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Reshaping the Digital Twin Construct with Levels of Digital Twinning (LoDT)

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Abstract: While digital twins (DTs) have achieved significant visibility, they continue to face a problem of lack of harmonisation regarding their interpretation and definition. This diverse and interchangeable use of terms makes it challenging for scientific activities to take place and for organisations to grasp the existing opportunities and how can these benefit their businesses. This article aims to shift the focus away from debating a definition for a DT. Instead, it proposes a conceptual approach to the digital twinning of engineering physical assets as an ongoing process with variable complexity and evolutionary capacity over time. To accomplish this, the article presents a functional architecture of digital twinning, grounded in the foundational elements of the DT, to reflect the various forms and levels of digital twinning (LoDT) of physical assets throughout their life cycles. Furthermore, this work presents UNI-TWIN—a unified model to assist organisations in assessing the LoDT of their assets and to support investment planning decisions. Three case studies from the road and rail sector validate its applicability. UNI-TWIN helps to redirect the discussion around DTs and emphasise the opportunities and challenges presented by the diverse realities of digital twinning, namely in the context of engineering asset management.

Keywords: digital twinning; digital twin; architecture; physical assets; asset management; LoDT; UNI-TWIN

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1. Introduction

1.1. Background

According to various studies [1–4], digital twins (DTs) stand among technological approaches with significant potential for value generation and substantial interest from businesses. This subject has garnered increasing attention within the scientific community, as evidenced by the marked upswing in publications over recent years [5,6]. According to the Digital Twin Market Report 2023–2027 [7], the software market supporting digital twins expanded by 71 percentage points between 2020 and 2022. Furthermore, 29% of manufacturing enterprises have either implemented or are in the process of implementing a Digital Twin (DT)-based strategy for their assets [8]. Today, there are institutions and working groups exclusively dedicated to the study of digital twins, such as the Digital Twin Consortium, Digital Twin Hub, Change2Twin Consortium, Working Group 6 of ISO/IEC JTC 1—Information technology Subcommittee 41, and Ad Hoc Group 2 of ISO/TC 184—Automation systems and integration.

Nevertheless, this topic has led to significant discussion within the literature, not only concerning its definition but also regarding the very boundaries of the concept itself. Despite noteworthy contributions from various authors and organisations aimed at harmonising the definition of the DT and its conceptual limits, the rapid proliferation of literature has led to considerable divergence of interpretations on the subject. There are studies (e.g., [9–12]) asserting that presently, no unified definition exists, and the context in which the term is frequently employed has drifted from its original framework. According to [8], the lack of consensus regarding the DT and its definition poses a hurdle for those seeking to delve deeper into the subject and serves as a point of resistance for organisations considering its development. It is also reported that professionals encounter difficulties in assessing the diverse capabilities of digital twins, further impeding the identification and implementation of these opportunities. Singh et al. [13] contend that, in addition to achieving consensus on the value and definition of digital twins, adequate standards and regulations, and technical competencies in human resources, a holistic perspective on the topic of digital twins is necessary. This perspective aims to qualify the concept and elucidate its characteristics, advantages, and implementation challenges.

On the other hand, Johnson et al. [14] have noted that research on DTs has focused on specific applications or frameworks for IoT sensors and data integration platforms, resulting in a dearth of research on the role that information requirements play in the development of a DT strategy.

Furthermore, certain sectors such as Architecture, Engineering, and Construction (AEC) have traditionally exhibited greater resistance to innovation, thereby lagging behind in the digital transformation journey compared to other sectors such as manufacturing [15]. In a survey of AEC companies in Portugal, DTs emerged as one of the least adopted technological approaches (7% adoption rate). Companies cited various barriers, including a lack of knowledge about return on investment (16%), difficulty in adapting existing processes (13%), interoperability issues between technologies (11%), and a lack of knowledge and/or understanding of the technology (10%) [16]. These findings align with another study by Opoku et al. [17], which identified the primary barriers to DT adoption in the construction industry as low levels of knowledge, limited technology acceptance, a lack of clear value propositions, project complexity, and the static nature of building data.

Stabilising these concepts is therefore an essential step towards a common understanding among the parties involved in the study and development of DTs [8]. The development of a common language is precisely one of the five priorities identified in a UK study on intelligent infrastructure [18]. The alignment between organisational needs and the opportunities presented by DTs can only be achieved if there is a shared language and understanding of the capabilities and functioning of DTs. It is within this context that the present study seeks to deepen existing knowledge and contribute to a utilitarian and strategic vision of DTs, one that is less focused on rigid definitions and more centred on functionality, diversity, and capabilities.

1.2. Research Objectives and Paper Organisation

Considering the multitude of definitions and interpretations that exist regarding the concept of DTs, this present study aims to redirect the discussion by placing greater emphasis, on the one hand, on the distinctions among DTs (reflected in their purposes, capabilities, and respective degrees of development), and, on the other hand, on the fundamental principles they share. To achieve this, this study will recover the concept of digital twinning as a common conceptual basis encompassing these characteristics and various concepts already associated with DTs. Digital twinning of physical assets is thus regarded as a process of variable complexity with evolutionary potential over time, which is aligned with the inherent life cycle approach of the physical assets to be twinned.

The primary objective of this work is to contribute to a clarification of the various functions and capabilities associated with digital twinning of physical assets in order to provide asset managers with conceptual foundations and a common language that facilitate the identification of digital twinning opportunities and the understanding of their value.

To this end, this study relies on the definitions proposed by leading entities in this field and the constituent elements of a DT to propose a harmonised functional architecture. With this architecture, the intention is to leave the debate over terminology and definitions of the DT in the background and emphasise how these differences can be organised and communicated according to different levels of development. These diverse capabilities and levels of development will be organised within an assessment model for the level of digital twinning, the application of which can assist organisations in planning the digital twinning journeys for their physical assets.

The present article is structured as follows: in Section 2, the model of functional architecture that supports the concept of digital twinning is presented; in Section 3, the evolution of the architecture and the different types of opportunities over the lifecycle of physical assets are discussed; Section 4 presents a model for assessing the level of digital twinning for various capabilities, highlighting the variability of DT types and supporting organisations in internally evaluating their current digital twinning context; finally, in Section 5, some conclusions are drawn, and potential future developments are identified.

2. Functional Architecture of Digital Twinning

2.1. Terms and Definitions

Previous research has been dedicated to both reviewing the knowledge on DTs and seeking a harmonised definition that could be adopted by peers in future works. Despite the succession of such endeavours, a systemic difficulty in adopting these contributions and interpreting the concept of DTs in a harmonised manner seems to persist.

In general, interpretations about DTs vary from the more purist, i.e., those closer to the original definitions and interpretations of digital twins, to the more comprehensive ones, which encompass not only what the former define as DTs but also the so-called digital models and digital shadows, for instance. These differences have been identified in literature reviews, such as those by Vieira et al. [6] and Liu et al. [10].

Although each author may have their own perspective on the subject and have a specific conceptual position within the spectrum of interpretations mentioned earlier, this article aims to focus on the structural elements that are broadly shared across various interpretations of DTs. In practice, each of these structural elements exhibits its own spectrum of variability. This variability is defined based on several factors, such as the objectives of a DT, the context (both internal and external), and the available resources, among others. This set of elements constructs the comprehensive concept of digital twinning.

The term "digital twinning" was implicitly introduced by Michael Grieves in 2002 when he presented the first model of a "digital twin" [19]. The term was explicitly used in 2005 in a UNESCO report titled "Towards Knowledge Societies" within the context of digital partnerships between local governments. Currently, the term is sometimes narrowly associated with the collection of point clouds of physical objects (e.g., [20,21]). This article does not adopt that perspective and favours a more comprehensive concept of digital twinning. This work embraces an interpretation shared by several authors [22–24], which presents digital twinning as the process of replicating physical objects and processes through digital technologies. The perspective of digital twinning offers the advantage of harmonizing discussions about what truly constitutes a DT by emphasizing that mirroring physical assets into the digital world can manifest in multiple dimensions. Furthermore, the concept of digital twinning does not dismiss the various and sometimes conflicting interpretations found in the literature. Instead, it establishes a shared understanding, enabling both authors and organizations to position themselves within the diverse levels of digital twinning. This can be particularly beneficial given the general lack of understanding among many organizations regarding the capabilities and functioning of DTs, as previously discussed.

According to Primalis and Kantaros [25], even though DTs hold significant value generation potential for organisations, their use may not be necessary for all physical assets. This is because not all assets and their respective uses require intensive and automatic data flows, and, therefore, their use may not be financially viable. Therefore, the primary objective of digital twinning should not be to achieve a specific level of development but rather to serve the purpose and meet the needs of asset management in the most effective and efficient manner possible. In other words, digital twinning should seek to generate the highest possible value for the organisation and its stakeholders from the opportunities offered by digital transformation.

