereas

a digital twin is distinguished by two-way information exchange. Taken together, these examples show that digital replica may refer either broadly to the digital representation of a physical entity or more narrowly to a specific component or more limited form of representation. Its meaning therefore needs to be made explicit when the term is used alongside digital model, digital shadow, and digital twin.

Distinguishing a digital twin from related digital constructs requires looking at a broader set of characteristics that capture both the scope and completeness of the digital representation and the nature of its connection to the physical object. In [13], an analysis of 87 digital twin applications led to a six-dimensional framework covering purpose, type of physical object, completeness of the digital representation, timing of its creation, the nature of the physical-digital link, and application context. Two dimensions are particularly relevant here: completeness, which reflects how much of the physical object is represented digitally, and connectivity, which can range from no automated exchange to one-way or two-way data flow. This view shows that digital twins can differ not only in their intended use, but also in how fully they represent the physical object and how closely the digital and physical entities are connected.

In [14], the digital twin is described in terms of three closely related dimensions: data and models, use, and application functions. The framework brings together a number of capabilities considered important to its operation, including a continuous digital connection between physical and virtual spaces, access to relevant, reliable, and secure data at the required level of accuracy, and the ability to extend and refine models over time. It also encompasses control, learning, and predictive functions. Importantly, these characteristics are not treated as fixed; they may evolve as the digital twin is adapted to new tasks and application needs.

In [15], a functional framework is proposed for comparing digital twins across different types of implementation. The framework groups their characteristics into four broad areas: digital coupling, digital representation, processing capabilities, and functional output. Digital coupling covers how the physical entity is identified, how data are transferred and preprocessed, how synchronization is maintained, and which protocols and standards support the connection. Digital representation concerns how the state of the physical object is captured, while processing capabilities refer to the analytical and modeling functions available within the twin. Functional output describes how the information generated by the twin is ultimately used. Taken together, these four areas provide a way to compare digital twins by the breadth and maturity of their capabilities rather than by simply checking whether individual components are present.

A more formal way of describing the relationship between the physical and digital sides is introduced in [16] through the concept of digital twin identicality. The framework considers four

attributes: completeness, trueness, accuracy and precision. Instead of reducing digital twin quality to a single measure, it separates physical-digital correspondence into distinct dimensions that can be evaluated individually, providing a clearer basis for assessing how closely the digital representation reflects the physical object.

In [17], the digital twin is characterized using five closely related dimensions: fidelity, intelligence, smartness, integration, and standards compliance. These dimensions are treated as mutually dependent rather than isolated. Improvements in one area may therefore place additional demands on others. Higher fidelity, for example, requires sufficiently timely updates, while more advanced intelligent capabilities depend on both stronger integration and a sufficiently accurate digital representation.

Taken together, the approaches reviewed here suggest that digital twins are best understood through a combination of interrelated characteristics rather than through any single defining property. These include the completeness and fidelity of the digital representation, the nature of its connection to the physical entity, the timeliness of updates, the degree of integration, and the range of functions supported by the system. The literature does, however, vary in which characteristics it emphasizes and how they are grouped.

Several of these ideas are reflected more explicitly in international standards. The ISO 23247 series provides a framework for digital twins in manufacturing. ISO 23247-1 [18] sets out the general principles, while ISO 23247-2 through ISO 23247-4 address the reference architecture, the digital representation of observable manufacturing elements, and information exchange between system components. From this perspective, a manufacturing digital twin is not defined simply by the existence of a digital representation. It also depends on how that representation is connected to the physical entity and incorporated into the wider system of data exchange and related services.

ISO/IEC 30173 [19] provides a common conceptual and terminological basis for digital twins. It defines key terms, identifies different types of digital twins, and describes functional views and lifecycle-related aspects. In doing so, the standard gives a more formal structure to characteristics that had previously been discussed mainly within separate conceptual and classification frameworks.

IEC 63278-1:2023 [20] focuses on standardized digital representation and interoperability through the Asset Administration Shell (AAS). It sets out a common structure for organizing and identifying asset-related information and for providing access to associated data and services. This creates a consistent basis for interoperability across distributed information systems. The AAS itself, however, is not equivalent to a digital twin. Rather, it provides a standardized digital representation of an asset and a structured means of accessing the associated data and services.

4. Discussion

The comparison presented here highlights a recurring problem in the digital twin literature: the same characteristics are often used to answer different questions. Some are used to determine whether a system should be considered a digital twin at all, while others are used to describe how complete, accurate, integrated, or functionally advanced a particular implementation is. When these two purposes are treated as equivalent, the boundary of the concept becomes difficult to define and advanced capabilities can be mistaken for basic requirements.

