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Digital Twins for Construction Assets Using BIM Standard Specifications

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Abstract: Digital twins (DTs) are one of the latest technology trends in all industries. However, DT development in the architecture, engineering, and construction (AEC) industry is still in its infancy. Digital twins have been proposed as tools that can be applied to several challenges in various areas of the built environment. However, their widespread use is hampered due to the slow pace of digitization of the AEC industry, in addition to the absence of a formalized standard for digital twins' implementation. We began this study by systematically reviewing publications related to DT applications in the AEC industry in four databases, resulting in 229 publications after applying the proposed criteria. The systematic review highlighted the lack of standardization for DTs in the AEC industry. Additionally, this study assessed the current status of DTs and analyzed the evolution of the concept of DTs in the AEC industry. We also proposed a conceptual framework for DT development for construction assets, using the existing BIM information management standards (i.e., ISO 19650) to promote a better interoperable digitalized built environment.

Keywords: digital twin; architecture; engineering and construction industry; review; building information modeling; ISO 19650; framework

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1. Introduction

The architecture, engineering, and construction (AEC) industry faces numerous challenges, including insufficient research and development, diminished productivity, and the poor embracement of technological advancements [1]. However, the adoption and spread of building information modeling (BIM) technology has prompted significant changes within the AEC industry [2]. BIM has played an increasingly central role in managing construction information throughout the lifecycle of a project, from the preparation and briefing to the use stage, which has helped to promote the digital transformation of the built environment [3]. BIM can also greatly improve data interoperability for building performance management [4]. Standard concepts and principles for business processes to support BIM are provided by the ISO 19650 series [5].

In recent years, integrating BIM with real-time data from Internet of Things (IoT) devices has been a trend for improving construction and operational efficiencies. IoT sensor networks enable the connection of real-time data streams to BIM models, facilitating many applications [6]. This integration of the physical and digital worlds by adding dynamic real-time data to a static BIM model is now known as digital twins (DTs) [7]. DTs are a valuable technology when applied to any industry due to their ability to: improve productivity, reduce the cost of maintenance, optimize operations, improve IT integration, increase owner/user engagement, and enable timely decision making [8]. The advantages described above are achieved by providing a better evaluation and prediction of unforeseen scenarios through holistic and realistic measurements [9]. Global DT implementation is expected to grow exponentially, with its market estimated to increase from USD 6.9 billion in 2022 to USD 73.5 billion by 2027 [10]. DTs are considered a rising technological trend in the AEC industry and other industries such as aerospace and manufacturing [11], and they have become increasingly prominent in academic research since 2017 [12].

However, existing DT solutions for the AEC industry are often vendor-dependent, making them limited in terms of their applicability to AEC sub-areas and their representation of what DTs are [11]. Additionally, the sudden increase in DT publications has contributed to the development of nonuniform DT frameworks and applications by academics due to the lack of standardization and misconceptions about the definitions of DTs [13,14]. Thus, developing a standardized DT framework for information management processes regarding construction assets is essential.

This study attempted to elucidate the development of digital twins in the AEC industry by analyzing the current status and the evolution of the concept. The use of BIM-related standards in the field of DTs was also assessed by reviewing and analyzing the available literature. A total of 229 journal papers from four different databases were reviewed with the objective of highlighting the lack of standardization of DTs in the AEC industry. In this paper, we tried to fill the gaps highlighted in the literature review, proposing an original framework for the development of DTs for construction assets, using existing information management standards (i.e., ISO 19650) as the basis of this framework. The proposed framework aims to promote a better interoperable digitalized built environment.

The paper is structured as follows: Section 2 explains the approach followed to develop the systematic search methodology and presents the reviews and analyses of the collected articles on the application of DT in construction. Section 3 explains the state of the art of DTs and presents a systematic review of the literature. Section 4 introduces the background of the current BIM information management system presented in the ISO 19650 series, highlighting its compatibility with DT development. Additionally, it provides a comprehensive summary of the limitations and gaps in the current research and standards. Furthermore, the authors propose a standardized DT framework for construction assets using the ISO 19650 BIM standard specifications. Finally, Section 5 presents the conclusions and identifies the future trends.

2. Systematic Review Methodology

A systematic review of the state of the art was conducted to analyze the use of BIM standardization procedures (i.e., ISO 19650) in DTs related to the AEC industry. In this section, the methodology followed in the systematic review is presented. A summary of previous studies on DT applications in the AEC industry and the identification of knowledge gaps in the published articles are presented. Throughout this review, the selection was limited to published or in-press journal articles and review articles. The review was conducted using the reference management software Mendeley and covered articles from four electronic databases: Scopus, Web of Science, ScienceDirect, and the American Society of Civil Engineers (ASCE). The databases were chosen to ensure the quality and reliability of the retrieved articles, which were from indexed scientific journals (e.g., Science Citation Index (SCI), Science Citation Index Expanded (SCI-E), or Engineering Index (EI)). The search was conducted under the "article title/abstract/keyword" field. A prior search with generic terms influenced the terminologies specified in the literature search. The search strings consisted of a list of keyword combinations, shown in Tables 1 and 2.

