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Seeking a Definition of Digital Twins for Construction and Infrastructure Management

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Abstract: The integration of digital twins (DTs) in construction is still in its infancy compared to other sectors. However, the potential for optimising project lifecycle management is significant, promising transformative impacts on safety and operational performance. In this study, the evolution of technologies preceding DTs is explored. A detailed description of the various platforms where DTs can be implemented is discussed and parallels are established with other sectors, such as manufacturing and healthcare, highlighting the successful application of DTs in these fields. The key benefits of integrating DTs in the construction industry and complex infrastructure management are assessed, emphasising that the accuracy of asset representation is crucial for their effective utilisation. Moreover, the challenges associated with recording, storing, and accessing both static and dynamic data are discussed, providing insights into the pros and cons of managing data through back-end versus front-end processes. Case studies of a transport railway station and an educational centre illustrate the practical applications and advantages of DTs, such as enhanced visual representation, improved understanding of construction and management dynamics, real-time information integration, and collaborative management processes. This paper advocates for the first steps toward establishing a European definition of DTs and standardising the relevant processes.

Keywords: digital twins; construction industry; standardisation; lifecycle management; built asset

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1. Introduction

Virtual models, mock-ups, and simulations, as well as the use of scale models of any construction project has been part of the design phase of most relevant buildings and infrastructure. In recent years, regulation in the use of building information modelling (BIM) for construction has updated this concept, raising new possibilities for its implementation and development in infrastructure management throughout the life cycle of the asset. Once a digital representation of the project and the construction information are obtained, a range of other technologies can be used for different purposes and become what has been identified as a digital twin (DT).

DTs have been applied successfully in relevant fields, such as aeronautics [1], medical applications [2], agriculture [3], and industrial processes [4]. The first definition of a DT is attributed to Michael Grieves [5,6] and was applied to industrial processes. Its main goal was focused on the possibility of product lifecycle management (PLM) as an integrated information-driven approach concerning all aspects of a product's life, from its design to its removal from service and disposal. This study shows that the advances in other fields have shown potential benefits for the construction industry which, if they are merged with BIM, can become of significance in the following years. According to [7], DT technology applied to the retrofitting buildings has the potential of reducing greenhouse gas (GHS) emissions during the operational stage by up to 30%.

However, the construction industry has important differences with other engineering fields where DTs have been implemented. Both building and infrastructure projects are performed only once with few repetitive processes as they usually depend on the topography of the terrain, characteristics of the soil, and climate and social needs, among other factors. The construction of two identical projects would not be performed in the same way for two different worksites, or by two different companies. These singularities have made the industrialisation of the sector a challenge in every country [8]. BIM has been a good step forward in this regard and the next expected step [9] seems to be the advancement of a DT for the built environment encompassing the use of DTs for building and infrastructure. Having said that, this definition is still a matter of research.

DTs originated in aerospace engineering and were defined, in the field of aerospace systems, as "a set of virtual information constructs that mimic the structure, context, and behaviour of an individual unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its lifecycle and informs decisions that realize value" [10]. A previous definition in the aerospace sector was provided by NASA in 2012 [11]: a Multiphysics, multiscale, probabilistic simulation of its corresponding flying twin, utilising the best physical models, sensor updates, fleet updates, history, and so forth.

ISO 23247-1 [12] refers to digital twins in the field of manufacturing as a fit for purpose physical element representing a set of properties of an observable manufacturing element with synchronisation between the element and its digital representation, but the definition is not yet consistent across the various standards that have been developed (or are under development) in different fields.

Khan et al. [13] reviewed the standards and the definitions applicable to DTs until 2023, concluding that the standardisation of DT technology is vital for its implementation.

This study seeks to address and advance the definition of DTs for the built environment by gathering the set of information and initiatives that are taking place and discuss the most important matters of disagreements with the aim of achieving a certain initial consensus. These initiatives include the standardisation work under development in CEN/TC 442/WG 9, "Digital twins in the built environment", the review of current systems used for DTs and research projects including Chronicle (GA 101069722) and DIGITWIN4CIUE (GA 101084054).

While it can be too early to develop a black letter definition of a DT for the built environment, the first bricks on this definition must be proposed to measure their fit in the industry. There is great interest not only in developing DTs for construction sites but for urban ecosystems. In this context, infrastructure and urban ecosystems work with quite different necessities. According to this, the importance of European and international standards for definitions, modelling, or data management is highlighted and detailed in this paper.

2. Methodology

The research is based on a structured and systematic review of existing definitions for digital twins and digital models applied to construction assets. The objective is to propose definitions for digital twins in the built environment, leveraging a comprehensive review of academic research and international standardisation efforts.

The methodology is designed to ensure inclusivity, accuracy, and relevance in the proposed definitions. It is based on the revision of existing definitions from the academic literature and standardisation documents at the international and European levels. A systematic literature review was conducted to gather existing definitions and conceptualisations of digital twins, searching in Scopus, Web of Science, and Google Scholar with combinations of the following keywords: "digital twin", "built environment", "standardization", "construction asset", "building", "BIM", and "definitions". The same search was made in repositories of standardisation organisations (ISO and CEN). The results were analysed during the study, grouping them into broader categories (e.g., components of digital twins, functionalities, implementation contexts) and comparing the definitions to identify consistencies, gaps and trends.

The results are also based on the analysis of digital twins from research projects (Chronicle and DIGITWIN4CIUE). It also considered the use cases submitted to CEN/TC 442/WG 9, "Digital twins in the built environment", published as CEN/TR 18077 [14].

3. Digital Twins Current State of the Art

3.1. General

The question of what a DT is, when it comes to civil infrastructure, is not clearly defined. There are different levels of representation of reality in a digital world, and different classifications have been developed accordingly.

Based on the level of organisation, Rudrappa [15] established that prototypes, instances, aggregates and environments can be differentiated. Prototypes (DTPs) are a description of the physical artifact and, before it is fully built and/or manufactured and thus ready to start its operation phase, contains the information of the real objects. For example, it could be a 3D model with the bills of materials, specifications and processes of such entity. Instances (DTIs) contain the information included in the prototype along with the results of measurements, service records, replaced components and other similar information. Aggregates (DTAs) are the sum of DTIs and the connections among them. It retrieves various data from the DTI, including sensor readings, and analyses them together. Environments (DTEs) are the end-to-end environment setup to operate DTs. The operation receives information from machines, analyses the data, and performs a predictive analysis behavioural analysis. As mentioned before, Grieves [5,6] proposed a definition with the same names but targeting different objectives. The first regarding the lifecycle of the product, the second regarding the degree of DT capabilities, powers, or levels of implementation.

When the functions of DTs are considered, DTs might be classified as status twins, operational twins, or simulation twins [16]. Status twins are integrated into analytics systems and include monitoring tools, such as alerting systems, which will simulate various scenarios and situations to ensure the system will have a perfect response after installation. Operational twins are used to collect information on a certain process. For instance, it might entail running an engine test in order to detect problems and produce solutions.

Lastly, simulation twins sustain an integration of AI capability to ease the decision-making process in understanding how a system functions.

Apart from these classifications, if future developments of DTs are considered another classification might appear [17]. A pre-digital twin is a virtual prototype used for a preliminary development in order to reduce risks and identifying an upfront design. A DT is a virtual system that can incorporate performance or maintenance data of the real asset. The following level is called an adaptative DT. Such an entity offers an adaptative user interface which is capable of studying the preferences of human operators in different contexts. Lastly, the highest level is defined as an intelligent DT. Such twins can discern patterns and objects that might be found in the operating environment and apply them to an unsupervised machine learning capability.

Apart from the potential classifications that have been mentioned, it can be said that city-scale DTs are focused on enhancing the lives of the citizenry, with mobility plus services through human-centred technological innovations, as stated in [18]. Some of these cities include Bogotá [19], Helsinki [20], Brescia [21], Valencia [22], Dublin [23], Herrenberg [18], Shenzhen [24], and Zurich [25]. Different strategies have been employed to initiate actual urban DTs in their development by integrating data from multiple sources that generates huge operational data and also presents challenges for diagnosis and prognosis [26]. This amalgamation is facilitated by different types of information, like traffic, transportation, power generation, utility provisioning, water supply, and waste management. All this information can be managed using machine learning algorithms, such as k-means clustering [23]. Additionally, other examples of DT applications in smart cities are centred on real-time IoT sensory information that is used to achieve urban efficiency, sustainability, and security through decreasing resource consumption, which is discussed in detail hereafter. Furthermore, the use of big data in urban applications makes it possible to detect behavioural patterns and lifestyle interactions with population dynamics as well as economic development and infrastructure, according to [27]. However, detailed modelling of real-life systems demands substantial computational resources, storage, and data management, posing challenges yet to be fully addressed, particularly in domains like smart cities, where infrastructure limitations persist, and close monitoring of big data sets is essential for accuracy and stakeholder consensus [18]. These difficulties have been faced by the development of digital twin frameworks. Some of the most relevant are presented in the following paragraphs.