According to the Gemini Principles (Figure 1), proposed by the Centre for Digital Built Britain [26], DTs must have a clear purpose, be trustworthy, and function effectively.

Figure 1. The Gemini Principles [26].

As with asset management, digital twinning should also follow a set of fundamental principles. In asset management, value, alignment, leadership, and assurance are the so-called fundamental elements. Several of the principles in asset management and those identified in Figure 1 for DTs are corresponding. Purpose, value creation, alignment, curation, and trust align with some of the fundamental principles of asset management outlined in ISO 55000:2014 [27].

Just as the main role of assets is to generate value for the organisation, the digital twinning of those assets must also enable the creation of value. Alignment in asset management is essential to ensure that asset management plans, decisions, and activities enable the achievement of organisational objectives [27]. Likewise, the purpose of digital twinning is crucial in defining the type of digital solutions that are most appropriate and, consequently, the processes, people, and technologies needed to help achieve pre-established goals.

Finally, in asset management, assurance aims to ensure that assets fulfil their function, which requires continuous monitoring, review, and improvement. Similarly, in digital twinning, it is necessary to ensure that digital solutions are reliable (through security, transparency, and quality of data, for example) and that there is curation (through accountability, governance, and regulation) to ensure that the purpose is achieved and the generated value is maximised.

Another characteristic of DTs outlined in the Gemini Principles is evolution. According to the authors, a DT should allow for adaptation as technology and society evolve. This principle precisely reinforces the idea that it is more important to understand what kind of opportunities can be addressed by digital twinning and how it can evolve over time (based on organisational objectives and the needs and expectations of stakeholders) than to delve into detailed debates about the best definition for a DT.

Having established the fundamental principles, it is now important to identify the structural elements that underpin the concept of digital twinning. To achieve that, the authors refer to the definitions proposed by some of the leading entities studying the concept of digital twins (Table 1).

Table 1. Definitions of the DT concept.

Source	Definition
[28]	A DT is a virtual representation of real-world entities and processes, synchronised at a specified frequency and fidelity. DT systems transform business by accelerating holistic understanding, optimal decision making, and effective action. DTs use real-time and historical data to represent the past and present and simulate predicted futures.
[29]	(. . .) simply having a model, or a simulation without real data, or a dashboard without feedback or control of a real entity is insufficient to be called a DT. You need all the criteria (. . .) to be categorised as a DT.
[30]	A digital representation of a physical asset or the service delivered by it, used to make decisions that will affect the physical asset. Any changes to the physical assets will be reflected in the DT.
[31]	A DT is a representation of a physical asset or system in a digital form. A DT allows visual performance insights through continuous data inputs.
[32]	A DT is a digital replica of an artefact, process, or service that is so accurate that it can be used as basis for taking *decisions*. The digital replica and physical world are often connected by streams of data.
[33]	[manufacturing context] fit for purpose digital representation of an observable manufacturing element with synchronisation between the element and its digital representation

From the previous interpretations, the following structural elements of digital twinning can be extracted:

- Physical entity: this can be a physical asset, a group of physical assets, or a process involving physical assets;
- Data: data is generated and exchanged between the physical and digital spaces, with different levels of automation and a certain frequency and precision, thereby ensuring synchronisation between physical and virtual spaces;
- Digital models: these models aim to represent the physical entity with a certain level of fidelity and, based on existing data, generate new data and information to support decision making;
- Decision making: the main use of DTs is to support decision making in view of realising value from the physical entity and the corresponding data and digital model.

These elements are further integrated with processes, people, and technological resources, such as data acquisition and storage systems, enterprise management systems, and security systems. These interact with the digital space and ensure data security, openness, curation, and federation, among other aspects.

2.2. The Architecture

From an organisational perspective, the digital twinning of physical assets aims to support and enhance confidence in asset management decisions, whether at a strategic, tactical, or operational level. This implies that digital twinning itself must undergo a process of continuous improvement to ensure that the solutions remain fit for purpose and aligned with the organisational objectives.

For instance, the quality of data feeding into digital models is crucial for the quality of the decisions they support. According to Redman [34], the use of poor-quality data costs companies an estimated 15% to 25% of their revenue. The Portuguese Association of Water Distribution and Drainage [35] states that the frequency of data collection, the parameters on which it focuses, its reliability, how it is processed, archived, and made available to users, as well as its capacity for integration with other data, are relevant factors for the success of implementing such a strategy.

Turning to the functional structure of digital twinning, the architecture proposed by the authors (Figure 2) is built upon the foundational elements of the model presented by Grieves in 2002 and the structural elements presented earlier. This architecture maintains the tripartite structure composed by the physical space (physical assets and their context), the virtual space (comprising digital assets), and the communication flows between the two. This architecture also adds detail regarding the activities that occur within these spaces in a cyclical operational perspective.

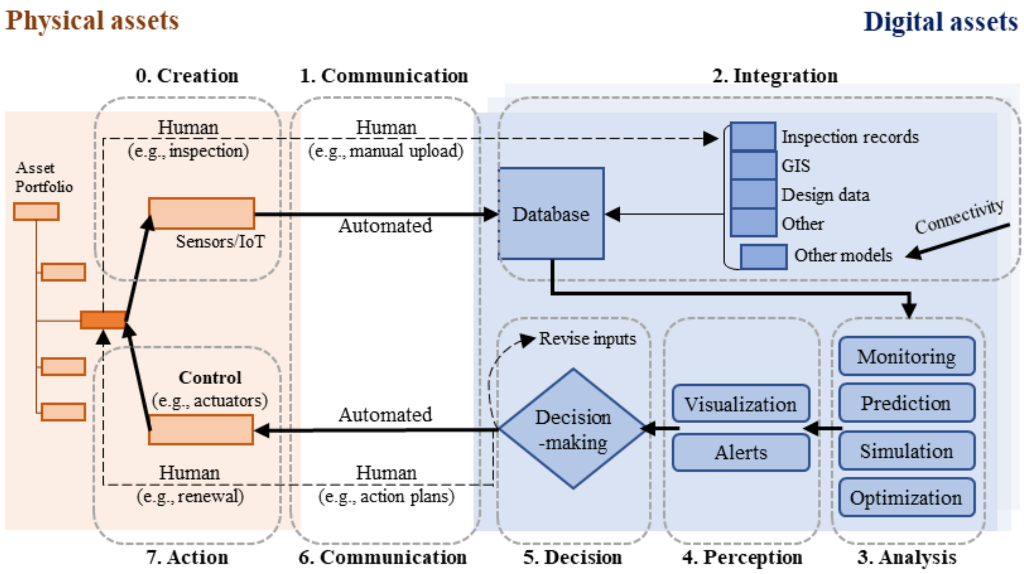


Figure 2. Proposed functional architecture for the digital twinning of physical assets.

Physical assets and their environment generate data, which is collected and then transmitted to the virtual space. The virtual space can be organised into three layers: data management, perception generation, and decision making [36].

The initial layer, data management, is responsible for integrating the data collected and communicated from the physical space, as well as their storage, cleaning, structuring, and other data processing and management activities. New data can be integrated with other existing data within the organisation in the form of other digital models and enterprise information systems. Ensuring data interoperability and security is essential for this purpose. In the next layer, data is modelled and analysed, and information is generated and made available to the user to support decision making, which corresponds to the last layer of this virtual framework. Decisions can also be more or less automated, as well as the information flow that leads to the action on the physical asset. The level of human intervention in this action depends on the purpose and the decision-making structure defined for the physical asset.

The so-called information value chain (Bolton et al., 2018) is present throughout the three layers that make up the virtual space. The volume of data used decreases while the meaning and value extracted from the data increases, in alignment with the well-known DIKW hierarchy (data–information–knowledge–wisdom) [37]. In this process of cumulative transformation of data into wisdom, data is collected from physical assets that ultimately become digital assets. These digital assets also have the particularity of being considered cognitive assets since they are necessary for converting individual knowledge into organisational knowledge, thereby ensuring coordinated actions within organisations [38]. Therefore, within the functional structure of digital twinning itself, it is necessary to ensure the management of various types of assets that support it, from tangible to intangible assets. In this context, the ISO/DIS 55013 [39] is under development, which will provide guidance, according to asset management principles, for managing data as assets and extracting the greatest value from them. Each of the aforementioned phases will be presented in the following sections.