The inclusion criteria for the selection process were as follows:

- Publication year: 2016 to 2021;
- Document type: articles and review articles;
- Source type: journals;
- Language: English;
- Others: subject areas limited to engineering, energy, and environmental sciences.

The number of articles was recorded after applying each limitation. A record of the initial number of articles and the number of articles excluded by each limitation was kept. Selected studies from each of the four databases were exported to "Mendeley" software (and, when necessary, added manually) for filtering by eliminating duplicated records. Afterwards, the titles and abstracts of the filtered documents related to the research objectives were screened. Full-text documents were collected for the articles when the title and the abstract met the inclusion criteria. If the relevance of the title or abstract to the research objectives was unclear, the article was considered relevant, and the full text was collected. Later, a backward-snowballing process was used to identify older articles that could provide complementary information. This procedure was repeated in the newly found records until no more relevant results were obtained. Studies that focused only on digital technologies, such as augmented reality (AR), virtual reality (VR), and blockchain, were omitted if they did not discuss direct applications in the AEC industry. Studies on smart cities that do not have a framework in the AEC industry were also not considered.

Table 1. Grouped list of search keywords.

Group 1	Group 2	Group 3	Group 4	Group X1	Group X2	Group X3
"Digital Twin"	BIM	AEC	Monitoring	"Safety Monitoring"	Construction	"BIM Standards"
"Digital replica"	"Building information modelling"	"Architecture engineering and construction"	Sensors	"Heritage"	"Operation and Maintenance"	"ISO 19650"
"Digital counterpart"		"Construction industry"	Simulation	"Renewable Energy"	Circularity	"PAS 1192"
"Virtual Twin"		Utilities	Dynamo	"Energy Efficiency"	Demolition	IFC
		"Building services"	IoT	"Indoor Environmental Quality"	Design	"ISO 16739"
		Infrastructures	"Internet of things"	IEQ		
		"Asset management"	"Real-time data"	"Structural Health Monitoring"		
		"Facility"		SHM		
				"Performance Monitoring"		
				Productivity		
				"Sustainable Management"		

Table 2. Keyword search combinations.

Combinations *
G1 AND G2
G1 AND G3
G2 AND G3 AND G4
G1 AND GX1
G1 AND GX2
G1 AND GX3

* Note: OR search operator was used within the keyword groups; AND search operator was used between keyword groups.

A total of 11,226 publications were identified through the database search. After applying the inclusion criteria, 3001 screened articles were considered for filtering. After removing duplicates, 988 publications, including journal and review articles, were retrieved. Publications on topics that were not related to the construction industry or just happened to contain some of the keywords in their "article title/abstract/keyword" fields were removed, leaving 639 articles for further analysis. A more critical and comprehensive examination of the title, abstract, and keywords to determine the eligibility of 639 articles was conducted to ensure that only articles on DT applications in the CI were included in the study. After the eliminations, 229 articles were found to be relevant for this study. A flowchart representing the search methodology is shown in Figure 1.