3.2. Digital Twin Development Frameworks

In the context of DT frameworks, numerous prominent open-source and proprietary solutions have emerged, each offering unique capabilities and applications across various domains, including smart cities, construction, Industry 4.0, and healthcare. This section highlights the most widely used frameworks; for more detailed information, readers are referred to [28], which provides an in-depth exploration, [29], which covers frameworks specification and requirements, and [30], which details approaches and methods. Additionally, systematic challenges associated with DTs are discussed by [31].

Eclipse Ditto [32] is an open-source framework that excels in creating and managing DTs, offering a middleware solution to abstract physical devices in digital representations. This abstraction enables both synchronous and asynchronous interactions through a comprehensive API, encompassing state management, secure access control, and extensive protocol integration. Particularly advantageous for construction, BIM, smart cities, and Industry 4.0, Ditto's capabilities facilitate diverse applications.

In construction and BIM, Ditto optimises building systems management by generating DTs for components such as HVAC systems, elevators, and security apparatus.

This functionality permits real-time monitoring, predictive maintenance, and operational enhancement. For instance, a DT for an HVAC system can continuously track performance metrics, forecast maintenance requirements, and optimise energy consumption based on real-time environmental data. Similarly, a DT for an elevator system can monitor usage patterns, anticipate potential failures, and schedule maintenance to minimise operational disruptions.

For smart cities, Ditto adeptly manages infrastructure elements, like street lighting, traffic signals, and waste management systems. By creating DTs for these components, cities can enhance performance, reduce energy usage, and improve service reliability. For example, streetlights can be monitored for energy efficiency, and traffic signals can be dynamically adjusted based on real-time traffic data to improve flow and reduce congestion.

In Industry 4.0, Ditto supports advanced manufacturing processes through the creation of DTs for factory equipment and production lines. This enables real-time monitoring, predictive maintenance, and optimisation of manufacturing operations. Abstracting physical machines into DTs allows manufacturers to simulate various scenarios, predict potential failures, and optimise performance without halting actual production. For instance, a DT for a CNC machine can monitor tool wear, predict maintenance needs, and adjust operational parameters to ensure optimal performance and reduce downtime.

Ditto's modelling capabilities are anchored in Vortolang, a metamodel based on the Eclipse modelling framework (EMF). This foundation allows for the precise and comprehensive modelling of DTs, capturing all pertinent properties and operations. DTs are connected to physical devices through protocols like AMQP, Kafka, and MQTT, ensuring robust data transfer and control. The framework supports bi-directional communication between digital and physical twins, fostering continuous development and maintenance—a critical feature for applications necessitating iterative improvements and feedback loops for performance optimisation.

Ditto's state management functionality is pivotal for synchronising physical devices and DTs, enabling real-time monitoring and predictive maintenance. By managing the reported, desired, and current states of devices, Ditto ensures synchronisation and the publication of state changes, allowing for precise system control and monitoring. The framework's fine-grained, resource-based access control guarantees secure interactions, essential for applications in sensitive or critical environments.

Eclipse Ditto's open-source nature offers significant advantages, including extensive customisation and community-driven enhancements. Users can modify and extend the framework to meet their specific requirements, ensuring suitability for unique system needs. However, challenges such as a steep learning curve and the necessity for familiarity with Vortolang and the Eclipse modelling framework may arise. Additionally, integrating Ditto with diverse systems may demand additional effort to ensure compatibility and performance.

Despite these challenges, Ditto's extensive features in state management, access control, and integration make it a robust and valuable framework for creating DTs in construction, BIM, smart cities, and Industry 4.0 applications. By leveraging these facilities, Eclipse Ditto enables the development of sophisticated DT solutions that enhance operational efficiency, predictive maintenance, and real-time monitoring across various domains.

Creating a DT with Eclipse Ditto involves several systematic steps. Initially, Vortolang is employed to define the digital twin's properties and operations through information models and function blocks. Integration follows, connecting the DT to physical devices via protocols, such as AMQP, Kafka, and MQTT, ensuring robust data transfer and control. State management is crucial, defining and managing the reported, desired, and current states to ensure synchronisation and the publication of state changes. This allows for precise system control and monitoring, enabling real-time adjustments and predictive maintenance. Secure access control is implemented using Ditto's fine-grained, resource-based access control, securing interactions with the DTs. Finally, visualisation and control are facilitated through Ditto's RESTful web services, enabling real-time monitoring, control, and optimisation of operations. For instance, in a smart city context, this might involve adjusting traffic signals based on real-time data to reduce congestion.

OpenTwins [33] is an open-source framework engineered for the development of next-generation compositional DTs, facilitating the creation of sophisticated DTs that interlink individual entities or subsystems into a cohesive higher-order DT. This approach enhances knowledge sharing data relationships, enabling seamless integration with 3D visualisations, IoT data streams, and real-time machine learning predictions. Built on a scalable platform for fault tolerance and high availability, OpenTwins supports the continuous development and integration of DTs, making it adaptable for diverse contexts, including Industry 4.0, construction, and smart cities.

In the domain of Industry 4.0, OpenTwins offers substantial benefits by enabling the composition of intricate DTs that can monitor, predict, and optimise various manufacturing processes. This capability is particularly evident in use cases, such as the petrochemical industry, where OpenTwins has been employed to develop a virtual analyser predicting the freezing point of lubricants based on real-time operational data. This application underscores the framework's potential to enhance process control and operational efficiency through continuous monitoring and real-time predictions.

OpenTwins excels in the integration of AI and machine learning, providing seamless orchestration with data streams for ongoing optimisation and prediction. The framework incorporates Kafka-ML, an open-source tool for managing the lifecycle of ML/AI applications with continuous data streams. This integration is pivotal for enabling predictive analytics and real-time decision-making in DTs, further augmenting their capabilities.

Another notable feature of OpenTwins is its support for 3D visualisation, achieved through integration with Unity. This capability allows for the interactive 3D representations of DTs, offering a more intuitive and comprehensive understanding of the monitored assets. The ability to visualise real-time and historical data in a 3D format enhances the user experience and facilitates superior decision-making.

The framework is architected with a microservice approach, increasing modularity, scalability, and reusability. This design allows for the addition, replacement, and connection of modules without disrupting the entire system, making it highly adaptable to various applications. OpenTwins also employs a container-based structure using Docker and Kubernetes, ensuring the efficient management, portability, and execution of the platform.

In the context of smart cities, OpenTwins can manage and optimise urban infrastructure components, such as street lighting, traffic signals, and waste management systems. By creating DTs for these elements, cities can achieve real-time monitoring, predictive maintenance, and operational optimisation, resulting in improved service reliability and reduced energy consumption.

OpenTwins' compositional approach also supports the creation of modular and flexible DTs, which can be reused and distributed across different devices. This capability is particularly beneficial for generating detailed and comprehensive analyses at both the individual and collective levels, significantly enhancing decision-making processes.

PhotoScene [34] is an open-source framework designed to convert images into detailed 3D scenes utilising advanced algorithms and pipelines. Integrating segmentation and material estimation tools, such as MaskFormer and MATch, PhotoScene excels in visualisation and modelling, making it particularly adept at creating high-quality, photorealistic DTs.

This framework's focus extends beyond 3D geometry and scene layout to include material properties and lighting, ensuring a comprehensive and realistic DT representation.

In the context of construction and BIM, PhotoScene offers significant advantages. It facilitates the creation of detailed and realistic 3D models from images, which are crucial for visualising and planning construction projects. By capturing high-quality materials and lighting, PhotoScene enables the creation of DTs that can be employed in various applications, such as augmented reality, photorealistic rendering, and simulation training. For instance, architects and construction managers can utilise these photorealistic DTs to simulate different lighting conditions and material appearances, thereby enhancing decision-making and project presentations.

The framework's ability to convert coarse 3D models and images into high-resolution, fully relightable 3D scenes is particularly beneficial for BIM. This capability allows for accurate visual representations of buildings and interiors, which can be rendered from novel viewpoints and under different lighting conditions. This is essential for planning and visualising the impact of design changes, material choices, and lighting setups on the final appearance of a construction project.

PhotoScene's integration with segmentation and material estimation tools, like MaskFormer and MATch, enhances its ability to create realistic and detailed 3D scenes. MaskFormer assists in segmenting the image into distinct material regions, while MATch provides procedural material graphs that represent photorealistic and resolution-independent materials. These tools enable PhotoScene to accurately capture and replicate the material properties and lighting conditions of the input images, resulting in high-quality DTs. One notable application of PhotoScene in construction and BIM is its use in converting indoor scene photographs into detailed 3D models. The framework can process input images of a scene along with coarsely aligned CAD geometry to build a photorealistic DT featuring high-quality materials and lighting. This DT can be re-rendered under arbitrary viewpoints and lighting conditions, providing a flexible and powerful tool for visualising and analysing construction projects.

For example, a study employing PhotoScene demonstrated its ability to create high-quality, fully relightable 3D scenes from images of indoor environments. The framework was evaluated on objects and layout reconstructions from datasets, like ScanNet, SUN RGB-D, and stock photographs, showing that it could reconstruct scenes with high accuracy and photorealism. The results included detailed materials and lighting that closely matched the input images, and the DTs could be rendered from different viewpoints and lighting setups, highlighting the framework's flexibility and power.