2.2.1. Creation

In the creation phase, data is collected according to the parameters chosen to assess the performance of the physical asset (flow rate, frequency, strain, voltage, etc.) and the environment in which it operates (air temperature, precipitation, humidity, wind speed, etc.). These measurements can be made in a more manual way (e.g., visual inspection) or more automated, using built-in sensors or instrumentation installed on the respective physical asset, or even from external sources. Data can also be generated and controlled by entities external to the organisation (e.g., atmospheric data, satellite-based InSAR data). Data can be integrated within the organisation and managed as information assets. However, organisations should identify and address the risks associated with dependence on external data sources. Sensors generate signals that, before being transmitted to the virtual space, can be transformed into secure messages through encoders [40], increasing the security mechanisms (and their complexity) associated with managing these non-physical assets.

In this phase, other factors should also be addressed, such as the variables to be measured, the type of sensors, and the choice of data acquisition frequency. Based on the defined objectives and the existing knowledge about the asset behaviour, the most relevant parameters for instrumentation should be selected, as well as the means and locations for their measurements. Factors such as the cost of instrumentation, accessibility for installation and replacement, and exposure to external agents (e.g., vandalism or the influence of nearby electromagnetic fields) should be considered in this decision. Phenomena that can distort the quality of the final information due to an incorrect data acquisition frequency (such as the aliasing effect) should be studied and prevented. The organisation should also aim to optimise the acquisition frequency considering the associated costs. Depending on the cases, a higher frequency rate may not add value to the phenomenon being measured and yet significantly increase the costs associated with data collection, communication, storage, processing, and analysis.

2.2.2. Communication

Communication aims to ensure the transmission of data between the physical and digital spaces. Various technological solutions can be incorporated to ensure secure, efficient, and real-time data transmission. Edge processing seeks to transform data created according to proprietary protocols (characteristic of commercially available solutions designed for specific environments) into formats better suited for communication, facilitating this process.

Communication interfaces, which encompass a range of possibilities such as Wi-Fi, 4G/5G, Ethernet, and Satellite, are responsible for transmitting data from sensors to the virtual space, where they are then integrated. This phase has evolved significantly in recent years, driven by technological developments such as the Internet of Things.

Finally, edge security aims to ensure the security of data sent through mechanisms such as firewalls, encryption keys, and device certificates [40]. As assets become more dependent on the Internet Protocol for data transmission, the development of such security measures becomes increasingly relevant for organisations.

Nonetheless, certain data may be communicated manually, for example, after asset inspection. These data, although not transmitted automatically—and thus not contributing to the real-time synchronisation of the DT—can be aggregated later into databases and become part of decision support models. From the digital to the physical space, this phase is responsible for sending information about the decision made regarding the physical asset. If performed automatically, the transmission of information involves a coding process and then its transmission through signals to the actuators.

2.2.3. Integration

The aggregation phase is responsible for creating a data repository (data lake) and processing it, which can be done either locally or in the cloud [40]. Sensor data is aggregated with other data held by the organisation and integrated into the System of Records. This can include static or dynamic data, such as project data, bill of quantities, geographic information, supplier data, inspection records, data from enterprise systems (Enterprise Resource Planning, Enterprise Asset Management), or even data from other DTs (connectivity). Data processing and treatment in this phase prepare the data for the analysis phase and may include tasks such as detecting and removing incorrect or outlier data (which, for example, may be created by malfunctioning sensors), converting categorical values into ordinal ones, or normalising variables [41,42].

2.2.4. Analysis

Data can be analysed using various techniques, which should be chosen based on the initial objectives. Data analysis can involve descriptive statistics (measuring trends, central or relative location, dispersion, etc.), statistical modelling and predictive models, classification techniques, pattern identification, optimisation, simulation, and more. In general, data analytics serves three types of data services (or applications):

- Monitoring, which can be descriptive (if perceptions focus on performance without analysing the underlying causes) or diagnostic (if there is a root cause failure analysis);
- Prediction and simulation, where the goal is to predict the future behaviour of a phenomenon based on historical data and the combination of multiple scenarios. This application includes predictive models, stochastic and deterministic simulations, etc.;
- Optimisation, which can be considered prescriptive (if recommendations for improving asset/system performance are proposed) or cognitive (if these improvement actions are performed autonomously by artificial intelligence mechanisms).

Artificial intelligence methodologies, which aim to mimic human reasoning when supported by significant computing and data processing capabilities, unlock new types of applications and business opportunities. Some of these techniques include rule-based logic, conditions ("if-then"), decision trees, and machine learning (which includes deep learning techniques such as neural networks) [43]. These techniques are applicable to various purposes, such as diagnostics, pattern recognition, and task optimisation. Some effects include an increased capacity for perception generation, substitution of human labour in these functions, and improved task performance. Despite being a controversial topic, especially when discussing the role of humans, the use of artificial intelligence techniques should begin by focusing on tasks where there are mutual benefits, such as increased operational performance and allowing humans to focus on more tactical/strategic, supervisory, and lower-risk tasks.

2.2.5. Perception

The insights generated from data analysis can be presented in different forms depending on their objectives. Visualisation should use representations that are compatible with the type and purpose of the information to be presented, and can have varying levels of detail. The presentation can use geometric representations of varying complexity (2D, 3D), with models that integrate information (such as BIM, GIS, etc.), and interactive environments like virtual reality, augmented reality, real-time visualisation dashboards, alert systems, etc. Information can also be shared with multiple users, and the content that is shared and how it is presented should be tailored to the profile of each user (e.g., operator, consumer/client, strategic decision-maker), considering their needs and expectations. This phase focuses on how insights are communicated to various stakeholders in a format that is meaningful and relevant to their roles and responsibilities within the organisation. It ensures that the value derived from data analytics is effectively communicated and can be acted upon by those who need it.

2.2.6. Decision

The insights generated from the DT feed into the decision-making process associated with physical asset management. Decisions should consider the information presented by the DT and existing decision-making criteria, which may be constrained by diverse factors, such as physical limitations, budget constraints, time constraints, etc. Decisions can also involve reviewing input data (due to data or model misalignments, for example) to improve the quality of decision-supporting information.

2.2.7. Action

This phase ensures that the insights and decisions derived from the DT are effectively implemented, leading to tangible actions that impact the management and performance of physical assets. Actions can include controlling physical assets (decentralised decision-making processes using actuators), updating their back-end systems, or more indirect changes with greater human involvement, such as creating action plans (identifying types of actions, priorities, required resources, and more). This phase closes the loop between the physical and digital dimensions of the digital twinning functioning cycle.

3. Digital Twinning throughout the Life Cycle of Physical Assets

3.1. Uses and Life Cycle Phases of Physical Assets

In general, physical infrastructure assets undergo a life cycle comprising four phases: planning and design, construction, utilisation, and end-of-life. These phases exhibit distinct characteristics such as the nature of activities undertaken, duration, stakeholders involved, and impacts on third parties. According to these characteristics, various purposes [44] are defined. These uses are the basis for defining the requirements in the digital twinning of physical assets.

Across these phases, the asset undergoes several changes in its physicalness. This is a crucial point, considering that, according to prominent models and the architecture presented herein, the presence of a physical entity is a necessary condition to the concept of a DT. Hence, the absence of a constructed physical asset (or the process leading to the creation of one) and the absence of an automatic data flow invalidates the very definition of a DT. In phases where the entity lacks physical materiality, and thus the establishment of an automatic data connection with the digital space is not feasible, its representation solely exists in the digital space. In the digital space, data and models representing these entities are integrated, forming what is known as a digital model [45].

The knowledge transfer between the aforementioned life cycle phases—facilitated by the so-called "digital thread" [46]—has a significant impact on the value derived from assets. Information loss during the transition between phases in the life cycle of physical assets is a prevalent issue in the construction industry, which is generally characterised by low productivity [47] and significant process fragmentation [48]. A more traditional and innovation-resistant culture in the sector [15] and the absence of open and trustworthy information across the value chain are some of the identified reasons for this problem [49]. Poor interoperability across life cycle phases can result in rework, restarts, and the risk of data loss. These issues take on a special dimension when numerous stakeholders are involved, asset life cycles are long, and organisations retain information in silos, which are characteristics easily found in the infrastructure sector.

3.1.1. Planning and Design

In the planning and design phase of physical assets, the asset begins as an idea, which subsequently evolves into design and detailed blueprints, all without physical existence. Prior to effective construction, the asset may be replicated in the form of a physical prototype. This prototype can undergo testing, generating crucial data to validate design assumptions or make design changes before construction. Although planning and design represents a relatively small portion of the expected lifespan (especially in the context of infrastructure assets), it has a significant impact on the asset's life cycle (Figure 3).