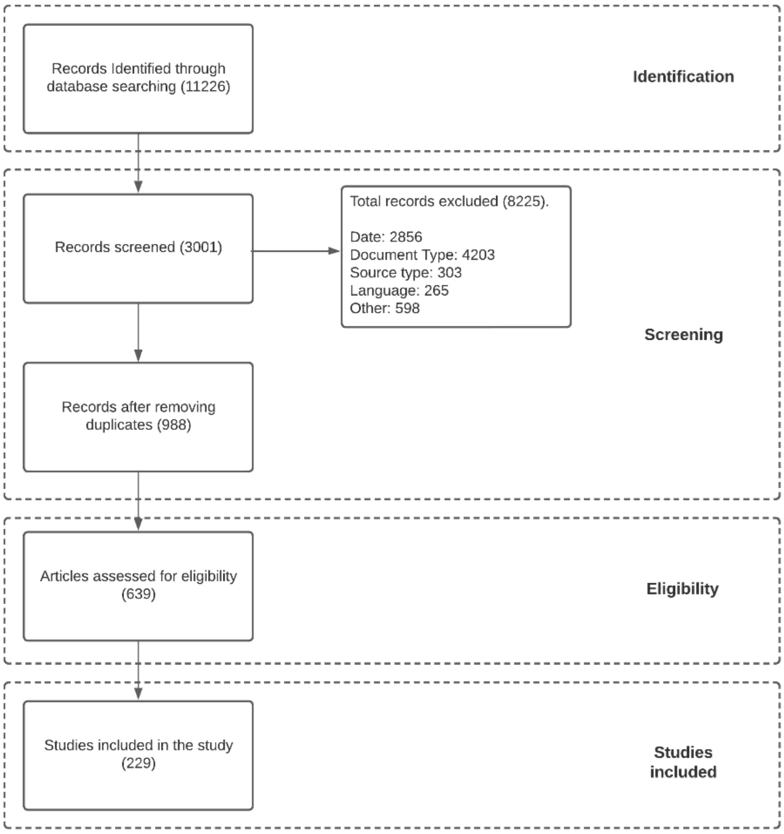

Figure 1. Systematic review methodological flowchart.

3. Digital Twins—State of the Art

3.1. Digital Twins: Origin and Concept

Within the recent wave of digitalization in several industries, the concept of digital twins (DTs) is considered one of the latest trends that can be utilized in various fields and technologies [13,15]. However, the concept of DTs is not new. The concept was initially introduced in the aerospace field in the 1960s, when the National Aeronautics and Space Administration (NASA) built at least two simulators to mirror space conditions to prepare for extensive pre-flight training in NASA's Apollo program [16]. These simulators were used to save the crew of the Apollo 13 mission by simulating alternatives on the earth-based model that were then passed up to the crew. The concept was revived almost twenty years ago by Grieves in 2002 as part of a presentation at the University of Michigan for the formation of a product lifecycle management (PLM) center. The proposed model consisted of three components: a real part, a virtual counterpart, and a system that enabled the data/information flow between the two parts. The model was named the 'Mirrored Spaces Model' [17] until 2006, when it was changed to the 'Information Mirroring Model' [18]. Later, in 2010, NASA introduced the first definition for the term DT, when a draft for an integrated technology roadmap was published under technology area 11 [19]. The final version of the roadmap was officially published in 2012, stating that "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin" [20].

Since then, the term DT has been used increasingly in research and industry initiatives. Moreover, Gartner ranked DT as one of the top ten strategic technology trends in 2018, and its market value is estimated to reach 15 billion dollars by 2023, based on the Market Research Future predictions [21]. Furthermore, since 2017, there has been significant growth in the research interest on the topic of DTs within academia and industry [12,14]. Efforts were made by Negri et al. in 2017 [22] and Fuller et al. in 2020 [14] to compare the definitions of DTs in the scientific literature between various disciplines. However, the DT definitions were not characterized by general computing models and simulations. Thus, there is no single definition of this concept due to the lack of standardization and misconceptions about DTs [13,14,22,23].

3.2. Digital Twins in the AEC Industry

3.2.1. Status of Digital Twins

DTs have been a rising technological trend in the AEC industry for at least a decade. These models have been referred to as "digital twins" or "digital replicas" of buildings, and their role in simulating physical objects in real time using sensors has been addressed by specialists [11,24]. "Digital replicas" or "virtual information models" can reflect all the relevant information throughout a building's lifecycle [25], which helps in the simulation and control of physical assets or built objects through the interconnection of sensors that, in turn, facilitate the collection, processing, and analysis of the required data [3,26]. In the AEC industry, this revolution is often known as Construction 4.0 [27]. Interest in digital twins has greatly increased since 2017 within academia and industry, accompanied by a growth in the number of related publications, processes, concepts, and envisaged benefits [12]. However, the most general definition proposed to embrace the DT concept for built assets in the AEC industry is "the connection between technologies in the form of a digitized model of a physical asset, transmitting data in at least one direction, and monitoring the physical asset in real-time" [15,28].

DT is still in its infancy in the construction industry compared to the aerospace and manufacturing sectors. Vendors in the construction market have already developed some commercial solutions, called asset DTs, in addition to a variety of DT frameworks proposed by researchers across different fields in the AEC industry [29]. However, these are often vendor-dependent and nonuniform in their use, content, or technical implementation [11]. Some think that a mere building information model is a digital twin, while vendors often present building digital twin solutions as 3D visualizations of a building supplemented with the monitoring of indoor parameters, generally indoor temperature or occupancy [11]. However, the use of 3D visualizations does not guarantee the simulation of the real world, since the same can be achieved using static drawings [30]. Research is still being carried out into DT solutions in different sectors of our society, but comprehensive building digital twins have not yet been presented. According to Halmetoja 2022 [11], construction industry digital twins present the following differences compared with those of other areas: (1) a large amount of data, (2) a lack of data standardization, and (3) a connection with the surrounding built environment.