A more consistent way forward is to separate digital twin identification from digital twin characterization. Identification concerns the minimum conditions that must be met for a system to qualify as a digital twin. Characterization, by contrast, concerns the properties of a particular implementation once that basic status has been established. The literature reviewed in this study points to a relatively stable set of core elements: a specific physical entity, a corresponding digital representation, an information link between the two, a mechanism for updating the digital state, and continued correspondence between physical and digital states over time. These features recur far more consistently than capabilities such as prediction, learning, optimization, or automated control.

This distinction also helps make sense of the wide range of characteristics used in existing frameworks. Fidelity, completeness, update frequency, direction of data exchange, degree of automation, integration, analytical capability, prediction, learning, optimization, and control all provide useful information about a digital twin, but they do not serve the same purpose. Some describe the quality of the digital representation, others the strength and timing of the physical-digital connection, and others the functionality available within the system. Treating these characteristics as dimensions of implementation rather than universal prerequisites would allow digital twins developed for different purposes to be compared without forcing them into a single rigid definition.

The same issue arises with related terminology. Terms such as digital model, digital shadow, and digital replica are not used consistently enough across the literature to function as reliable classification labels on their own. In some studies they denote clearly separate forms of digital representation, whereas in others their meanings overlap or are embedded within broader digital twin definitions. For this reason, classification should rely less on labels and more on the actual properties of the system. In particular, studies should state explicitly how data move between the physical and digital entities, whether that exchange is automated, how the digital state is updated, and how closely the two states are kept aligned. Describing these properties directly would make differences between approaches easier to interpret and would reduce ambiguity when comparing results across studies.

International standards provide an important foundation for this shift, although they address the problem from a different angle. ISO 23247, ISO/IEC 30173, and IEC 63278-1 formalize terminology, architecture, digital representation, information exchange, and interoperability. Their main contribution lies in establishing common structures and interfaces that support implementation and integration. They do not, however, fully settle the conceptual question of which properties should be regarded as necessary for identifying a digital twin and which should instead be used to describe its capabilities. This leaves room for a complementary conceptual framework focused specifically on identification and characterization.

A two-level structure offers a practical way to address this gap. The first level would establish whether a system meets the core conditions required for digital twin identification. The second would describe the implementation using additional dimensions related to representation quality, temporal consistency, integration, analytical depth, and functional scope. Under such an approach, a system could be recognized as a digital twin on the basis of its maintained physical-digital relationship, while its degree of sophistication could be described separately through characteristics such as fidelity, prediction, autonomy, or control.

This separation has several advantages. It avoids turning advanced functionality into a mandatory requirement, makes it easier to compare digital twins developed for different domains, and provides a clearer basis for distinguishing them from simpler forms of digital representation. It also creates a more transparent link between conceptual definitions and maturity-oriented descriptions: identification establishes what the system is, while characterization describes what the system is capable of.

From this perspective, a digital twin is best understood not as a single fixed technical configuration, but as a class of systems built around a maintained relationship between a physical entity and its digital representation. The defining features establish that relationship, while the additional characteristics describe how accurately, consistently, and extensively it is implemented in a particular system.

5. Conclusion

This study examined how the digital twin is defined across the literature and how its key features are reflected in international standards. Although definitions vary in terminology and emphasis, they share a common conceptual core: a digital twin is linked to a specific physical entity, represented digitally, connected through ongoing information exchange, and updated as the physical object changes. By contrast, characteristics such as completeness, fidelity, synchronization,

integration, analytical capability, prediction, and control are treated less consistently and are better understood as features of particular implementations rather than universal requirements.

The analysis also shows that terms such as digital model, digital shadow, and digital replica are not used consistently enough to provide a reliable basis for classification on their own. International standards bring greater consistency to terminology, architecture, information exchange, and interoperability, but they do not fully resolve the conceptual boundaries of the digital twin. A clearer separation between the features that define a digital twin and those that describe the capabilities of a particular implementation may therefore provide a more consistent basis for future comparison and classification.