NVIDIA Omniverse [35] is a comprehensive open computing platform designed for creating, managing, and operating high-fidelity DTs with real-time simulation capabilities. Leveraging cutting-edge technologies, such as the Universal Scene Description (USD), a framework developed by Pixar, NVIDIA RTX technology for real-time ray tracing, and advanced AI and machine learning capabilities, Omniverse supports detailed 3D visualisation and robust collaboration across various domains. The platform integrates seamlessly with industry-standard tools through Omniverse Connectors, enabling it to ingest and work with diverse data sources, facilitating a unified workflow.

Omniverse Nucleus is a core component that enables multiple users to collaborate on the same 3D models and scenes, managing data storage, access controls, and live synchronisation. This ensures that all stakeholders can work with the most current information, enhancing decision-making processes. The platform also includes Omniverse Kit for developing custom applications, Omniverse View for reviewing and interacting with 3D scenes, and Omniverse Create for content creators to build, animate, and render complex 3D scenes.

In construction and BIM, Omniverse enhances design and planning processes by enabling real-time collaboration among architects, engineers, and construction professionals. It allows for the creation of highly detailed and interactive DTs of buildings and infrastructure, facilitating virtual walkthroughs, stress tests, and identification of potential issues before actual construction begins. This helps reduce the risk of errors and optimises designs based on the real-time simulations of lighting, material behaviours, and structural responses. For example, implementing Omniverse in a BIM project can reduce design errors by up to 30%, cut project timelines by 20%, and decrease material wastage by 15%.

For smart cities, Omniverse enables the creation of DTs for urban infrastructure, such as transportation networks, utilities, and public spaces. These DTs help city planners and managers monitor and optimise the performance of these systems in real-time, improving efficiency and reducing operational costs. For example, a DT for a city's transportation network can simulate traffic flows, identify congestion points, and suggest optimal routing strategies, potentially reducing traffic congestion by up to 25%. Similarly, DTs of utility systems can monitor energy usage, detect leaks, and optimize resource distribution, leading to energy savings of up to 20%.

In Industry 4.0 applications, Omniverse supports the creation of DTs for manufacturing processes and industrial equipment. These DTs enable real-time monitoring, predictive maintenance, and optimisation of production workflows. For instance, a DT for a factory floor can simulate different production scenarios, identify bottlenecks, and suggest process improvements to increase efficiency and reduce downtime. Integration with IoT sensors and data streams ensures that DTs are always up to date, reflecting the current state of physical assets. Quantitative benefits in this context include a 15% increase in overall equipment efficiency (OEE), a 10% reduction in unplanned downtime, and a 12% improvement in production throughput.

A notable industrial application of NVIDIA Omniverse is its use in developing a DT for the GA/DIII-D tokamak fusion reactor. In collaboration with Princeton University, this DT incorporates AI-driven real-time simulations to model plasma dynamics and control systems, enabling near-real-time experiments and accelerating the development of fusion energy technologies. This application demonstrates Omniverse's capability to support advanced scientific research and engineering projects by providing a realistic, interactive, and high-fidelity digital representation of complex physical systems.

Overall, NVIDIA Omniverse offers a powerful and versatile platform for creating, managing, and operating DTs across various industries. Its robust capabilities in real-time simulation, collaboration, and integration with industry-standard tools make it an invaluable asset for advancing technology and improving efficiency. By implementing Omniverse, organisations can expect significant improvements in operational efficiency, reduced costs, and enhanced decision-making capabilities, contributing to overall productivity gains.

Microsoft's Azure IoT Hub and Azure Digital Twins (ADTs) [36,37] provide a robust platform for building, managing, and leveraging DTs across various industries, including construction, smart cities, and manufacturing. These proprietary tools offer comprehensive capabilities and integration options that enhance the creation and utility of DTs.

The Azure IoT Hub acts as a central message hub for bi-directional communication between IoT devices and the cloud. It supports protocols like MQTT, AMQP, and HTTPS, ensuring secure and scalable connectivity for numerous devices. This connectivity is crucial for real-time data ingestion, command and control functionalities, and seamless integration with other Azure services.

Azure Digital Twins (ADTs) extend these capabilities by offering a rich set of APIs and tools for defining DT models using the Digital Twins Definition Language (DTDL). The DTDL, a JSON-based schema, allows developers to create detailed and custom models of physical environments, including their properties, relationships, and behaviours. This flexibility supports a wide range of applications, from simple asset tracking to complex simulations of entire ecosystems.

One of the standout features of ADTs is their support for 3D visualisation, which enhances the ability to interact with and analyse DTs in a more intuitive and immersive manner. This is particularly beneficial in construction and BIM, where stakeholders can visualise and simulate building designs, optimise construction processes, and manage facilities with greater efficiency and accuracy.

Integration with other Azure services further amplifies the capabilities of ADTs. Azure Functions allows developers to implement custom business logic and event-driven processing, while Azure Stream Analytics, Azure Machine Learning, and Azure Cognitive Services provide powerful tools for real-time data processing, predictive analytics, and advanced machine learning applications. This ecosystem enables the comprehensive monitoring, analysis, and optimisation of DT models.

In practical applications, ADTs and the Azure IoT Hub have been used in various innovative projects. For example, Johnson Controls utilises ADTs in their OpenBlue platform to create smart building solutions that enhance operational efficiency and occupant comfort. Thyssenkrupp leverages ADTs to develop DTs for their elevator systems, enabling predictive maintenance and improved service reliability. Similarly, Bentley Systems employs ADTs in their iTwin platform to manage and optimise infrastructure assets, ensuring better performance and reduced lifecycle costs.

These technologies are also pivotal in smart city initiatives, where they help in managing urban infrastructure, such as transportation networks, utilities, and public spaces. By creating DTs for these systems, city planners can monitor performance, predict maintenance needs, and optimise resource allocation to improve service delivery and sustainability.

In the industrial sector, companies like Ecolab use ADTs for water management solutions, optimising water usage and ensuring compliance with environmental regulations. The ability to integrate IoT data, perform real-time analysis, and drive actionable insights makes ADTs and the Azure IoT Hub invaluable tools for enhancing efficiency and sustainability in various industrial applications.

Overall, Microsoft's Azure IoT Hub and Azure DTs provide a comprehensive and versatile platform for developing and managing DTs. Their robust capabilities in real-time data processing, predictive analytics, and seamless integration with other Azure services make them invaluable assets for advancing technology and improving efficiency in numerous applications. By leveraging these tools, organisations can achieve significant operational improvements, cost savings, and enhanced sustainability, making them essential components in the modern digital landscape.

Chronicle (GA 101069722) is developing a physics-based digital twin framework to perform analysis modelling for the physical interactions between various aspects of a building, such as heat transfer between rooms, occupant behaviour, and the impact of the external environment. This functionality is implemented in real buildings (pilots) and can be used to test the impact of proposed operational changes or building upgrades for the energy performance of the building.

3.3. Digital Twins in Other Fields

In the field of medical uses, DTs are used in various ways, such as the monitoring of physical activity [38] simulations of viral infections [39], remote surgery [40] and health care management [41]. In [41], the concept of human digital twins (HDTs) is presented with an emphasis on security and ethics. The purpose of HDTs is to expose the human body in cyberspace by making use of information from wearables, mobiles apps, and medical records that change through web services. Another challenge comes from the trait's complexity, which is influenced by genetic factors, like culture and heredity, and considers interdependence among other issues. The athlete specific HDTs discussed in [38] have been developed to monitor parameters, such as heartbeats and activity levels, using the Smart Fit app for trainers and educators. To analyse data, ML or DL algorithms can be used, but difficulties include the size of data being handled, at the same time, sorting both huge volumes of data out within processing time limits which have since been dealt with by incremental learning. Laubenbacher et al. [40] focus on a hierarchical multi-scale DT modelling framework for simulating host responses to viral infections over a range of scales; it is essential for testing models against sensor/medical data. Expert validation must be undertaken because understanding these phenomena is still limited.

In the automotive sector, while DT concepts are increasingly used, focus remains on manufacturing processes and prototype testing. The DT is pivotal for data-driven manufacturing [42]. Benefits include productivity boosts, reduced complexity, time and cost savings, and quality improvements [43]. DTs facilitate product development and optimisation by providing unique insights [43]. Various DT configurations impact different stages of a vehicle's lifecycle, from conceptual design to end-of-life considerations. Szalay [44] introduces an advanced X-in-the-Loop framework integrating DTs and the IoT to connect physical and virtual vehicle representations for testing. This framework is applied in diverse test environments, including real-time vehicle simulation, urban testing for automated cars, and connectivity platforms [44]. Mixed reality enhances reproducibility, flexibility, scalability, cost efficiency, and realistic simulation [44]. Key technologies include simulation tools, like CarMaker VTD, sensors, such as LIDAR and RADAR, GPS, IMU, CAN bus, and cameras [44].