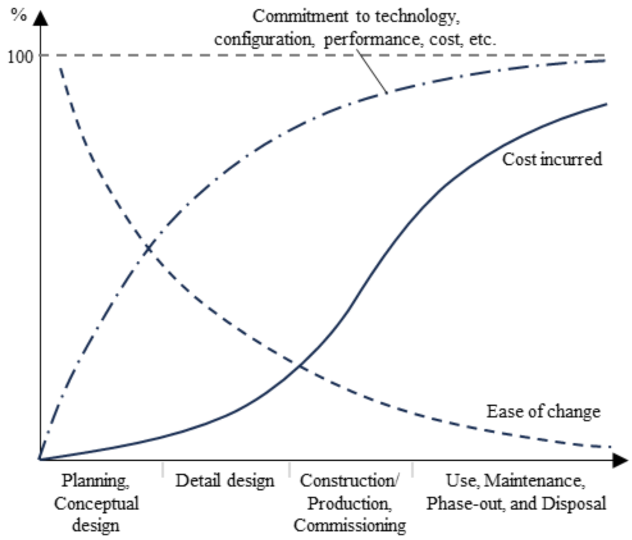


Figure 3. Ease of change and incurred cost across the physical asset life cycle (adapted from [50]).

During planning and design, there is a significantly greater ease of making changes and influencing the life cycle costs when compared to subsequent phases, where this flexibility diminishes sharply as the design is executed and the asset materialises [51]. In this phase, digital simulation and optimisation models prove valuable in reducing potential errors in the following phases, thus mitigating risks related to quality, safety, delays, and financial performance, among others. Although the design may need to be modified due to unforeseen circumstances during the construction phase, there is a range of opportunities for reducing the quantity and the impact of "avoidable" errors. These opportunities include joining and updating design versions, clash detection, and anticipating changes, assisted, for example, by interactive and immersive design visualisation.

Digital models, when used in a systematic and coordinated way, can also expedite permit emission processes by extracting crucial information required for accurate, transparent, and efficient licensing, such as minimum dimensions. However, it is important to note the existence of certain challenges, including the current lack of municipal capacity to handle this innovative methodology and the risk of data tampering, which should be mitigated through research and development. In this regard, ongoing projects like the European Network for Digital Building Permits at the European level and the Portuguese LiMA Platform are already addressing these issues.

Furthermore, there is potential to leverage more advanced analysis tools, such as machine learning techniques, to optimise and expedite the design phase. For example, machine learning methodologies can be applied to modular construction projects. They can help to identify the most suitable base module based on space characteristics and design requirements, reducing the process duration while ensuring a high-quality solution [52].

3.1.2. Construction

The construction phase represents the materialisation of the design phase, during which the asset transitions from the virtual space to the physical space.

During construction, costs increase significantly as the asset is brought into the real world (Figure 3). The ease of making changes to the asset decreases and the associated cost rises as construction progresses. Nevertheless, any errors in design or construction still have a relatively lower impact on the asset's life cycle compared to the subsequent phases. The construction sector remains one of the least productive, making the introduction of digital processes and technologies in this phase a promising opportunity for innovation and process transformation. Although the physical asset does not yet exist during the construction phase, the digital twinning of its construction process is still possible. The equipment and labour used in construction can be monitored for various purposes. Monitoring can help fine-tune equipment productivity estimates through data collection, enhance on-site safety by creating alerts or protection zones for workers (digital shielding, [53]), or provide more accurate progress tracking. Additionally, the entire logistics chain can be monitored and optimised. Tracking the arrival of specific materials at the construction site can be used to adjust project planning, communicate with interested parties, and improve the quality of constructed assets. For instance, in concrete pouring, the timing of fresh concrete arrival at the site is crucial for coordinating tasks (like formwork, reinforcement, concrete pouring, inspection, and safety control), as well as for guaranteeing the proper quality of the constructed elements. Once the task is completed, the physical properties of the constructed element can be monitored through embedded sensors in the material. Data such as temperature and strength can be useful for optimising subsequent activities (e.g., formwork removal) and ensuring proper execution of elements. Another example is the monitoring activity of paved roads, where the paver itself reads the pavement temperature and geolocates it for quality control and traceability purposes. Noteworthy examples include the BET4.0 and PAV4.0 demonstrators, developed under the Rev@Construction project [54], which are dedicated to integrated and optimised management of concrete pouring and pavement processes, respectively.

Beyond the opportunities presented by data collected from construction activities, there are also opportunities associated with other dimensions of digital twinning. Digital modelling of the construction site throughout the various construction phases can aid in site planning. Visual overlay of the design with the actual constructed elements presents valuable opportunities for multiple stakeholders. It serves as a straightforward and transparent means of communication among various parties involved in the construction project and a tool for quality verification and work planning. An example of such initiatives is the PointCloud4BIM activity of the Rev@Construction project [55], where a point cloud of the built environment is collected and then transformed into a BIM model (as built). This as-built model is subsequently compared with the as-designed model to estimate constructed volumes and analyse progress. These applications can also be highly useful in increasing the accuracy of estimates for the quantity of work and materials actually executed on-site, streamlining and expediting the invoicing of completed work.

3.1.3. Use

During use, the asset undergoes a continuous cycle of operation and maintenance, which typically has a longer duration than all previous phases, especially for civil infrastructures. In addition to the various opportunities identified during the planning, design, and construction phases, the use phase places extra emphasis on the dimension of time. This is because the asset's condition gradually deteriorates over time as it strives to maintain the desired performance levels. Hence, monitoring actions concerning both asset performance and condition (or risk of failure) become crucial in the overarching goal of extracting maximum value from it.

Sensors can be installed or be already embedded in some assets, allowing for preventative decision making and quicker response times. Reducing response times is essential for enhancing the resilience of infrastructure assets, a key objective of sustainable development [6]. For example, in the study by Yu et al. [56], a combination of BIM methodology and the Internet of Things is proposed to monitor the operational state of 100 jet turbines in a road tunnel. This system can anticipate potential failures and optimise maintenance activities through rule-based inference. These opportunities pave the way for a shift from a preventive or condition-based maintenance approach to a predictive one, wherein asset interventions are adjusted based on real-time performance data. This leads to increased resource efficiency (human, financial, and material), which is key to assuring environmental, social, and economic sustainability [6].

It is worth noting that there are also opportunities for sensor application involving external data acquisition means. In the operation of complex systems such as train operations, maximising the number of trains in circulation while adhering to demand and safety constraints is crucial. Satellite data, used to track the instant positioning of trains (via the GSM-R communication system), can reduce distances between trains, and consequently increase system capacity with ensured safety. In another example, satellite data (e.g., InSAR, i.e., Interferometric Synthetic Aperture Radar) is employed to monitor displacements in geotechnical structures and potentially detect early signs of instability [57]. Such solutions can present significant opportunities in addressing the barrier of high implementation costs identified by the industry, often cited in the literature [13,58]. Other technological tools, such as drones (UAVs), can be customised for specific uses, such as inspecting hard-to-reach locations (e.g., bridge piers and bridge decks) or large areas (e.g., vegetation near railway catenary). Besides improving data acquisition efficiency, these tools also reduce safety risks associated with such activities. Data acquisition using current technologies can also expand existing knowledge about asset behaviour (e.g., degradation models), potentially leading to more optimised life cycle management.

At certain times during the use phase, interventions may be required on the asset to restore the expected performance and mitigate risk levels. In such cases, having an adequate asset register and complete information (such as records of previous interventions, suppliers, costs, etc.) contributes to the quality and efficiency of the work to be carried out.

Opportunities also arise from automating construction processes based on the current condition of assets. One such case study is the RoboShot@FRC project [59], in which a robot shoots fibre-reinforced concrete into the voids found in tunnel walls (detected in the point cloud), and based on the structural reinforcement design specifications (e.g., concrete layer thickness), it automatically adjusts the amount of concrete to be shot along the tunnel surface. This solution optimises material consumption (with positive economic and environmental impacts) while reducing execution errors, time, and safety risks.

3.1.4. End of Life

Finally, when the asset no longer meets the needs and expectations, it may undergo more profound interventions, such as renovation or replacement, or even be deactivated or dismantled, marking the end of its useful life. Although this phase is often underrepresented in the literature on DTs [10], it is extremely relevant to the asset's life cycle. According to Azevedo [60], the end of life is one of the phases with the most deficiencies in organisational policies and strategies. Determining the optimal time for replacement is a recurring challenge in physical asset management activities, as multiple variables and inputs from different organisational levels contribute to this decision. Integrating relevant information for such decisions (such as replacement costs, operation and maintenance costs, available budget, condition, risk, lifespan, etc.) from dispersed information sources is a significant interoperability challenge.