3.2.2. Digital Twin Concept Evolution (BIM Dependency)

Besides the digital transformation advancements in the AEC industry, the growth of interest in the application of DT technology is also aligned with:

- The considerable advancements in related technologies, such as the Internet of Things, Industry 4.0, real-time sensors, and wireless sensor networks (WSN) [31–35];
- The significant increase in BIM adoption and implementation in the AEC industry;
- The increase in BIM software packages currently on the market due to the pressing need to integrate BIM in the management of building information;
- The issuance of initiatives that demonstrate how digital technologies can effectively contribute to a more sustainable and digital future [36,37].

Initially, BIM and DTs were largely overlapping terms in the AEC industry. However, more recently, BIM has often been considered a sub-component of DTs [26], due to the latter's information richness and higher analytical capability [38]. It has also been said that "the digital twin is the next evolution of the BIM model, as BIM has enabled the design, construction, operation and maintenance cycles of an asset to be blended" [39]. The differences between BIM and DTs are clearly stated in the literature, including the potential for DTs to offer possibilities beyond those of information modeling systems [40] such as

BIM. Boje et al. [26] emphasized the comparative structural rigidity of BIM and its reduction in scope compared to DTs. BIM stands out for its ability to allow a standardized semantic representation of objects present in the built environment, whereas DTs provide a more holistic characterization of the existing complex elements, allowing sociotechnical characterizations and bi-directional communications between the physical and digital/cyber environments. In addition to the above, BIM still does not provide semantic fullness in the areas of monitoring system sensor networks, management and control systems, and objects outside the scope of buildings. In summary, there is some agreement in the literature that BIM is mainly used to enhance design and construction efficiency [41] through clash detection [42,43], site monitoring [44,45], cost estimation [46,47], lean construction [48], and enhanced stakeholder interoperability [41].

On the other hand, DTs are enriched with real-time data to provide a responsive model that acts dynamically in relation to the surrounding environment [1]. The responsive model is enriched by real-time data provided by sensors and synthetic data generated from simulators. These data allow more informed decision making and predictions about how an asset will evolve or behave in the future. Thus, a DT should emulate a physical asset in terms of appearance and behavior, but with the added advantage of making future predictions [13]. In fact, DTs can be used for assessing the current structural conditions of buildings/infrastructure through structural health monitoring (SHM) [49], preventive maintenance [50,51], facilities management [4,28,52,53], and circularity management [54,55]. The literature also refers to cyber-physical systems (CPSs), which in some cases could have similar characteristics to DTs and BIM. According to Jiang et al. [56], DTs differ from BIM and CPSs because they necessarily have a physical counterpart (a virtual model), connections between physical and virtual models, and a twin relationship between the physical part and the virtual model. BIM does not need a physical part, a connection between physical and virtual models, or a twin relationship between the physical part and the virtual model. CPSs do not require a virtual model (just a cyber model), and there is no need for a twin relationship between the physical and virtual parts.

Based on the literature review related to the AEC industry, DTs are considered to be an evolution of BIM, and the differences could be presented in three branches:

1. Scope;
2. Communication;
3. Structure.

While BIM is a standardized structure designed for the built environment, DTs add to existing BIM models the possibility to characterize complex elements that are not included in building designs but are part of the holistic built environment of the different lifecycle phases of the constructions. Furthermore, DTs also add the ability to run online data-based numerical simulations and provide predictions about the future state of the physical twins. In this way, DTs not only inform end-users about what is happening in the physical twin, which BIM achieves through online data collection, but also provide anticipatory knowledge about future events.

3.3. Clustering DT Studies

The literature review identified the most recurrent fields of investigation in the study of DTs in the AEC industry. The 229 articles selected from the systematic review were grouped by research fields, as shown in Figure 2.

The research field with the most studies (69) was facility management. The type of buildings used as case studies were the following: generic buildings [15,27,35,53,57–82]; renovated buildings [83]; critical infrastructure [84–95]; large service buildings [28,96–99]; and university buildings [32,55,100–119]. Although most studies concerned generic buildings, an important percentage of the studies were conducted on university campuses and involved the application of pioneering research methodologies. Most of the studies considered the operation and maintenance phase of constructions. The fields addressed in the research included the following: energy management [32,53,55,62,66–68,70,81,94,97,99–

102,104–106,109,111,112,116,119]; building systems, including mechanical, electrical, and plumbing (MEP) parts [27,59,60,65,78,82,86,92,93,96–98,107,108,113,120,121]; indoor environmental quality (IEQ) [35,53,55,59,64,80,100,101,103,104,106,109,110,117–119]; cybersecurity, safety, and emergencies [28,72,73,75,87,92,98]; building elements [15,69,76,95,121]; water management [84,85,88–91,115]; occupancy [77,106,112,114]; and worker safety [63,74]. Some of the works were included in more than one field. The studies concerning facility management were mostly related to energy management (22 studies). A considerable number of studies (17) were related to the maintenance of building systems, usually HVAC or pumps, while 16 were associated with IEQ. However, regarding the IEQ studies, only seven did not concern thermal comfort: one pertained to indoor air quality (IAQ) in parking garages [35], others monitored CO_2 and thermal comfort [55,106,110], one study monitored CO_2 and visual and thermal comfort [109], one study monitored illuminance and thermal comfort [100], and only one had a more holistic approach in terms of IEQ [104]. No water management studies focused on the water consumption of single-family buildings, and just two focused on city water demand [90,91]. Concerning the studies focused on occupancy, two were related to optimizing cleaning activities [77,114], and the other two were related to energy efficiency [106,112].