ISO/IEC 30173:2023 [45] provides horizontal definitions for the digital twin concept, valid for any sector. It is conceived as a digital entity defined by a set of properties and/or behaviours representing a physical or nonphysical entity, which has data connections to synchronise the physical and digital states. The definitions provided in the international standard are used in CEN/TC 442/WG 9 to create a set of definitions applicable to the built environment.

4. Potential Benefits of DTs for Construction and Complex Infrastructure Management

There are many definitions for DTs and each definition can be linked to different benefits. Bolton et al. [46] define a DT as a digital representation of the infrastructure [39]. Rudrappa [15] goes deeper and divides the DT concept into prototypes, instances, aggregates and environments. According to Rudrappa, a Digital Twin Prototype details the main information of the real objects in the digital environment, such as 3D properties or detailed specifications. The Digital Twin Instance, second type, is always linked to the real management of the object or asset. One step beyond is the Digital Twin Aggregate, which all the data captured by the Digital Twin Instance is analysed and even linked to sensors. At last, Rudrappa details the Digital Twin Environment, which is the final step to achieve a complete DT concept with real time data, real time analysis, and even predictive maintenance.

As indicated above, DTs have different implementation levels, starting as a 3D representation with data hosted in it, which could also be seen as a BIM model. The user of the DT will find different benefits for each level within the DT concept (prototypes, instances, aggregates, and environments). The infrastructure constructor or the final infrastructure manager must be considered to ensure the adequate level for the DT implementation. In this respect, each infrastructure has its own management needs, and not all of them demand

IA or IoT for their daily usage. For instance, real time data of internal displacements are more important in tunnels than in conventional buildings. In this sense, the design and implementation of the DT must consider those differences.

Considering different levels of a DT, Figure 1 details the information flow inside a complete digital environment. As detailed in previous DT definitions, basics levels could include (1) 3D representation, (2) data hosting, (3) real time information, and (4) predictive maintenance. It is important to highlight that the higher the DT implementation, the more technologies will be needed to achieve it.

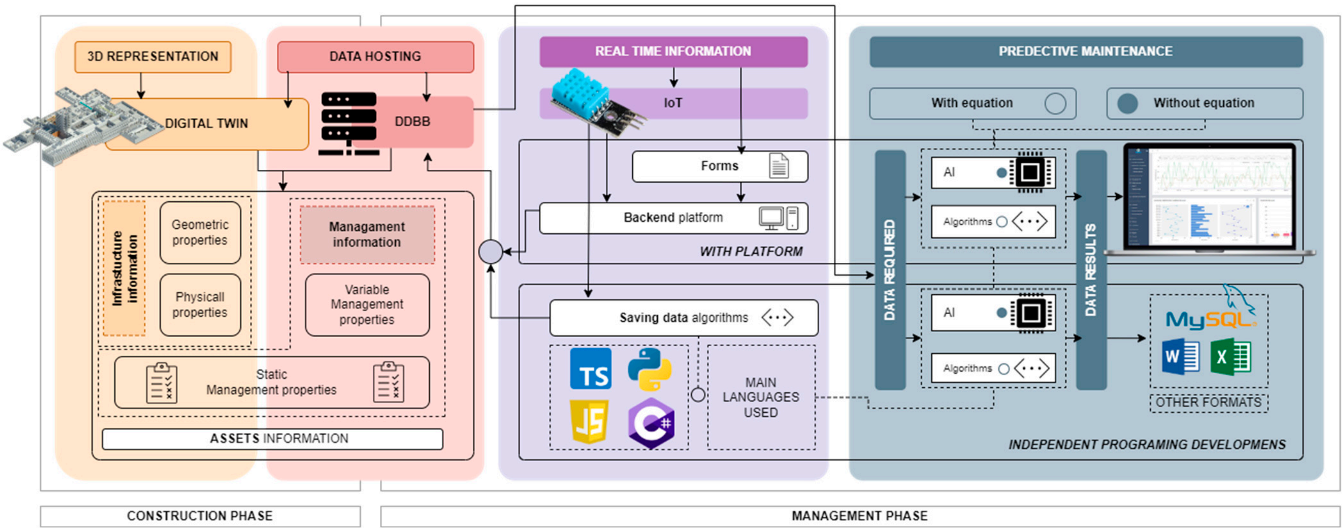

Figure 1. Data workflow considering different levels of DT definitions.

As shown in Figure 1, and considering most authors definitions of a DT, the base of the concept is a three-dimensional representation of the main geometric properties of the infrastructure; however, geometry visualisation is not a compulsory needed to create a DT. The most common technologies or methodologies used to archive geometry visualisation and initial data hosting are BIM and geographical information systems (GIS), but other technologies can be used depending on the nature of the infrastructure. While BIM is focused more on medium–small infrastructure, GIS has important benefits for bigger construction assets, such as roads, or to consider districts. Different construction assets will require different levels of detail. For example, bridges with large spans may need the use of 3D models, other bridges with modest distances among piers could be easily monitored only with a certain number of sensors. In any case, a different data nature could be implemented in a DT. Examples include geometric properties, like length or height, and physical properties of the materials, like density or compressive strength. Of course, this DT must be able to link any available information, providing quantity take-offs or cost estimations. However, data related to a DT should be divided into two types: the static (i.e., identification of a room or material) and the variable (owner of one locker or number of persons inside a one room). In this respect, to achieve an efficient DT implementation, data hosting must be designed as static data in the DT 3D representation and hosting dynamic data in external databases. In this sense, the system will be able to deal with several technologies, like IoT or AI, overpassing the lack of interoperability of the most important 3D representation systems.

External databases will be able to host dynamic data, linking them with different infrastructure elements with foreign keys located into the databases (DBs), but without modifying internal 3D representation parameters that supposes a quite important step to overpass an important lack of interoperability. Using external data, hosted in spreadsheets or a structured/unstructured DB, the project obtains an important level of interoperability. For example, as shown in Figure 1, external DBs will be able to host real time information based on IoT or front-end platforms, collecting real time data and sending it to those external DBs, which will allow the interoperability and data connection between 3D representation and, for example, IoT devices. As shown in Figure 1, for real time information and predictive maintenance, a management platform linked to 3D representation is the most common environment. Most outstanding projects develop an online platform able to (1) visualise 3D elements and their information and (2) provide to the user management functionalities linked with the 3D visualisation. The complete platform environment provides a total accessibility for infrastructure managers. However, it demands more software programming skills than without it. In this regard, IoT devices could perfectly be stored in a local database and then provided to the infrastructure managers through most commercial formats, such as Word, Excel, or a PDF. However, who is in charge of providing them those files? This is not a problem related with the online platform environment. In this sense, the IoT devices will be linked to the platform back-end, which will register all the data into the DB. Moreover, thanks to the internet, the infrastructure manager will be able to easily render graphical data or even download common format files.

The last step, or the DT implementation level, is the one which hosts predictive maintenance. This topic is related to what has been previously mentioned regarding real time information. Of course, deep learning network developments could be trained outside the environment of the online platform. However, how will the data be provided? Or how will the prediction be visualised by the infrastructure manager? All AI developments could be implemented inside the platform back-end. In this sense, thanks to being inside this online environment, periodically AI training could be asked by the final infrastructure user, without any software programmer or researcher, just all conducting it thought the online platform. However, predictive maintenance could also be reached without AI implementations. As shown in Figure 1, AI developments are used when no equation or relation between variables are known. Nevertheless, not all variables of infrastructure management are undefined. For instance, in the case of the management of a study centre, the estimation of the number of rooms needed for each subject could be extrapolated from the students enrolled and the room capacity. Thus, no AI implementation based on previous experiences is needed. However, most impressive predictive maintenance functionalities can only be achieved with AI. For instance, considering the example of the study centre, making an estimate of the number of students for the first-degree year considering specific parameters, such as gross domestic product related to the degree sector, previous years students enrolled, or degree fees there is no known relation between those variables. In those cases, AI developments are highly important.

DT Case Studies

The DT environment is apt for any kind of infrastructure. According to their management needs, the management systems must have enough flexibility to provide demanded tools. An example of a management system based on a DT is detailed in Figure 2. Bidebieta-Basauri is a railway station on the Bilbao–Orduña network, located in the Basque Country of Spain [47]. Due to a remodelling project promoted by the Spanish Ministry of Transport, Mobility and Urban Agenda (MITMA), the research team developed a DT-based management system proposal for the infrastructure. In this regard, the management system developed was able to provide a complete management tool, linking technologies such as BIM, GIS, IoT, and cloud computing. Based on an online web platform, the system had a great level of accessibility, being accessible through any device.