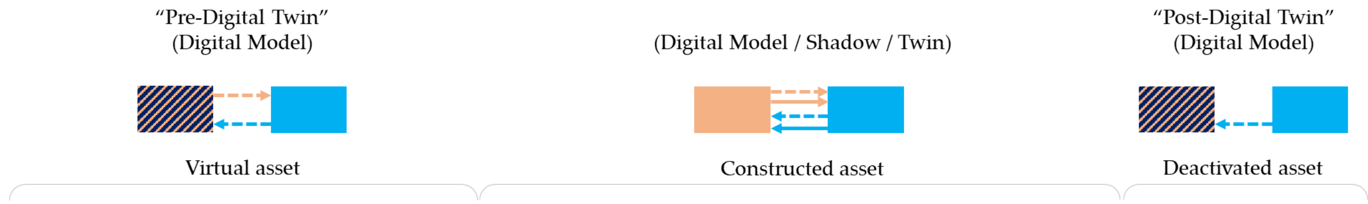
Some assets can still hold value when they reach the end of their useful life, such as historical or material value (selling the asset raw materials). In the latter case, the asset itself can be reintegrated into the life cycle of other assets, as with the incorporation of recycled aggregates in road pavement construction. These opportunities can improve the economic performance of asset life cycles and contribute to reducing the environmental impact of the new asset through material circularity. However, to achieve this, it is essential to know the type and quantity of materials available for incorporation. This information spans the entire life cycle of the asset, from the moment it was designed to the renovations it underwent over time. This type of information is particularly relevant when environmental or safety risks are associated with handling or disposing of certain materials. Therefore, knowing the type of materials involved and their location is key to ensuring efficient and safe end-of-life activities. Although much of this information can be included in BIM models, it is often not. Even highly detailed BIM models are not updated throughout the life cycle of the infrastructure. It is therefore critical to develop suitable workflows and semantic enrichment processes that enable non-geometrical information to be updated regularly [61,62].

When dismantled, the asset ceases to have physical materiality once again. Only its records of existence (digital thread) remain in the digital space. These records can be used, from a continuous improvement perspective, to optimise the management of the life cycle of current or future assets.

3.2. Summary

Table 2 summarises some of the opportunities previously mentioned, according to the four life cycle phases.

Table 2. Summary of digital twinning opportunities across the asset life cycle.



Planning and Design	Construction	Use	End of Life
Comparison and analysis of solutions	Timeline planning of construction	Operations planning	Prediction of the “optimal replacement” point
Budgeting and tender preparation	Quantity take-off for market consultation	Monitoring operational conditions	Extraction of types and quantities of materials
Detection of design conflicts	Quantity extraction for measurement reports and billing	Communication with users and stakeholders	Planning of repurposing, deactivation or dismantling
Design solution optimisation	Execution control (schedule, cost, quality, etc.)	Service optimisation	
Accelerating the licensing process	Planning of activities involving special safety risks	Response to unforeseen events	
	Human resource training in construction	Optimisation of maintenance activities (predictive)	
	Optimisation of the construction supply chain	Human resource training in operations and maintenance	
	Automation of construction processes		
	Accelerating construction commissioning		

4. Assessing the Level of Digital Twinning (LoDT)

As previously discussed, the digital twinning of physical assets unfolds in several dimensions, each of which may exhibit different degrees of complexity, requiring alignment with the pre-defined purpose. Therefore, the digital twinning of physical assets is an ongoing evolutionary process [63], albeit limited by its own scope, context, and application purpose.

Some authors have attempted to demonstrate the existence of different maturity levels of DTs through models of variable complexity and scope. For instance, Kritzinger et al. [45] focused solely on classifying differences in terms of connectivity. The International Data Corporation maturity model [64] addressed the perspective of collaboration within DTs. On the other hand, the models proposed by Digital Government Authority [65], TechUK [66], and Lamb [67] sought to distinguish the hierarchical levels of DTs.

Other authors such as Evans et al. [68], CDBB [69], Kim et al. [70], Bray [71], and BSI [72] focused on classification models with generic levels of DT.

Furthermore, authors like ARUP [73], IoT Analytics [7], Stark and Damerau [74], Harper et al. [75], Woods and Freas [76], Turner et al. [77], and Uhlenkamp et al. [63] identified specific dimensions in which the concept of DT may exhibit variability. Nevertheless, these proposals were often unclear regarding the distinctions between certain dimensions, incomplete, or overly detailed for an implementation that aims to be accessible and clear for most organisations.

Therefore, the authors of this study aim to harmonise the functioning of the proposed architecture with existing evaluation models into a unified assessment tool. This assessment model of digital twinning levels—entitled UNI-TWIN—seeks to support digital twinning strategies within organisations through a continuous process of evaluating the current situation, comparing it with other contexts (internal or external), and identifying potential development opportunities [63]. UNI-TWIN is not a maturity assessment model, wherein higher levels of digital twinning do not necessarily imply greater maturity. Conversely, relatively simple models in terms of digital twinning complexity may exhibit a higher level of maturity in some applications. Indeed, as specified in ISO 19650-2, an increase in detail can lead to waste, which should be avoided by carefully specifying and complying with information requirements [78]. Rather than assessing maturity, the UNI-TWIN model provides a comprehensive representation of the complexity in current or possible scenarios based on the dimensions that constitute the overarching concept of digital twinning.

The LoDT proposed in this paper shares common aspects with the Level of Information Need from the field of BIM. Since the publication of PAS 1192-2:2013, there has been a transition in requirement specification from a Level of Development (LOD) to a Level of Information Need. The evolution of BIM standards from a more prescriptive approach to one in which the requirements of the appointing party dictate the level of information requested [79,80] has taken decades and has required increasing maturity from the entities involved in the contracting processes, as well as the development of a broader regulatory context (including standards for models and for information management processes). As discussion continues in the field of BIM regarding the different levels of geometrical and non-geometrical requirements, still with a major focus on construction projects, there is a need to look outside the design and construction phases of physical assets and discuss if the existing requirement structure is sufficient to cover the broad concept of digital twinning. Because DTs are mostly known for integrating real-time data into the digital models, with major impacts on the use phase, there is a need to expand both the scope and the structure of the existing frameworks (e.g., [79]) to accommodate such differences. Some studies already address the potential integration of DT requirements into the existing BIM standards, such as [81], which can help bridge the two worlds in the future. As mentioned in [79], setting out concepts and principles for defining levels of information can deliver clear benefits to all participants in the various lifecycle phases of built assets, as they provide a common understanding on the level of information (needed or existing) at a certain time. This is exactly what the LoDT proposes to address, since there is an absence of a harmonized framework when discussing the many dimensions of DTs. Such proposal can be used, for example, to establish the minimum information requirements to be procured or to support the planning for investing in digital twinning.

Table 3 presents the dimensions of UNI-TWIN, which is a comprehensive and unified representation of the digital twinning of physical assets. Section 4.2 describes with more detail each of these dimensions. Table 4 provides the complete assessment model.

In addition to the dimensions presented in Table 3, other dimensions could be considered, such as the asset life cycle phases. The life cycle phases of physical assets have specific time periods and uses. In the case of physical infrastructure assets, which typically have extended lifespans compared to other types of physical assets (e.g., movable assets, products), the phases of operation and maintenance assume increased importance. However, the requirements of these phases and the associated degree of complexity are significantly different from other equally relevant phases, such as construction or planning and design, which, as discussed, have a significant impact on the asset's life cycle. Furthermore, the phases of operation and maintenance are strongly dependent on the previous phases due to a series of factors, such as construction quality, information availability and quality, etc. Therefore, in this work, the authors argue that the distinction between life cycle phases does not represent, in a clear way, the level of digital twinning of the asset, and thus the life cycle phases are considered purely descriptive. Eventually, one could consider that the number of life cycle phases integrated into the digital space would be a way to address this dimension. Nevertheless, non-geometric representation, which will be presented and discussed further in this section, can partially represent the temporal dimension, as the relevant non-geometric requirements for a given objective can span several phases of the life cycle, and any lack of this information (due to information loss in the transition between phases) should be demonstrated at the LoDT.

Table 3. Proposed model for assessing the LoDT.