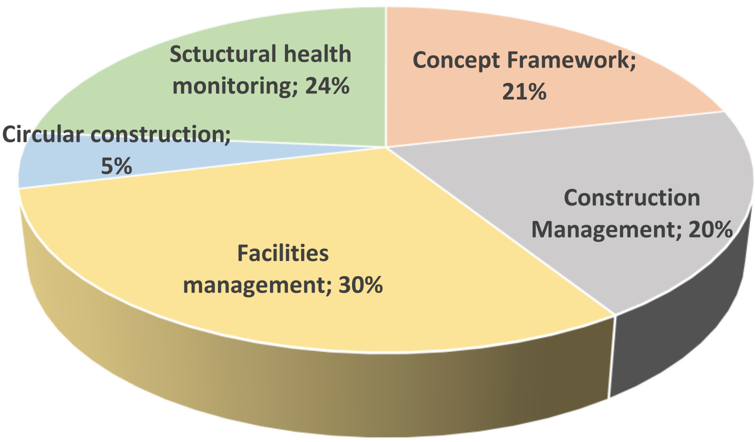

Figure 2. Distribution of the DT studies within AEC research fields.

Structural health monitoring (SHM) was also the focus of many studies (54). This group included studies involving the structural analysis of: generic buildings [122–134]; historical buildings [51,135–139]; wind turbine structures [140–143]; critical infrastructure, e. g., roads, bridges, dams, water and sewer systems, railways and subways, airports, and harbors [49,50,144–170]; and other structures [171–173]. Within this cluster, the studies related to bridges received the most attention, representing nearly 50% of the sample. Almost all studies were related to the building phase of operation and maintenance.

Furthermore, construction management has also received considerable attention from researchers (45 studies). Almost all of these studies were based on on-site case studies, except for [174–176], which fully or partially focused on the off-site production of modular pre-fabricated building components. The studies in this field were divided into the following groups: robotics in construction [177–180], safety management [52,181–196], and project performance monitoring [45,126,174–176,180,189,197–215]. These were generally studies of the construction phase. The “construction safety” and “project performance monitoring” groups included studies focused on workers.

Circular construction was addressed in 12 studies. The case studies used can be grouped into the following categories: critical infrastructure [54,216–220], PV panels [221], residential buildings [222], and generic constructions [223–226]. Furthermore, the addressed topics were as follows: the selection of sustainable materials [216,219], the resource and sustainability performance of building component/material lifecycles [54,221,222,225,226], and green buildings and infrastructure [217,218,220,223,224]. Some of the studies included in the "resource and sustainability performance of building component/material lifecycles" group differed from the works included in the facility management cluster "building systems including mechanical, electrical, and plumbing (MEP) parts" group, as they included an analysis of the carbon footprint, taking into account the embodied material. However, they shared the monitoring of specific parameters of a building/infrastructure component considered important for maintenance operations.

Concept frameworks were considered in 49 studies. Many of the studies included in the "conceptual framework" cluster were literature reviews related to the conceptual, formal, and organizational aspects of DTs; the difference between DTs, BIM, and cyber-physical systems; and their implementation in the AEC industry [1,13,26,40,56,227–239]. Reviews of the integration of BIM with digital technologies [6,40,83,240–249] and proposals for frameworks and methodologies also received some attention [250–259]. Some frameworks and methodologies using DTs or BIM with digital technologies were also proposed to enhance AEC digitalization and solve the current problems of the industry [260–267]. The main difference between this group and the facility management group was the former's methodological purpose. Also included in this research field were several studies that implemented and referenced BIM standardization. Most of them were focused on proposing solutions to improve the quality of information exchange using the industry foundation classes (IFC) (i.e., ISO 16739) [53,247,251,263]. However, only a few studies recognized the use of the ISO 19650 series to improve information management processes in DTs. No research was found using the ISO 19650 standard as the basis for DT frameworks [55,268]. Furthermore, DTs are yet to be described as functional digital entities according to standard specifications. The requirements of building DTs have not been defined in well-established technical documents, nor have the roles of the actors who develop, use, and own them. It is thus impossible to commission the development of a DT using existing technical references. In the field of BIM, the standards mentioned above established a set of procedures and terminology that might be applicable to the development of DTs.