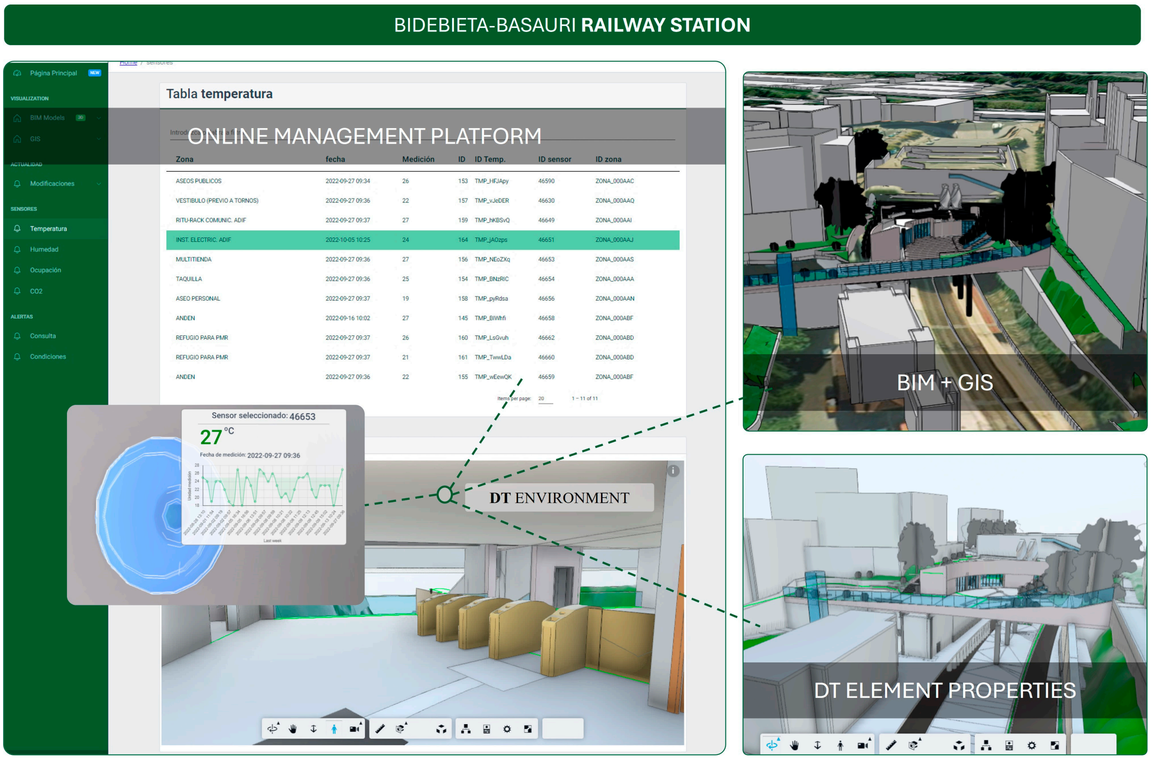

Figure 2. DT-based management system of the Bidebieta-Basauri railway station.

Thanks to the DT, the system, as detailed in Figure 2, can provide to the user a complete digital visualisation of each element of the infrastructure. Moreover, and thanks to the usage of external DBs, the relation between sensors and their representation in the DT has been achieved. With this high interoperability, the DT environment is able to provide to the users and infrastructure managers real time information of CO_2, occupancy, temperature, and humidity. Also, a complete record of previous incidents is implemented. Thanks to the digital representation of each element, the managers could easily attach incidents to that element, as well as being able to check element properties. For instance, it could consult the maintenance dates, subcontractor, materials, or supplier to call.

Figure 3 shows the infrastructure to manage the Civil Engineering School of the Universidad Politécnica de Madrid (UPM). The benefits and applications are similar to the Basauri management system previously detailed. However, the infrastructure needs are totally different. In this sense, not just real time data, incidents registrations, or 3D visualisation is provided. In this kind of infrastructure, spaces reservations and occupancy are also quite important. In this regard, the DT environment was of notable importance for the infrastructure managers under the COVID pandemic. As shown in Figure 3, thanks to the DT environment, each student was able to check their positions in images, and locate them with the DT representation, always maintaining the compulsory interpersonal distance [48]. Also, Origin–Destiny Matrices techniques were applied using the web platform and the DT, being able to detail the busiest internal routes for different time periods [48].

The aforementioned DT project, the Bidebieta-Basauri railway station, and the Civil Engineering school in Madrid are good examples of linking different technologies. IoT, BIM, cloud computing and our own software developments are tools implemented in both cases [48–50]. Research is the nature of both projects. Some limitations are the lack of AI or simulations protocols that are being researched and implemented currently. Nevertheless, both projects provide outstanding results on data interoperability under a DT environment.

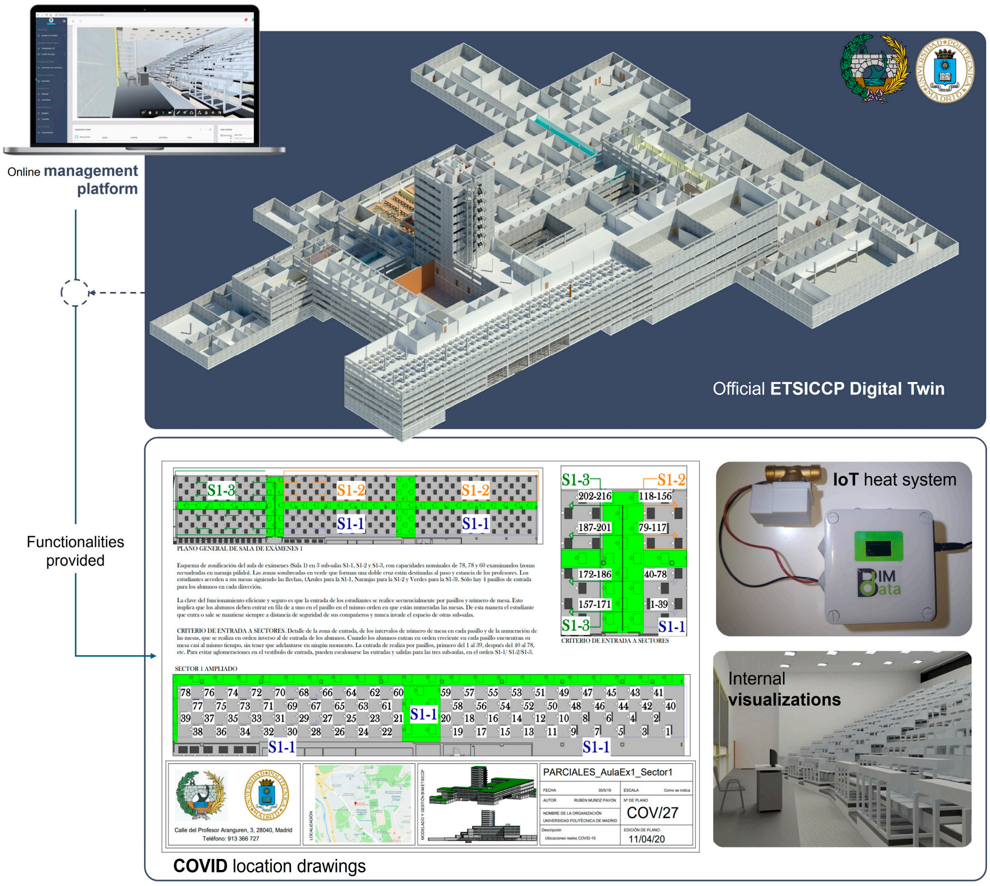

Figure 3. DT-based management system of the Civil Engineering School, UPM.

DTs are also gaining importance in teaching environments. Thanks to virtual reality (VR), a DT provides an excellent teaching space for real demonstrations and simulations. In this regard, the research team has developed a metaverse concept where the students can be in a realistic representation of an infrastructure through the Meta Quest Pro 2 glasses. To achieve this, an internal program based on Unity was developed and implemented into the aforementioned glasses. The feedback of the students was excellent due to the great quantity of information they were able to reach thanks to the DT. Check main properties and see specific construction details were the main points related by the students.

Seeing the overall context provided in this point, the main benefits of DTs are countless. Visual representation, better construction and management understanding, data hosting either for construction or management, real time information linking with devices representation, collaborative management processes, total accessibility for all infrastructure managers or users, and teaching tools are just some examples of the great importance of DTs. Moreover, it must be highlighted by the scalability of this concept. The scientific community and digital developments are moving towards the smart city concept, in which multiple nodes of DTs will be interconnected. In this sense, forthcoming new technologies, like 5G, reducing the latency or improving the quantity of data, are remarkable. Proof of this is the tendency of public administrations to not only increasingly digitise all their data but make that data public and accessible. Depending on the entity, data formats vary. An example of this is the official geoportal of the Madrid City Council [51], in which a great amount of data is provided to all users, mainly in GIS format. Some examples of data provided include 3D cloud points, urban planning, 3D GIS building environments, or different statistical data.

This tendency is the first step to reach that smart city concept. Public and official digital data is remarkable for researcher and private companies. In that sense, official information of public administrations provides a great scalability for any DT project development, which are the base of future digital and smart cities.

5. Defining and Standardising the Concept of a Digital Twin for the Built Environment

5.1. Creation of a European Standardisation WG for Digital Twins

During the SPHERE EU project (GA No. 820805), a new association was born with the name of the Building Digital Twin Association (BDTA). Based in Belgium, this association aims to develop new standards to enable interoperability and advanced simulation applications in DTs. The first step is to clearly define the meaning and scope of DTs in the construction industry. Following one of the white papers published during the Sphere project execution, some definitions were presented [52].