Dimension	**Description**
Hierarchy	The hierarchical level of the physical assets pertaining to the case
Connection	The type of data connection between the physical and digital spaces
Synchronisation	The frequency at which data is integrated into the digital space
Geometric representation	The type of geometric representation of the physical space
Non-geometric representation	The level of representation of non-geometric characteristics of the physical space that are relevant to the defined purpose
Intelligence	The type of intelligence associated with data analysis
Interface	How users interact with the information generated in the digital space
Accessibility	The scope of users that access the information generated by the digital space
Autonomy	The autonomy level of digital space in decision making

4.1. UNI-TWIN—The Unified Digital Twinning Assessment Model

The proposed UNI-TWIN model for assessing the level of digital twinning of physical assets comprises nine dimensions: hierarchy, connection, synchronisation, geometric representation, non-geometric representation, intelligence, interface, accessibility, and autonomy. Each dimension has its own level of complexity, ranging from "1" (least complex) to "5+" (most complex). The "5+" rating is assigned to comprise cases that meet these criteria and those with even greater (and, sometimes, unforeseeable) complexity.

According to the presented model, the following remarks can be established:

- Since the concept of a "Digital Twin" requires a digital representation and a real-time data connection from the physical space to the virtual space, this interpretation can be associated with a minimum development level of 4 in the "connection" dimension and a level 2 in the geometric representation;
- Narrower interpretations of the term "Digital Twin" (e.g., [45]), such as the so-called "true Digital Twins" [91], which only admit automatic bidirectional connections between the physical and virtual spaces, correspond to a level 5+ classification in the "connection" dimension;

Table 4. Proposed UNI-TWIN model for assessing the LoDT.

Level	Hierarchy	Connection	Synchro.	Geom. Rep.	NGeom. Rep.	Intelligence	Interface	Accessibility	Autonomy
1	Component	No connection	No synchronisation	No geometric representation	No representation of non-geometric characteristics	Descriptive (what is happening)	No interface	Single user	No autonomy (decisions and actions executed exclusively by humans)
2	Asset	Manual data flow in both ways (from physical to digital and vice versa) (digital model)	Monthly/ yearly	Conceptual (the model is mass-indicative of area, height, volume, location, and orientation. It consists of symbols or other generic representations)	Only the necessary non-geometric requirements are represented, with flaws in quality, quantity and granularity	Diagnostic (why is it happening)	Local access	Minimal (multiple users in one team/department)	User-assistance (alerts and notifications are produced)
3	Asset class/group of assets	Semi-automatic in one way (e.g., manual acquisition supported by automatic tools like drones, RFID, or LiDAR)	Daily/ weekly	Approximate (the elements are partially defined by outlining their approximate quantity, size, shape, and location)	The necessary requirements are represented with adequate quality, quantity and granularity, without major data flaws	Predictive (what could happen)	Decentralised and shared access (e.g., cloud, smartphones/tablets)	Limited (multiple users across same-level teams/departments)	Partial autonomy (it has control over some activities)
4	System of assets	Automatic in one way (e.g., digital shadow, from physical to digital)	Hourly/ minutes	Precise (specific elements are confirmed as 3D object geometry. The model contains the accurate quantity, size, shape, location, and orientation.)	Both the necessary and important requirements are represented with adequate quality, quantity and granularity. Some data flaws can exist	Prescriptive (what should be done)	Immersive (Virtual Reality/Augmented Reality/Metaverse)	Advanced (multiple users across company structure)	High autonomy (critical tasks are performed autonomously, with little human intervention)
5+	System of Systems (portfolio)	Automatic in both ways (digital twin)	$\leq$seconds/ event-driven	As-built (a verified representation in terms of size, shape, location, quantity, and orientation)	All non-geometric requirements (necessary, important, nice-to-have) are integrated with adequate quality, quantity and granularity	Cognitive (application of human-like intelligence to cause something to happen)	Smart hybrid (e.g., multi-sense technologies)	Full (multiple users across stakeholders)	Limited options for human intervention
Ad. from:	[82,83]	[45,63,74]	[63,74]	[63,84–86]	[87,88]	[63,89,90]	[74,76]	[63]	[63,70,73,74]

- The so-called "Digital Shadows" [45], which envision an automatic data connection only between the physical and virtual spaces, correspond to a level 4 in the "connection" dimension;
- "Digital Models" [45], "Pre-Digital Twins" [58], or "Geometric Digital Twins" [92], which may not have connections to the physical space or have only manual or semi-automatic ones, correspond to levels equal to or lower than level 3 in the "connection" dimension;
- The so-called "Advanced Digital Twins" or "Intelligent Digital Twins" [58], because of their advanced analytical capabilities, using cognitive models that attempt to replicate human intelligence (artificial intelligence), correspond to level 5+ in the "intelligence" dimension;

- Because cyber–physical systems possess all the characteristics of a "true Digital Twin" but lack the geometric representation of the physical entity, these are assigned level 1 in "geometric representation".

4.2. Digital Twinning Dimensions

The descriptions of each of the nine dimensions are now detailed, as well as the main differences between the five levels of development.

4.2.1. Hierarchy

Hierarchy is directly associated with the hierarchical level of the physical assets to which the purpose refers. At the lowest level of the hierarchy, the focus is on specific components of a physical asset, while at the highest level, it is on systems of systems of physical assets, such as portfolios of infrastructure (water, transportation, energy, etc.). Examples of this level include DT projects at the city level, such as Zurich [93], or at the national level, as seen in projects like Virtual Singapore [94].

4.2.2. Connection

In accordance with existing classifications, the data connection between the physical and digital spaces can vary in terms of automation or, in other words, of manual intervention. At the lowest level, there is no connection (e.g., in the initial phase of the asset's life cycle). Level 2 is associated with manual bidirectional connection between the physical and virtual spaces, while the maximum level, 5+, is assigned to cases where bidirectional connection occurs exclusively in an automatic way. There can be mixed cases between these levels, where one direction of connection is handled both by manual and automatic means, resulting in a semi-automatic connection. A semi-automatic data connection occurs, for example, when data is collected using automatic digital technologies (e.g., point cloud collection using drones), followed by its manual processing and transmission to the digital space.

4.2.3. Synchronisation

Synchronisation reflects the frequency at which data is updated in the digital space through the communication phase (Figure 2). Each information requirement will have a minimum update frequency associated with it, and this dimension should reflect that. There are cases where certain data will only have a single update throughout the asset's life cycle (e.g., serial number or supplier), and depending on the defined purpose, this frequency may be adequate. However, there are cases where a higher update frequency is required to ensure that the collected data and the types of analyses remain valid and representative of the phenomenon under study.

4.2.4. Geometric Representation

The authors consider that, in a simplified manner, there are two types of information to represent in a digital model: geometric information (such as shape, appearance, detail, position, dimensions, etc.) and non-geometric information (asset type, design specifications, materials, dates, historical records, supplier data, etc.) [95]. Each digital twinning case has a specific purpose, and that purpose should specify and justify the type of needs for both geometric and non-geometric information [79]. Both geometric and non-geometric dimensions are aligned with the concept of Level of Information Need [80], which defines the requirements for geometrical and alphanumerical information needs for BIM. The Level of Development (LOD) [88,96] and the Level of Information (LOI) [87,97] proposed for BIM models are conceptually equivalent to the levels of geometric and non-geometric representations in the context of digital twinning.

Nevertheless, there are important differences that need to be addressed. While LOD and the LOI are commonly used for BIM project requirements, the levels of geometric and non-geometric representation are defined internally by the model owner to support the planning activities of the digital twinning journey. Moreover, the descriptions in the literature for the different LOD and LOI are closely related to some specific phases in the asset life cycle. However, the authors argue that the LoDT should not be directly defined by the asset life cycle phases. Instead, the life cycle phases should define the purposes that underpin the digital twinning construct, as outlined in Section 2.1. Therefore, the LoDT in terms of geometric and non-geometric information remain neutral with respect to life cycle stages, in contrast to existing proposals for LOD and LOI.

Mapping these information needs is key to guaranteeing that they are incorporated into the model according to the identified purpose. Moreover, the representation should be "fit for purpose", meaning it should not be more complex than necessary, as this can lead to inefficiency and no added value [63].

Geometric representation should align with the type of assets and the specific purpose at hand. In the asset management activities of infrastructures like roads, railways, water supply and drainage networks, and electricity and gas distribution networks, the traditional focus is on their geographical location and a network view rather than detailed geometry. For example, when making decisions at the level of a municipality's water supply network, data and digital models must be adjusted to the scale of the physical entity in question. Instead of a 3D geometric representation focused on asset details and geometric accuracy, there is usually a need for a broader view of the system, facilitated, for example, by Geographic Information Systems (GIS). However, if, for example, the purpose of digital twinning is to extract quantities of labour or materials for design and construction phases, geometric detail becomes more relevant, as it will influence the quality of the results. Therefore, there is a need for alignment between the defined purposes for each type of asset and the levels of geometric representation, which may require the same asset to be represented in different ways to meet different uses throughout its life cycle. This technological challenge is already being addressed by the industry, for example, through integrated and interoperable solutions between BIM and GIS models [54,98].