4. Framework Proposal

4.1. Standards in DTs

There are various AEC DTs models and architectures available in the literature. However, a consistent framework for AEC DTs is required, as it would provide uniformity through the mutual understanding of interfaces and standardization. Furthermore, standardization would promote a more efficient dataflow design, making it easier to access data without compromising security [9]. Moreover, standards and standards-based interoperability are required to address the social and organizational challenges caused by the fast increase in digital transformation within industries [269]. Furthermore, the lack of device communication and data collection standards affects the quality of data being processed for DTs, which is reflected in their performance [9].

Since the manufacturing industry is a leader in the research and development of DTs, a standardized framework was published at the end of 2021. ISO 23247 (Automation systems and integration—Digital Twin Framework for Manufacturing) aimed to provide the manufacturing sector with guidelines and methods for developing and implementing DTs. The framework included four parts [270]:

1. Overview and general principles;
2. Reference architecture;
3. Digital representation of manufacturing elements;
4. Information exchange.

BIM-related standards such as the ISO 19,650 series can be used to build DTs of construction assets, as supported by the UK BIM Alliance [7], which suggests using the BS EN ISO 19650 "process" to deliver a DT "output". However, a review of publications pertaining to "Digital Twins" and "ISO 19650" did not yield a detailed framework, which highlights a gap in the research. Thus, in this section, ISO 19650 is briefly reviewed.

To aid the effective implementation of BIM throughout the lifecycle of an asset, it is essential to maintain a common data environment (CDE) with flawless information exchange between project parties, guided by standards and protocols [271]. Several countries and regulatory organizations have developed an array of such standards. Notably, the British Standard Institute (BSI) published the BS 1192:2007+A2:2016 standard and the PAS (Publicly Available Specifications) 1192 suites for projects using BIM level 2 [272]. The suites provided specific guidance for setting out the required level of information, level of detail, model definition, and model information exchange. However, several limitations of the BS 1192 series have been identified [273]: the methodology for implementing the concept is not provided; there is a lack of technical details; and it fails to acknowledge the fundamental processes of asset management, due to the isolated development of the standards based on organizational management processes. In addition, the failure to explicitly identify the stakeholder BIM requirements in the asset information model (AIM) during the O&M phase and the complexity of converting the project information model (PIM) to the AIM highlight the need to promote the holistic organizational adoption of BIM during the O&M phase [274].

The International Organization for Standardization (ISO) published the ISO 19650 international series of standards to replace the abovementioned PAS 1192 series [272]. At the time of writing, the series "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling" is divided into ISO 19650-1 "Part 1: Concepts and principles"; ISO 19650-2 "Part 2: Delivery phase of the assets"; ISO 19650-3 "Part 3: Operational phase of the assets"; and ISO 19650-5 "Part 5: Security-minded approach to information management" [5,275–277].

The transition to the ISO 19650 series aimed to support information management throughout the lifecycle of built assets and assets under construction using BIM, which helps to overcome the limitations of the PAS 1192 series. These improvements were highlighted as key transitions, with EN ISO 19650-1 presenting holistic information management concepts and principles that address the project delivery and asset operation phases of the asset's lifecycle, supported by the detailed information requirements during the project delivery phase described in EN ISO 19650-2 and the operational phase described in EN ISO 19650-3. Moreover, the inclusion of explicit information management processes and workflows that embrace how delivery teams establish information and the more detailed breakdowns of the documents to be developed by the lead appointed parties allow the standards to be adapted to projects or asset management activities of any scale or complexity [5,275]. The ISO 19650 series describes the information delivery planning process by providing principles for preparing responsibility matrices covering the assignment of information management activities and allocating the responsibility for information delivery [272]. Furthermore, ISO 19650-1 [5] presents a more comprehensive overview of information archiving, in addition to fundamental principles for achieving information-container-based collaborative working.

4.2. Limitations of Current Research and Standards Pertaining to DTs

We concluded that there is a lack of high-quality standardized information that follows agreed-upon information exchange protocols and processes for DTs in the AEC industry. Unlike BIM, for which standard processes have been developed in recent years, in particular PAS 1192 and ISO 19650, DTs for the AEC industry are yet to be described as functional digital entities according to standard specifications. On the contrary, the ISO 23247 series of standards, published in late 2021, defined a framework that supports the development of DTs for observable manufacturing elements [270]. Indeed, the requirements for developing DTs with terminologies compatible with the AEC industry have not been defined in well-established technical documents, nor have the roles of the actors who develop, use, and own them. It is thus impossible to commission the development of a DT using existing technical references.