In 2021, the SPHERE project contacted the Spanish Association for Standardisation, UNE, to develop a standardisation document with the results of the project. Several options were assessed, including a CEN Workshop Agreement (CWA) [53]. The activities and ongoing projects of existing standardisation groups were reviewed at the international (ISO and IEC) and European (CEN/CENELEC) level in order to establish a group dealing with DTs in the AECOO (Architecture, Engineering, Construction, Owner Operator) sector:

- International level: ISO/IEC JTC 1/SC 41, "Internet of things and digital twin", which had an existing WG 6 for DTs; ISO/TC 59/SC 13 for BIM; and ISO/TC 184/SC 4, "Industrial data", which had several standards and projects for DTs in manufacturing, like the ISO 23247 set of standards.
- European level: CEN/TC 442 building information modelling (BIM).

The preferred option was to create a group in CEN, as European EN standards are a very important advantage for the dissemination of the results: all CEN members must adopt them as national standards before the withdrawal of any conflicting standards [54]. Furthermore, once the project of a European standard is registered, CEN members cannot develop a national standard for the scope of the proposed EN, due to the "standstill". In addition, SPHERE was a European project, and the Building Digital Twins Association (BDTA) was focused on the European market. Thus, the decision was to create a new working group (WG) for DTs in the built environment in the existing committee for BIM (CEN/TC 442).

To assess the feasibility of this new WG, a presentation was made during the plenary meeting of CEN/TC 442 in November 2021 [55]. After the positive feedback during the meeting, a formal proposal for a new WG was presented by UNE, which was balloted and approved, creating the CEN/TC 442/WG 9, "Digital twins in the build environment", in April 2022, with Eduard Loscos (BDTA) as Convenor and Aitor Aragón (UNE) as Secretariat. The kick-off meeting took place in April 2022 and the activation of a European project covering definitions and framework was discussed. During the meetings of 2022, the state of the art for DTs was evaluated and, in the meeting held in December, it was considered necessary to start with an analysis of the actual use cases of DTs in Europe. Thus, a proposal for a new technical report was launched for ballot in January 2023 and approved in March.

To gather existing use cases, a template was circulated in March 2023 [56]. Before the deadline (27 April 2023), a total number of 37 use cases were gathered, and some more after that deadline, including office and residential buildings, schools, airports or train stations, roads and railways, bridges, etc. The use cases were shared in the working group and a reduced task group made an initial assessment and, where necessary, contacted the authors to gather additional information to facilitate an understanding and benchmarking of the different cases. The working group reviewed the results at regular meetings and the final decision on acceptance was based on the completeness of the content and the clarity of the information provided.

The final text included 34 selected use cases and an assessment of the main and secondary uses of the DT, including construction optimisation, operation optimisation, marketing, training, etc. The final draft was sent for ballot within CEN/TC 442 in March 2024 and approved in June. CEN/TR 18077 was published in September 2024 [14].

CEN/TR 18077 structures the information in four categories: main use, secondary use, asset type, and phase of the life cycle in which the DT is implemented. The predominant use cases primarily facilitate the operation of the constructed asset, with optimisation and maintenance of operations representing the primary applications. Design optimisation, safety measures, and training are included only as secondary use cases. A special typology, "test lab", was created to group DTs used to enhance products and services developed in real laboratories. The miscellaneous category of "other uses" includes irrigations, occupants' wellbeing, or the analysis of climate change resilience.

D^2EPC [57] is a EU funded project which fed other research project, Chronicle, with relevant data regarding digital twins applied to the energy performance of buildings. D^2EPC presented a pilot building in Thessaloniki (Greece) used as both a residential and an office, as well as a University building in Nicosia (Cyprus). The experience with these pilots were used both in CEN/TC 442/WG 9 for the definition of digital twins and in CEN/TC 371/WG 5 for the development of a methodology for operational energy performance of buildings.

Digital twins for other purposes, not conceived as "built environment", were analysed in ISO/IEC TR 30172:2023 [58].

Once the draft was agreed in WG 9 and sent to CEN/TC 442 for ballot, the EN standard for concepts and definitions of DTs in the built environment was proposed. It will consider the recently published "horizontal" standard ISO/IEC 30173:2023 [45]. The ballot was launched in February 2024 and approved in April 2024. The draft should be ready for the CEN Enquiry ballot before the end of 2024 and, if approved, should be published in 2025. This European standard will harmonise the definitions applicable to DTs, providing a common solid ground for practitioners and researchers, helping the procurement process and other related activities.

This standard aim is to provide the information management framework for DTs in the built environment, enabling an ecosystem of connected digital twins. This would release even greater value, using data to support a more efficient design, construction, operation, and end-of-life processes for buildings and infrastructures.

The absence of standardised definitions for the qualitative specification of a digital twin p1ses a significant challenge in differentiating this concept from BIM or in categorising the DTs based on their intended use and the technology applied. This lack of definitions endangers the application of digital twins in public or private procurement. To address this issue, it is imperative to have reliable definitions in international standards, thereby fostering a shared understanding of the underlying concepts.

The European standard developed in CEN/TC 442 should ensure transparency, efficiency, and high-quality outcomes in the DT field. It should foster collaboration and innovation in the construction industry, in particular:

1. Improving communication and collaboration: shared language among stakeholders (researchers, architects, engineers, contractors, suppliers, surveillance authorities, etc.).
2. Enhancing data interoperability across various software platforms: seamless exchange and integration of data, preventing errors and inefficiencies caused by incompatible formats or interpretations.

3. Providing criteria for consistency checks and quality control, including auditing and monitoring compliance with legal requirements or the client's brief.
4. Fostering innovation, as clear and shared definitions will reduce barriers to entry for new firms by setting transparent expectations and consistent benchmarks.

In parallel, other related standardisation projects are using BIM models or DTs with sensors to analyse buildings, gathering real-time data from sensors to propose cost-effective, long-term maintenance and renovation plans. The Chronicle (GA 101069722) is developing a methodology, based on real buildings, to improve the performance of buildings to increase energy efficiency, comfort, and well-being. The pilots are in Denmark, Ireland, Greece, Spain, and Switzerland. This project continues the work developed in D^2EPC and is developing standardised methodology for the operational energy assessment of buildings based on DTs; considering the occupants behaviour should improve the energy efficiency of buildings [59], contributing to the ecological transition. Thus, the Chronicle is working with SmartLivingEPC (GA 101069639) developing a European standard for the operational energy performance assessment of buildings in CEN/TC 371/WG 5, with Paris A. Fokaides (SmartLivingEPC) as Convenor and Aitor Aragón (Chronicle) as Secretariat.

Another important element to be integrated in the DT is the Digital Product Passport (DPP) defined in the sustainable products Regulation (ESPR) and in the new construction products regulation (CPR). CEN/CLC/JTC 24 is developing European standards for the DPP system of the ESPR and CEN/TC 442/WG 12 is developing a European standard for the BIM data templates for construction products, which can be used in the future DPP system for products covered by the CPR.

The DPP will contain LCA-based environmental indicators for construction products, communicated using Environmental Product Declarations based on ISO 21930 (at international level) or EN 15804 (in Europe). This information can be included in the DT using the data templates defined in EN ISO 22057. However, this standard has several limitations for computer-interpretability [60], which should be solved in the next revision of the document.

5.2. The Importance of Standardisation in DTs for Construction

The standardisation of DT technologies in construction and infrastructure management is pivotal for achieving widespread adoption and maximising their potential benefits. Standardisation ensures compatibility, interoperability, and efficiency across different systems and projects, and is especially important in sectors such as construction, where projects often involve multiple stakeholders with diverse technological platforms.

Standardisation plays a critical role in enhancing the interoperability among the various digital systems used in construction. For instance, the integration of BIM, GIS, IoT, and cloud computing in the DT-based management system for the Bidebieta-Basauri railway station underscores the need for standardised protocols to ensure seamless data exchange and system functionality. Without standardisation, the potential for DTs to provide real-time actionable insights could be significantly hindered by compatibility issues.

Collaboration between architects, engineers, contractors, and operators is essential for construction projects. Standardised DT frameworks can facilitate this collaboration by providing a common language and a common set of expectations. This was evident in the UPM's Civil Engineering School DT implementation, where various administrative and safety protocols were effectively managed through a standardised DT platform during the pandemic.

Standardisation can also foster innovation by establishing clear guidelines for technology development, data management, and system integration. This encourages technology providers to develop innovative solutions that are compliant with industry standards, thereby ensuring broader applicability and adoption.

Also, a unified definition can provide a consistent educational framework, ensuring that all learners receive the same concepts and applications regarding DTs, regardless of who is providing the training. This consistency allows training materials to be standardised, facilitating more efficient learning processes and reducing potential confusion or unclear definitions. Moreover, with a standardised definition, educators can develop comprehensive curricula that cover the full spectrum of DT technology, from data integration to real-time simulation and analysis, improving the overall quality of built environment projects.