4.2.5. Non-Geometric Representation

Like geometric representation, the non-geometric information included in the model should attend to the needs defined by the application's purpose. One of the challenges in this dimension is to understand, right from the beginning of the asset's life cycle, what the non-geometric information requirements should be and how each of them will contribute to various purposes throughout the life cycle of these physical assets. On the one hand, there is a desire to acquire, store, and integrate as much information as possible into the model to prevent data deficits in the future. On the other hand, there is a desire for the model to be agile, with low implementation, operation, and maintenance costs.

Thus, a rational weighing of these approaches should exist, preferably from the early stages of the life cycle, to generate the most value from this type of information and its impact on physical asset management. A methodology like MoSCoW [90] can be adopted to achieve this. In this method, information needs are identified and classified according to priority levels ("Mo"—"must have", "S"—"should have", "Co"—"could have", and "W"—"won't have"), making the process more expedient, objective, and effective. This methodology also makes it easier to evaluate the effective level of non-geometric representation that the model can achieve in relation to global information needs, giving higher weight when priority needs are satisfied ("must have" and "should have") and lower weight when the opposite occurs.

The proliferation of enterprise management systems in organisations is another challenge. This turns data integration and interoperability into a complex task [99]. Additionally, data silos in organisations make the challenge even more complex, as the location and ownership of data are often unknown, resulting in duplicate information.

Therefore, agile access to asset data and the expedient identification of information requirements are crucial for a digital twinning strategy. For a digital twinning strategy to maximise its value, it should be built on robust information management processes [14].

Although contributions in this area are still lacking [14], there are initiatives aimed at developing the aspect of information requirements in DTs. For example, Johnson et al. [14] propose a library of asset information requirements (AIRs) that covers various phases of the asset life cycle to support the development of DTs in the context of railway assets. The authors use the organisational objectives to find the AIRs through simple and critical questions that ultimately clarify the requirements for each asset type and use.

Following the purpose and context identification, the requirements to incorporate the digital space should be mapped. These requirements must be necessary and sufficient to address the various management decisions throughout the life cycle. Since some requirements can only be addressed with data in later phases, the model must be prepared from the outset to receive them. Other requirements, such as those associated with maintenance and repair, require information to flow from the design and construction phases to ensure the effectiveness and efficiency of activities during that phase. Therefore, mapping the non-geometric information requirements according to the expected uses is a key task.

The "non-geometric representation" dimension seeks to map which non-geometric information requirements were actually integrated into the digital space to support decision making relative to the non-geometric information needs. The UNI-TWIN model contains a qualitative scale of non-geometric information requirements integrated into the virtual space. At the lowest level, the model represents only the necessary requirements ("Must have", according to the MoSCoW method) with flaws in quality, quantity, and granularity. At the highest level, the model contains the necessary, the important ("Should have") and the nice-to-have ("Could have") non-geometric requirements. Users of this model should adjust the classification considering factors such as the quantity and the detail of data, which may influence the quality of representation.

4.2.6. Intelligence

The "intelligence" dimension reflects the complexity level of data analysis for each case study.

Descriptive analysis has the lowest complexity level. This type of analysis seeks to answer questions about what happened, using techniques for summarising large amounts of data, such as arithmetic mean, frequency, range, etc.

Diagnostic analyses, aimed at understanding why something happened, correspond to complexity level 2. In these analyses, there is a need to understand how data interact with each other, and data mining techniques like classification, pattern identification, and clustering are used.

Level 3 of this dimension is related to predictive analysis. Predictive analyses seek to answer what is likely to happen in a future scenario. In this type of analysis, historical data are often used to identify trends and statistical regression analyses are used for such cases. In other cases, the use of physical-based simulation models (e.g., structural behaviour, energy performance) and different input data also allows for predicting the response of the asset or process in future scenarios.

Prescriptive analysis is classified with level 4 of complexity. It aims at identifying what should be done based on multiple forecasts. A common application of this type of analysis is route recommendations in applications like Google Maps, Waze, etc.

Finally, cognitive analysis represents the highest level of complexity. This type of analysis employs various techniques that simulate human reasoning (artificial intelligence) to solve highly complex problems. Cognitive analyses frequently involve vast amounts of data, significant computational capabilities, and sophisticated algorithms. A recent example of this type of application is ChatGPT.

4.2.7. Interface

As crucial as the analysis being conducted is how the results are presented to the user, both for review and decision support purposes. The level of interface ranges from Level 1, where users have no means of interacting with the results generated by the virtual space, to Level 5+, where users can interact with the information in a multisensory manner. The higher the level on this dimension, the greater the associated complexity. However, there is also a closer connection between the user and the information pertaining to the physical entity. This may enable the generation of perceptions and increase both their richness and the quality of decision making.

4.2.8. Accessibility

Besides the way users interact with information, it is also relevant to understand who has access to it and who should collaborate in the decision-making process. In certain cases, the specificity of the information generated must be confined to a limited number of users, while in others, participation and sharing of information with other entities are necessary to ensure work review and quality of the decision. Thus, the dimension of "accessibility" ranges from a single user (Level 1) to multiple users belonging to various stakeholders within the organisation (Level 5+).

4.2.9. Autonomy

Lastly, the dimension of "autonomy" seeks to assess the level of dependence on human action during the decision-making process. The autonomy of a system, like all other aspects, should be designed according to the context and purpose at hand. High autonomy may allow for the relocation of human resources to other tasks (impacting productivity and even occupational safety). On the other hand, it may result in less control over decisions. The autonomy level varies from the complete absence of autonomy in the digital space (Level 1) to such high autonomy that human intervention is limited to certain cases (Level 5+).

4.3. Summary and Additional Observations

Table 5 summarises the relationship between the structural elements of the DT concept, the phases of the digital twinning functional architecture, and the corresponding dimensions.

Table 5. Correspondence between DT elements and digital twinning phases and dimensions.

<table>
<tr><th>DT Element</th><th>Architecture Phase</th><th>Dimension</th></tr>
<tr><td>Physical entity</td><td rowspan="2">Creation</td><td>Hierarchy</td></tr>
<tr><td rowspan="3">Data</td><td>Connection</td></tr>
<tr><td>Communication</td><td>Synchronization</td></tr>
<tr><td>Integration</td><td>Non-geometric representation</td></tr>
<tr><td rowspan="2">Digital models</td><td>Analysis</td><td>Intelligence</td></tr>
<tr><td rowspan="2">Perception</td><td>Geometric representation</td></tr>
<tr><td rowspan="3">Decision making</td><td>Interface</td></tr>
<tr><td>Decision</td><td rowspan="2">Autonomy</td></tr>
<tr><td>Action</td></tr>
</table>

In addition to the dimensions previously discussed, connectivity between DTs is also a relevant and frequently mentioned topic in the literature. According to prominent perspectives, a DT of a specific physical entity can be connected to other DTs, from which it can extract more and better information to generate greater value for the set of assets in question and the services they provide [67]. This is particularly relevant in the case of networked asset systems.

Emerging projects related to smart cities and national-level DTs make the discussion about connectivity and federation even more significant. The structure in which DTs are constructed and then integrated into organisational systems can vary depending on the purpose and context of each. There can be an ecosystem of connected and federated DTs, as well as a DT of various connected physical asset systems.

Nevertheless, it is essential to clarify that the concept of a National Digital Twin (NDT) will never truly be achieved because not all physical space will be or can be digitally twinned, and not all digital models will be federated. On the one hand, physical space is continually evolving, and only a portion of it is useful to represent. On the other hand, connectivity between various digital models should serve a specific purpose and should only occur when the generated value justifies it [26], meaning that not all models should be connected. An NDT will always result from the digital twinning of several physical entities within its scope, whose models are federated into groups according to the various defined purposes. The significant challenge of a NDT lies in ensuring interoperability among all these elements, rather than whether all physical entities in the real world are represented or their models are federated. The connectivity and federation of digital twins also bring other challenges, including data storage, security, and information sharing.

Therefore, security, ownership, resilience, and interoperability requirements must be incorporated from the beginning of digital twinning strategies [67,100]. As an example, there are ongoing efforts to leverage blockchain technology to ensure data integrity and increase trust in data transactions in collaborative construction environments [101].