The use of a common set of basic rules, even if further specifications are required, should result in a compatible, coherent link between the digital model and the intelligent building systems (smart sensors) used to synchronize real-time data. In particular, ISO 19650-1 [5] established the concept of an information container as a "named persistent set of information retrievable from within a file, system, or application storage hierarchy". These containers can include sensor data and be linked explicitly with model components, thus guaranteeing that the DT is fully compatible with the BIM software tools and technical specifications used worldwide, which are increasingly imposed by national and regional legislation. The analysis of publications matching the keywords "Digital Twins" and "ISO 19650" showed that the importance of using the ISO 19650 series to manage DT data was recognized in the literature. Still, the available studies did not propose solutions for how to apply this standard to DT frameworks. For example, Tagliabue et al. [55] introduced what they called a sustainable DT (SDT) for sustainability dynamic assessment, adding that it was designed to be "as compliant to the ISO 19650-3, as possible". Zhao et al. [268] introduced a DT framework for facilities management and highlighted the need to convey the use of the information management framework as per the ISO 19650 series and implement an open data format to ensure the smooth application of DTs. Thus, it is essential to conduct more detailed studies on the application of the ISO 19650 series to a DT framework for construction assets.

To conclude, as DTs are mostly application-driven nowadays, the feasibility of adopting an interoperable, standardized DT for construction assets has been substantially diminished. Thus, the development of a framework for DTs for construction assets relying on the advancements and spread of BIM processes provided by the BIM ISO 195650 standard specifications is proposed in the next section.

4.3. A Framework for DT Development for Construction Assets Using BIM ISO 19650 Standard Specifications

After reviewing the literature and analyzing the limitations of current research and standards, we next proposed a framework that could effectively assist in tackling these limitations. The framework was intended to aid in developing standardized DTs for construction assets. The authors suggest using the existing information management standards (i.e., ISO 19650) that are available for BIM as the basis for the standardized DT framework. The developed framework is illustrated in Figure 3. Furthermore, a recommendation for its application in the AEC industry is presented.

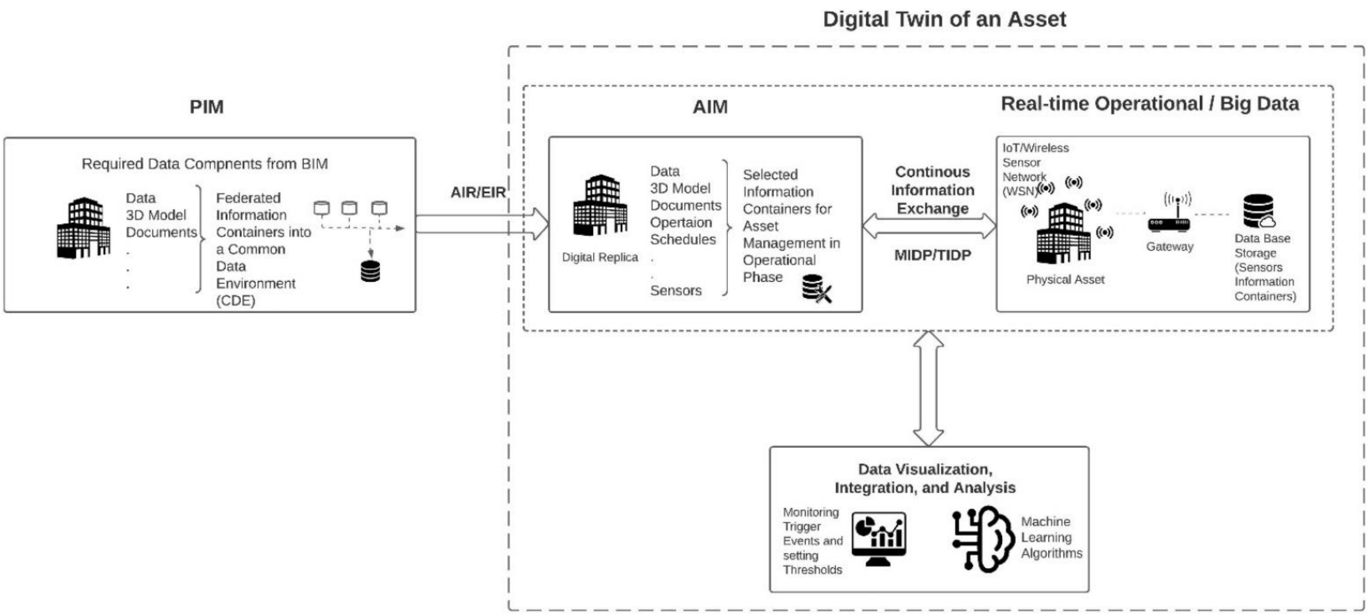

Figure 3. DT framework for construction assets based on BIM ISO 19650 standard specifications.