As seen with the initiatives undertaken by the BDTA and discussions in international and European standardisation bodies, such as ISO/IEC and CEN, regulatory frameworks are beginning to recognise the importance of DTs. Standardising DT practices helps align them with regulatory requirements, ensuring that construction projects not only benefit from advanced technologies but comply with existing and emerging regulations.

In SPHERE, the ongoing efforts to standardise DT concepts illustrate the global movement towards a unified approach to DT technology. Standardisation at this level not only impacts local markets but sets the stage for international collaborations and advancements in construction technology.

The standardisation of DTs within the construction industry is essential to ensure that these technologies deliver their full potential in terms of efficiency, safety, and sustainability. It also prepares the sector for future technological integration, which will inevitably result in the evolution of the digital infrastructure.

5.3. Education and Training

Developing a complete digital twin environment involves many technologies. The general management of a digital twin demands a multidisciplinary profile. Inside the digital twin, we can find different objectives, such as 3D representation, data simulations, or data hosting. According to the main functionalities inside a digital twin, Figure 4 details the different objectives inside a DT and a training proposal according to them.

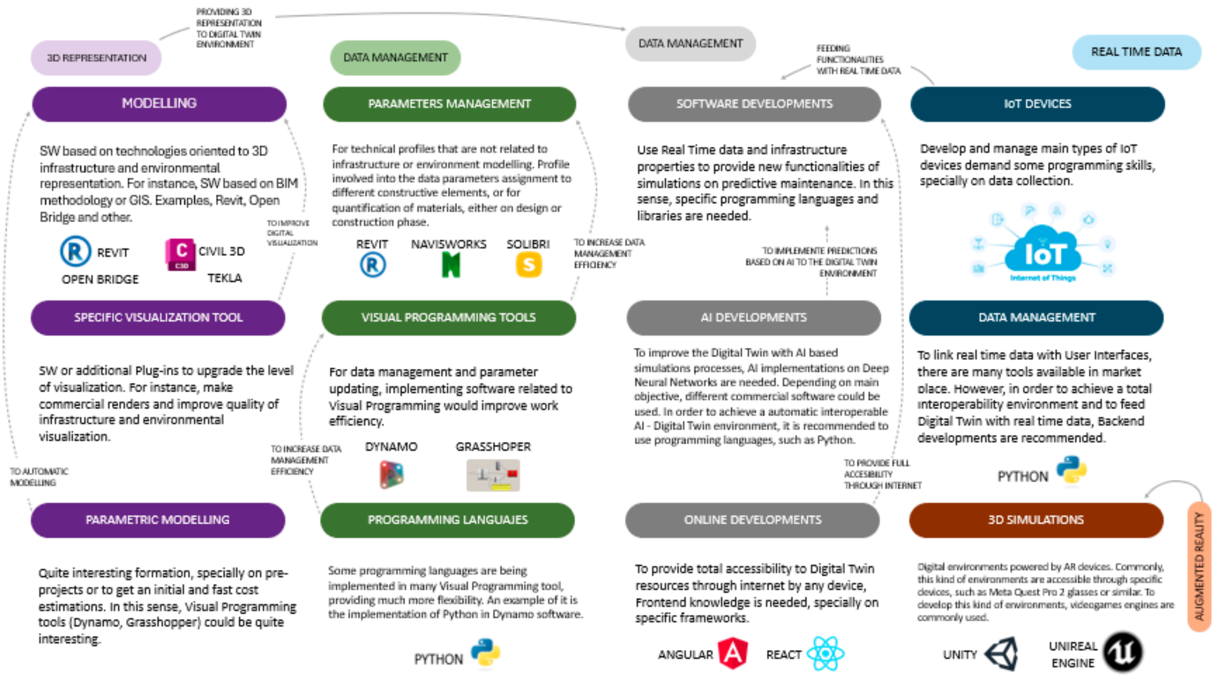

Figure 4. Main technologies and their relationship between them inside a DT.

Based on Figure 4 different technologies can be considered as a part of a DT. If the DT requires a 3D representation, technologies and the methodologies associated to the building information modelling could help to achieve not only a virtual representation but a geometrical and cyber-physical database. If a more realistic visualisation is desired, specific visualisation tools could be implemented. Some tools are totally interoperable with BIM software, making it easier to achieve renders of the infrastructure modelled. Moreover, parametric modelling is also a quite interesting tool, especially on initial project phases, when quick cost-estimation or material quantification is needed.

Data management is probably the most important part of any DT. Depending on the final purpose of the DT, the existence of 3D models, or even the software implemented, the methodology used to manage data might differ. Moreover, in many cases, the most common issues are related to interoperability. Some BIM software codes are currently in demand as they enable a user-friendly interaction with the 3D models. They cater important parameter management tools avoiding the modelling of repetitive parts of the infrastructure or even enable advanced virtual representation functionalities. In this sense, data management could be improved with visual programming tools or even different programming languages which might be connected to BIM models.

Another possible way of visualising the 3D models is by applying the technologies that currently stand out mostly in video games, such as augmented reality or virtual reality. Even in a DT, the most common programming languages are left aside in order to use platforms such as Unity or Unreal Engine. These tools provide a great immersive metaverse of the infrastructure and its environment but, as of now, its everyday use is limited.

It should not be forgotten that a DT is a live entity, and validity depends on its updates. For that task, the state of the DT is updated by a myriad of sensors which employ IoT technology and might provide the real time data of the infrastructure and environment. The IoT could be divided in two main parts inside the DT: (1) IoT devices and (2) data management. Regarding the IoT devices, it is necessary to deploy them and define a communication protocol, such as with MQTT data or a LoRa network. However, after defining it, it is necessary to establish the communication process inside the DT. In this sense, the development of internal API for connecting online platforms and IoT devices could be considered a suitable alternative.

All these skills have been traditionally taught in several undergraduate and graduate degrees which have no common ground. Consequently, a new syllabus had to be created to provide proper competences to the required labour force. The Executive Master in Digital Twins for Infrastructures and Cities is a clear example of these new programs. This Degree is promoted by several highly-ranked European Engineering Universities: Universidad Politécnica de Madrid, École Nationale des Ponts et Chaussées, Budapesti Műszaki és Gazdaságtudományi Egyetem, and the National University of Science and Technology Politehnica Bucharest. The Degree provides interdisciplinary training in digital skills (AI, data science, BIM, cloud computing, language programming, etc.) and DT implementation (management of DT, design and deployment, etc.). This kind of training fills the current need for DT profiles in the AECO sector.

5.4. Data Management

As is detailed in Section 5.3, “Education and training”, many technologies and digital skills are needed to set up a complete DT environment. Figure 5 details the most common interoperability issues under a DT structure. Starting with 3D representation and 3D as a database, the infrastructure and environmental modelling is crucial, especially if data inside the model is needed for DT functionalities. In this sense, use of a common standard for defining elements and parameters is needed. Also, the output information format must be defined. In this regard, Industry Foundation Classes (IFC) is an extended format.

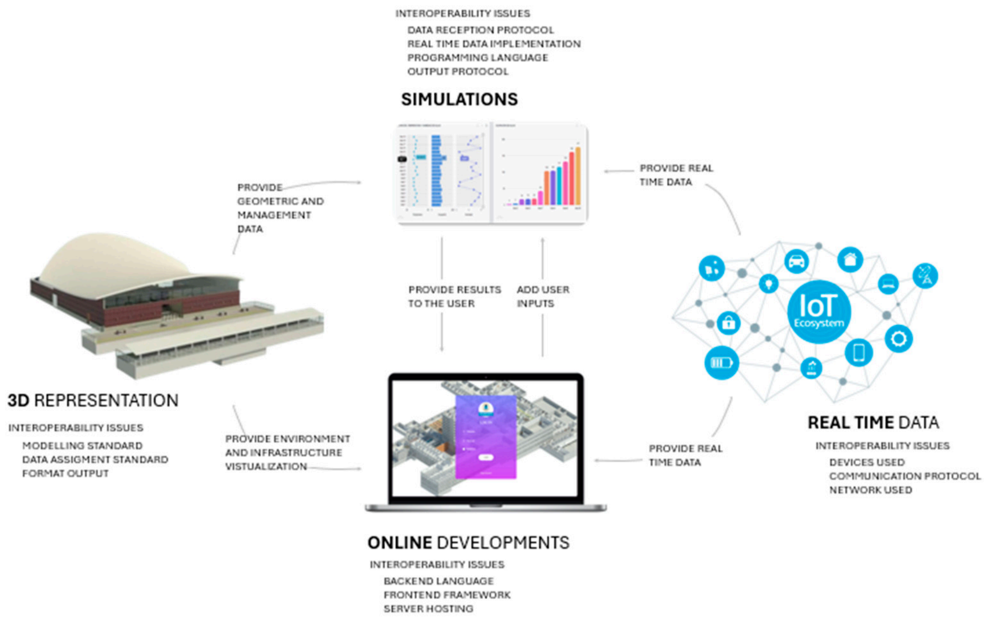

Figure 5. Technologies and interoperability issues.