4.4. Digital Twinning Level of Road and Rail Case Studies

4.4.1. Context

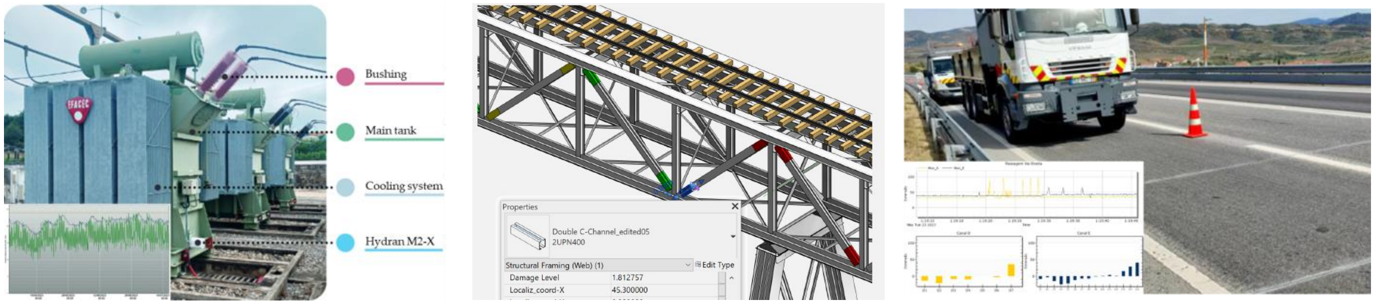
Infraestruturas de Portugal (IP) is the biggest transport infrastructure manager in Portugal and is responsible for the construction, operation, and maintenance of road and railway networks. This organisation manages almost 15.000 km of national roads and more than 3.000 km of railway networks [102], distributed by multiple asset groups (road pavements, rail track, switches and crossings, power equipment, engineering structures, etc.). In 2023, IP established 50 innovation challenges [103], one of which related to the creation of digital twins of road and rail infrastructure. While IP recognizes DTs as innovative solutions, their full meaning and potential impacts remain incompletely understood. To bridge this gap, a series of case studies were undertaken to first validate the UNI-TWIN model and subsequently communicate, both internally and externally, how the various dimensions of digital twinning are embedded in IP's innovation projects.

4.4.2. Case Studies

Three case studies (Figure 4), covering both road and rail networks, were selected to validate the applicability of the UNI-TWIN model:

- Case study [A] [104] involves a real-time Dissolved Gas Analysis (DGA) system in a power transformer at the Salreu traction substation, located on Linha do Norte railway line. The Hydran M2-X unit continuously monitors and communicates gas and moisture levels in the power transformer oil. It promptly alerts the user to abnormal readings, minimizing the risk of unplanned outages and reducing the associated costs of reactive interventions.
- Case study [B] [105] focuses on the federation and interaction of a Fatigue Analysis System and a BIM model for the Várzeas railway bridge, located on the Linha da Beira Alta railway line. This integrated solution enables decision-makers to simulate traffic scenarios and predict the fatigue life of the bridge, facilitating informed long-term investment decisions.
- Case study [C] [106,107] is a real-time monitoring system for a section of road pavement on the IC5 route, km 75 + 700. The project goal is to develop a pavement condition prediction model, integrated with a geometrical model, to support long-term renewal planning. At the present time, the system has only real-time monitoring capabilities (e.g., strain, temperature, and number of vehicles), so the predictive capabilities and the integration with the geometrical model are still to be achieved.

Case study [A] (Rail) Case study [B] (Rail) Case study [C] (Road)



Real-time DGA system in a power transformer Fatigue life prediction of a metallic bridge Real-time monitoring of pavement condition

Figure 4. Identification of case studies.

Table 6 provides a brief description of the case studies and their characteristics according to the nine dimensions of digital twinning. Each description is based on available documents and project information provided by the experts of IP.

Table 6. Digital twinning level of road and rail case studies.

Case Study	Hierarchy	Connection	Synchron.	Geom. Rep.	NGeom. Rep.	Intelligence	Interface	Accessib.	Autonomy
[A]	(1) Component (oil of a single power transformer)	(4) Automatic from physical to digital space (via Ethernet)	(5+) Readings sent to user every 15 s	(1) No representation needed for this testing phase	(3) PT ID, location, temperature, moisture and gas readings; it lacks gas characterization	(1) Has the ability to detect abnormal readings according to pre-defined thresholds	(2) Local computer with specific software	(1) A single user has access to these data	(2) Sends alerts in case of abnormal gas concentration values
[B]	(2) Asset (Várzeas bridge, with component detail in the results)	(2) Input of internal and external data were mainly manual/off-line	(1) One-shot data inputs and simulations	(5+) As-is BIM model, LOD 300	(3) There is a lack of historical data related to a key variable (historical loads), but recent data and estimates are key inputs	(3) Predictive capabilities through the analysis of past demand and structural simulation	(2) The integration between FAS and BIM is supported by Dynamo API, accessible on one local computer	(1) Single user	(1) No autonomy
[C]	(1) Two lanes of a road section	(4) Automatic from physical to digital space (via Ethernet)	(5+) Real-time data (<seconds)	(1) No representation for this testing phase	(3) Strain, temperature, time	(1) Descriptive analysis Goal: prediction of pavement behaviour through ML (level 3)	(1) Local computer Goal: an integrated APP (level 3)	(1) Single user	(1) No autonomy

Based on the characteristics of each case study and the levels assigned to each dimension of digital twinning, it is possible to construct the digital twinning radar shown in Figure 5.

As shown in Figure 5, the case studies of the power transformer ([A]) and road pavement ([C]) have a more pronounced level of digital twinning in the components of connection and synchronization. This is justified by the real-time monitoring purpose of these assets. On the other hand, the metal bridge case study ([B]) exhibit a high degree of development in the geometric representation component, indicating some expertise in this dimension. Case study [B] stands out with the highest level of intelligence, attributed to its goal of predicting the long-term fatigue life of the bridge. Case study [C] also aims to develop predictive capabilities based on collected data but currently only has the capacity for descriptive analyses. It is essential to investigate whether the development of machine learning models, as initially envisioned in the project's objective, can generate sufficient value for the organization to justify its investment. The dimensions with lower levels of development are hierarchy, interface, autonomy, and accessibility, which, at most, reach level 1 or 2. This is generally attributed to the fact that the projects are recent and still remain in an exploratory phase. Thus, the current priority is to understand the impacts generated by these implementations and not so much on developing other dimensions (e.g., expansion to more assets, creation of shared interfaces, etc.).

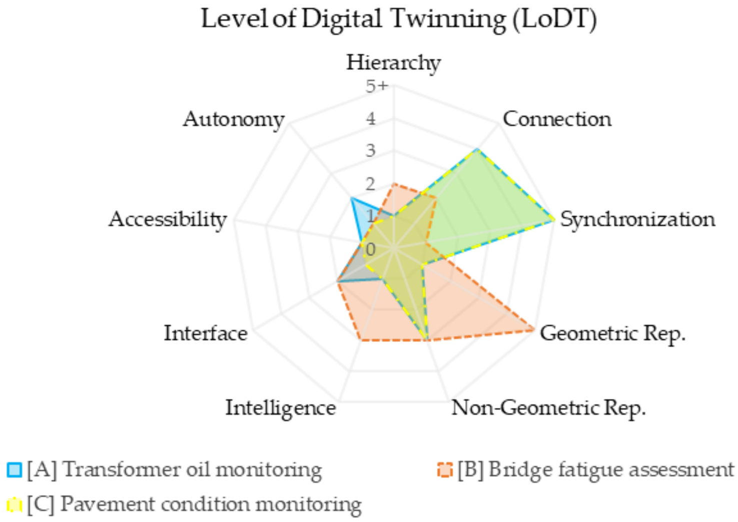


Figure 5. Level of digital twinning for each case study and respective capabilities.

5. Conclusions

This article proposes an approach to the study of DTs that is less focused on specific definitions and more centred on the principles that gave rise to this popular concept. This approach, named digital twinning, is presented here as an evolving process that must satisfy the fundamental principles of DTs and the intended purposes for each physical asset throughout its life cycle. To achieve this, the study relied on the main interpretations of the concept to establish the fundamental principles of digital twinning and proposed a harmonized functional architecture. Given that digital twinning is a continuous and variable process across a set of dimensions, this study sought to map the main uses of digital twinning in the lifecycle of physical assets, as well as the dimensions that define this variability. Recognizing the importance of having a model that distinguishes different levels of development within the concept of DTs, this article proposes an evaluation model considering nine dimensions of digital twinning. Although some dimensions are easier to interpret and assess than others, the main objective was to identify and harmonize these dimensions and propose the model for discussion. This study used three ongoing innovation projects in the domain of road and rail infrastructure in Portugal to validate the model's applicability. Each project was classified according to the levels of development in each of the nine dimensions. In future work, the authors intend to expand the asset base and case studies to further emphasize the benefits of such assessments.

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