The developed framework consists of four major parts. The first part comprises the PIM, which contains all the data components required during the design and construction phases from the BIM authoring tool (e.g., 3D models and documents). Data components are considered information containers that are federated into a CDE during the delivery phase. The second part comprises the AIM, which supports strategic day-to-day asset management processes during the operational phase. The appointing party establishes these processes based on the information for which systematic management is considered valuable. Thus, only information containers required for asset management are transferred from the PIM to the AIM. The information containers included in the AIM should be based on the asset information requirements (AIR) defined by the appointing party according to the level of information needed to meet the predefined organization information requirements (OIR), depending on the complexity and type of the project/asset to be managed. The remaining unneeded information containers from the PIM are to be retained as read-only and can be used for dispute resolution or instructional references.

The third part of the framework enables real-time monitoring by using technologies that support a CDE workflow. IoT/WSN are the technologies used to monitor the performance of physical assets during the operational phase. Data are collected and can be stored in static or cloud databases. From the authors' perspective, one can consider the stored data as being included in information containers fed into the AIM (i.e., the sensor information containers, as illustrated in Figure 1). Lead appointed parties and appointed parties who are assigned to specific monitoring tasks for DT synchronization are responsible for establishing a task information delivery plan (TIDP) for each appointment (monitoring task), which is aggregated into a master information delivery plan (MIDP) developed by the lead appointed party in order to meet the AIR/EIR. The continuous information exchange between the physical asset and the AIM should result in a federated information model. The synchronized federated model represents the main difference between a static BIM and a DT. Since the AIM includes content from different information providers (appointed parties), a federation and information container breakdown strategy should be communicated to all appointed parties that are seen to be relevant.

The fourth part of the framework tackles the use of data collected from monitoring the physical asset and stored as information containers in the CDE of the AIM. Monitored data can be visualized to review the performance of the physical asset and control foreseeable trigger events by setting thresholds, which can be useful for taking actions regarding the physical asset. Furthermore, the use of machine learning (ML) algorithms is essential to facilitate decision-making processes that can lead to prompt actions regarding the physical asset (i.e., through actuators). Furthermore, ML plays a key role in making construction "smart" by assisting in future planning and predictions using data-driven algorithms [278,279].

Finally, the authors believe that the second, third, and fourth parts of this framework could be used to generate a general standardized DT of an asset based on the ISO 19650 standard. The framework provides advancement towards a digitalized built environment by introducing an interoperable DT framework based on the well-established terminologies of the BIM standards that AEC industry practitioners commonly use.

5. Conclusions

This study contributes to the body of knowledge on digital twins in the AEC industry. The application of DTs in the AEC industry is still in its infancy. However, the yearly increase in studies in this field is notable. Initially, DTs in the AEC industry overlapped with BIM, but more recent and holistic studies have highlighted the broader characteristics of DTs. The literature review showed that DTs are considered to be an evolution of BIM in terms of scope, communication, and structure.

The systematic review, which considered 229 articles between 2016 and 2021, revealed some discrepancies between the fields of study. In the facilities management field, almost one third of the studies were related to energy consumption, but a few considered the related issue of occupant behavior. Most of the indoor environmental quality studies were related to thermal comfort, and only a few works focused on the other three aspects (indoor air quality, visual comfort, and acoustic comfort). Of the structural health monitoring articles, bridge-related studies accounted for almost half. Few studies focused on circular construction. Furthermore, concept frameworks were addressed in 49 studies; however, few studies recognized the use of the ISO 19650 series to improve the information management processes in DTs. The systematic review also showed that building DTs are yet to be described as functional digital entities according to standard specifications. Indeed, the requirements of DTs have not been defined in well-established technical documents. The ISO 19650 standards established a set of procedures and terminology that might apply to developing DTs.

Therefore, this study reviewed the BIM ISO 19650 series, presenting its suitability for use as a foundation for DT development. Furthermore, we presented a DT framework for construction assets using the ISO 19650 standards. The proposed framework aimed to promote a better interoperable digitalized built environment. In the framework, the BIM processes described by ISO 19650 are implemented throughout the lifecycle of the construction asset to maintain a CDE with flawless information exchange between project parties. The resulting enhanced information flow between different stakeholders would provide better opportunities for making effective decisions and more accurate predictions for the future regarding the built environment. For the AEC industry to keep pace with other industries, it is essential that it embraces the opportunities that come with standardizing DT processes and applications, which have the potential to transform the AEC industry. Indeed, the importance of standardization has been proven in other industries, such as manufacturing (i.e., ISO 23247).

The authors recommend exploring the application of the proposed framework in multiple case studies with diverse asset uses and complexities in order to prove the applicability and success of this framework in various fields. Energy efficiency and IEQ is a recommended field of application, as it was observed in the review to be one of the most neglected research fields.

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