Regarding the simulations, if data from IoT devices and 3D representation is required several issues might appear if the correct data transformations and formats have not been defined. These transformations should consider not only the programming languages used, APIs or communication protocols, but the characteristics of the simulation software. In this sense, a lack of standards is detected. Also, real-time data and simulation results should be provided not only for DT developers but for final infrastructure and environment users, aiming to achieve the maximum accessibility possible. This step demands interoperability between the front-end platform, back-end developments, IoT devices, and 3D representations. As it is common to find different standards for IoT devices, 3D modelling, data assignment, and AI simulations, it is of key importance to find formal guidelines to connect them. However, in the authors' knowledge, no general practice has been developed yet. Consequently, to achieve a total interoperable DT, it is recommended to use the most widespread formats in each technology. For instance, a LoRa network for IoT devices connecting IFC formats for 3D representation, API (Python or Java Script) for data management, and frameworks like Angular or React for front-end developments.

6. Discussion of the Proposed Definitions and Use Cases

6.1. Introduction

The utilisation of DT technology in various industries, particularly in construction and infrastructure management, emphasises its potential to transform conventional methods and results. This research has revealed that DTs function as a technological innovation and a paradigm shift, promoting a more integrated and sophisticated strategy for building and infrastructure management.

In construction, DTs offer a significant leap in how projects are visualised, managed, and delivered. The data-driven nature of DTs allows for a more accurate and dynamic representation of projects, facilitating better decision-making and efficiency. Our findings suggest that, while the integration of DTs in construction is still in its promising stages compared to sectors such as manufacturing and aeronautics, the potential for optimising project lifecycle management is immense. This potential is particularly notable in complex projects where multiple stakeholders require real-time data to make informed decisions.

For example, in the development of a DT-based management system for the Bidebieta-Basauri railway station as part of a remodelling project. This system exemplifies the practical benefits of DTs in construction and ongoing infrastructure management. By integrating technologies, such as BIM, GIS, IoT, and cloud computing, the system provides a comprehensive management tool that enables real-time monitoring and management of critical parameters, such as CO_2 levels, occupancy, temperature, and humidity. This case highlights how DTs can optimise operational efficiency and proactive maintenance in real-world settings.

Another compelling example from our research is the DT implementation at UPM's Civil Engineering School. The DT environment was crucial during the COVID-19 pandemic, facilitating space reservations and managing occupancy to adhere to health guidelines. DTs have allowed for the detailed visualisation and management of space utilisation in real time, ensuring safety and compliance with public health protocols. This example underscores the role of DT not just in project management but in facility management under crisis conditions, demonstrating its adaptability and critical importance in emergency response and health safety management.

These examples vividly illustrate how DTs in construction go beyond mere theoretical applications to deliver tangible actionable benefits. By enabling a more integrated, real-time approach to project and facility management, DTs enhance the responsiveness and flexibility of construction and infrastructure operations, leading to improved project outcomes and more efficient resource management.

The implementation of digital technology in the construction industry is hindered by various obstacles. One of the primary concerns is the requirement for substantial initial investments in technology and training. Additionally, the conventional resistance of the construction industry to change and the fragmented nature of its operations pose significant barriers to DT adoption. Nevertheless, the strategic implementation of DTs can result in long-term cost savings, improved project outcomes, and enhanced sustainability.

6.2. Comparison with Other Fields

In the aeronautics industry, DTs are extensively used for the maintenance, repair, and operation (MRO) of aircraft. The level of precision and real-time data integration observed in aeronautics is something that construction is beginning to emulate. For example, the systematic approach to data handling and predictive maintenance in aeronautics can be paralleled with the integration of IoT and real-time data management in the Bidebieta-Basauri railway station project, albeit with a focus on infrastructure health monitoring instead of aircraft.

In the medical field, DTs enable precision medicine through simulations of human physiological conditions, which can be likened to the manner in which construction DTs simulate building conditions. The UPM's Civil Engineering School's use of DTs during the COVID-19 pandemic to manage physical distancing and safety protocols mirrors the medical industry's use of DTs to enhance patient care management and emergency response strategies.

The application of DTs in smart cities, such as in the management of urban infrastructure in Herrenberg, Germany, involves integrating data from diverse sources to improve city planning and citizen services. Similarly, the DT-based management systems developed for railway stations and UPM demonstrate that integrating multiple data streams can significantly enhance operational efficiency and service delivery in construction and infrastructure management.

The construction industry can draw valuable insights from these fields to accelerate the adoption and optimisation of DT technologies. This could lead to enhanced project delivery, better resource management, and improved safety and sustainability practices, paralleling the advances in other technologically advanced sectors.

The application of DTs in construction is less mature than that in fields such as aeronautics and medicine. The successful deployment of DTs in these sectors provides a valuable roadmap for the construction industry. For example, the precision and efficiency achieved in aircraft maintenance and healthcare management through DTs can be adapted to enhance building maintenance protocols and infrastructure management, potentially revolutionising safety and operational standards.

6.3. Competences

Competence, understood as a combination of skills, abilities and knowledge needed to perform a task, is a field gaining maturity in the BIM ecosystem. In the field of digital twins, there is a lack of experience and trajectory required to be properly assessed. This research therefore has focused on the state of the art of competences in BIM. BIM teams should include technical competences (software, hardware, etc.), organisational competences (model management, workflows and collaboration management, human resources, collaboration with external organisations, quality management, etc.), legal and procurement competences (contract and tender management, compliance, etc.) and research. These competences will usually be covered by different professionals. The structure of competences should be similar in the digital twins ecosystem with different requirements (for example, hardware will include IoT elements).

There are currently few standards dealing with competences. One example is UNI 11337-7 [61], covering the knowledge, skill, and competence requirements of those involved in BIM. It describes several professional profiles, including the Common Data Environment Manager, the BIM Manager, the BIM Coordinator, and the BIM Specialist.

BuildingSMART has its own professional certification scheme, but there is no current equivalent in the digital twins field. CEN/TC 442/WG 8 is currently working on the definition of competences for BIM professionals.

The educational framework is described in Section 5.3.

6.4. Future Research Directions

This research also provides avenues for future investigation, particularly in the development of standardised methods for incorporating DTs across all stages of construction projects. There is a need for a more comprehensive understanding of how DTs can be customised to address the unique requirements of various construction projects, while retaining scalability and interoperability.

Digital twins and the digital building logbook (DBL) [62] may be used as interconnected tools to promote an efficient and sustainable management of built assets. The DBL can be seen as a structured archive of static building information, such as construction specifications, maintenance logs, and renovation records, but linked with a digital twin it will allow the use of data for dynamic and real-time optimisation, providing predictive insights. A DT will also facilitate cooperations between different stakeholders (facility managers, construction companies, etc.).

The new Regulation 2024/3110 [63] laying down harmonised rules for the marketing of construction products, also known as the new Construction Products Regulation (CPR), defines a mandatory Digital Product Passport (DPP) for the construction of products placed on the EU market. The DPP will contain performance characteristics and LCA-based environmental information as structured data, which can be included in the DBL during the construction or refurbishment stages. This structured data can feed the DT with reliable information to be used in predictive assessments, such as the energy performance of a building.

The integration of DTs with policies and public strategies, such as the DBL or the DPP, opens a promising field of research and practical implementation of these technologies.

Although the extensive application of DTs in construction and infrastructure management presents numerous challenges, the potential benefits it offers are revolutionary. By applying insights from other industries and focusing on overcoming sector-specific obstacles, the construction industry can not only enhance its current practices but establish new standards for effectiveness and innovation.

7. Conclusions

Although the integration of DTs in construction or urban ecosystems is still in its infancy compared to other sectors, the potential benefits from integrating them in day-to-day practices are countless. To date, there are no standard techniques or procedures that describe how to develop a DT due to the wide variety of applications that might range from transport systems, water management, traffic optimisation, etc. Standardisation will play a pivotal role for the use of the DT concept to the built environment, with CEN/TC 442/WG 9 standards and also with other related documents developed at the European or international level in the fields of IoT, Building Digital Logbooks, or Digital Product Passports.

DTs offer a transformative approach to managing, planning, and enhancing urban ecosystems and infrastructure. By providing real-time monitoring and maintenance capabilities, these digital models enable proactive interventions that reduce costs and downtime. In urban planning, accurate simulations of growth scenarios assist in informed decision-making regarding land use and transportation. DTs also promote energy efficiency and sustainability by optimising building performance and integrating renewable resources. Moreover, they play a crucial role in disaster preparedness by simulating emergency scenarios and enhancing public safety through traffic and crime pattern analysis. By fostering community engagement and serving as centralised data hubs, DTs enable advanced analytics that drive informed decision-making. Their integration contributes to building urban resilience against climate change and evolving population dynamics while creating economic opportunities.

This goal requires not only the definition of what a DT is when it is applied to infrastructure but a unified and streamlined educational effort aimed at providing a consistent framework and standardising training materials. This might ensure that learners receive clear and consistent instruction when seeking to incorporate to the labour force skilled professionals in this field to fully harness the potential of DT technology.

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