References

1. Grieves, M. Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems / M. Grieves, J. Vickers // Transdisciplinary Perspectives on Complex Systems / eds. F.-J. Kahlen, S. Flumerfelt, A. Alves. – Cham: Springer, 2017. – P. 85-113. – DOI: 10.1007/978-3-319-38756-7_4.
2. Glaessgen, E. H. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles / E. H. Glaessgen, D. S. Stargel // 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, USA, 23-26 April 2012. – 2012. – AIAA Paper 2012-1818. – 14 p. – DOI: 10.2514/6.2012-1818.
3. Digital twin in manufacturing: a categorical literature review and classification / W. Kritzinger, M. Karner, G. Traar [et al.] // IFAC-PapersOnLine. – 2018. – Vol. 51, No. 11. – P. 1016-1022. – DOI: 10.1016/j.ifacol.2018.08.474.
4. Characterising the digital twin: a systematic literature review / D. Jones, C. Snider, A. Nassehi [et al.] // CIRP Journal of Manufacturing Science and Technology. – 2020. – Vol. 29, Part A. – P. 36-52. – DOI: 10.1016/j.cirpj.2020.02.002.
5. Rasheed, A. Digital twin: values, challenges and enablers from a modeling perspective / A. Rasheed, O. San, T. Kvamsdal // IEEE Access. – 2020. – Vol. 8. – P. 21980-22012. – DOI: 10.1109/ACCESS.2020.2970143.
6. Digital twin paradigm: A systematic literature review / C. Semeraro, M. Lezoche, H. Panetto, M. Dassisti // Computers in Industry. – 2021. – Vol. 130. – Art. 103469. – DOI: 10.1016/j.compind.2021.103469.
7. VanDerHorn, E. Digital Twin: Generalization, characterization and implementation / E. VanDerHorn, S. Mahadevan // Decision Support Systems. – 2021. – Vol. 145. – Art. 113524. – DOI: 10.1016/j.dss.2021.113524.

8. The Concept of Digital Twin and Digital Shadow in Manufacturing / T. Bergs, S. Gierlings, T. Auerbach [et al.] // Procedia CIRP. – 2021. – Vol. 101. – P. 81-84. – DOI: 10.1016/j.procir.2021.02.010.
9. Kuehner, K. J. Digital Twin: Finding Common Ground – A Meta-Review / K. J. Kuehner, R. Scheer, S. Strassburger // Procedia CIRP. – 2021. – Vol. 104. – P. 1227-1232. – DOI: 10.1016/j.procir.2021.11.206.
10. Digital Twins: State of the art theory and practice, challenges, and open research questions / A. Sharma, E. Kosasih, J. Zhang [et al.] // Journal of Industrial Information Integration. – 2022. – Vol. 30. – Art. 100383. – DOI: 10.1016/j.jii.2022.100383.
11. Tekinerdogan, B. On the Notion of Digital Twins: A Modeling Perspective / B. Tekinerdogan // Systems. – 2023. – Vol. 11, No. 1. – Art. 15. – DOI: 10.3390/systems11010015.
12. AboElHassan, A. A digital shadow framework using distributed system concepts / A. AboElHassan, S. Yacout // Journal of Intelligent Manufacturing. – 2023. – Vol. 34, No. 8. – P. 3579-3598. – DOI: 10.1007/s10845-022-02028-6.
13. Enders, M. R. Dimensions of Digital Twin Applications – A Literature Review / M. R. Enders, N. Hoßbach // AMCIS 2019 Proceedings. – 2019. – Paper 20. – URL: https://aisel.aisnet.org/amcis2019/org_transformation_is/org_transformation_is/20/ (accessed: 30.09.2026).
14. Julien, N. How to characterize a Digital Twin: A Usage-Driven Classification / N. Julien, E. Martin // IFAC-PapersOnLine. – 2021. – Vol. 54, No. 1. – P. 894-899. – DOI: 10.1016/j.ifacol.2021.08.106.
15. Boyes, H. Digital twins: An analysis framework and open issues / H. Boyes, T. Watson // Computers in Industry. – 2022. – Vol. 143. – Art. 103763. – DOI: 10.1016/j.compind.2022.103763.
16. Characterisation and evaluation of identicality for digital twins for the manufacturing domain / S. Su, A. Nassehi, B. Hicks, J. Ross // Journal of Manufacturing Systems. – 2023. – Vol. 71. – P. 224-237. – DOI: 10.1016/j.jmsy.2023.09.004.
17. A generic framework for qualifications of digital twins in maintenance / J. Liu, X. Liu, J. Vatn, S. Yin // Journal of Automation and Intelligence. – 2023. – Vol. 2, No. 4. – P. 196-203. – DOI: 10.1016/j.jai.2023.07.002.
18. ISO 23247-1:2021. Automation systems and integration – Digital twin framework for manufacturing – Part 1: Overview and general principles. – Geneva: International Organization for Standardization, 2021. – 12 p.

19. ISO/IEC 30173:2023. Digital twin – Concepts and terminology. – Geneva: International Organization for Standardization, 2023. – 28 p.
20. IEC 63278-1:2023. Asset Administration Shell for industrial applications – Part 1: Asset Administration Shell structure. – Geneva: International Electrotechnical Commission, 2023. – 149 p.