urban science

Review

Evolution of BIM to DTs: A Paradigm Shift for the Post-Pandemic AECO Industry

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Abstract: The architecture, engineering, construction, and operation (AECO) industry is evolving rapidly. In particular, technological advancements and lessons learned from the COVID-19 pandemic are shaping the industry's future. Various artificial intelligence (AI), building information modeling (BIM), and Internet of Things (IoT) techniques have contributed to the industry's modernization by enabling more self-reliable, self-automated, self-learning, time-saving, and cost-effective processes throughout the various life cycle phases of a smart building or city. As a result, the concept of digital twins (DTs) has recently emerged as a potential solution to optimize the AECO sector to achieve the required cyber-physical integration, particularly following the pandemic. Based on a systematic review, the study develops and proposes theoretical models that examine the evolution of DTs in the context of BIM, cutting-edge technologies, platforms, and applications throughout the project's life cycle phases. This study demonstrates DTs' high potential as a comprehensive approach to planning, managing, predicting, and optimizing AECO projects that will achieve more Sustainable Development Goals (SDGs). However, while DTs offer many new opportunities, they also pose technical, societal, and operational challenges that must be addressed.

Keywords: artificial intelligence; building information modeling; digital twins; life cycle; smart building and cities; Sustainable Development Goals

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Citation: Megahed, N.A.; Hassan, A.M. Evolution of BIM to DTs: A Paradigm Shift for the Post-Pandemic AECO Industry. *Urban Sci.* **2022**, *6*, 67. https://doi.org/10.3390/urbansci6040067

Academic Editors: Atiq Zaman and Luis Hernández-Callejo

Received: 27 July 2022
Accepted: 28 September 2022
Published: 30 September 2022

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1. Introduction

The onset of the COVID-19 pandemic disrupted nearly every industry, including the architecture, engineering, construction, and operations (AECO) industries. Prior to the global pandemic, a gradual shift toward digitalization was taking place. Then, in 2020, this shift accelerated dramatically; digitalization went from a luxury to a requirement in the AECO sector, and the changes are likely to continue indefinitely, to meet the needs of the new normal [1–3]. This will involve using techniques outside the mainstream by offering alternatives, exploring innovative modes, and inspiring new ways of constructing a more sustainable and safer built environment. As a result of the lessons learned from COVID-19, specifically those that require AECO specialists to remotely plan, design, monitor, and manage their projects, digital transformation has developed faster than expected [4,5].

Emerging building information modeling (BIM) tools and technologies have gradually changed the way information is created, stored, and exchanged between AECO specialists and other stakeholders [6–8]. Currently, BIM and the Internet of Things (IoT) as computer-based technologies are widely used in the AECO industry to help engineers, architects, and managers achieve best practices in different life cycle phases of a project. Recently, with the popularization of such smart technologies and tools, the industry has been undergoing dramatic changes. While BIM has advanced significantly over the years, architects and engineers have been requesting the next step in the evolution of the AECO industry, as the current state of BIM is incompatible with IoT integration due to its specific formats and standards, which limit BIM usability and extensibility with a semantic web paradigm [6,9].

The digital revolution continually spawns new terms, which become iconic phrases and paradigms. For instance, in the last 10 years, terms such as “artificial intelligence (AI) agents”, “cloud computing”, “platforms”, “IoT”, “machine learning (ML)”, “big data”, and “smart cities” have been created to describe modern trends in computation and communication, driving the automation of society. The latest term to be added to this arsenal of paradigms is “digital twins (DTs)”, which has found widespread favor as the advance in digital infrastructure becomes ever more embedded in our built environment and AECO industry [10]. As a result, the idea of DTs has developed into a thorough strategy for managing, planning, predicting, and optimizing construction projects. DTs integrate the IoT, AI, ML, and analytics to develop interactive, dynamic, and ever-evolving digital simulation models. DTs models continuously learn and update themselves from several sources, to represent their near real-time status. As such, DTs technology has the ability to revolutionize the AECO sector and address some of its problems [11–13].

In achieving Sustainable Development Goals (SDGs) in the post-pandemic era, DTs align well with BIM in the context of smarter buildings and cities. In this context, the DTs concept has recently gained the attention of architects in the AECO industry; however, some issues need to be resolved. First, BIM and the DTs idea are frequently conflated. Secondly, the constituents of DTs applications and platforms for architects are not well-defined. To address these problems, this research provides a holistic view of the state-of-the-art of DTs and reviews how this concept evolved from BIM across a wide range of life cycle phases of a project.

2. Methodology

This study provides an overall understanding of the development of technologies that have enabled DTs in urban science. The current research methodology is primarily based on a systematic review, and applying appropriate analysis tools for conducting a synthesis of findings and other key aspects aimed at the AECO sector, in order to investigate the idea that DTs technology can revolutionize this sector and address some of its problems, particularly in the post-pandemic AECO industry.

A keyword based on “digital twin (DT)”, “digital twins (DTs)”, “AECO industry” or “AECO sector”, and “built environment” in the title, abstract, or keywords search was first conducted in Scopus and Web of Science Core Collection to obtain documents relevant for this study. In addition, Google Scholar was also searched to identify any relevant papers that are not included in those two databases. A systematic review was performed using the preferred reporting items for systematic reviews and the meta-analysis (PRISMA) method, and then a bibliometric analysis of the extracted data using the VOSviewer software.

This keyword search yielded 3012 results. The quick filters on databases were used to filter the results into broad categories such as document type, and the search results were limited to only books, book chapters, journals, and conference proceedings; for language, only the articles written in English and documents published up until the first half of 2022 were selected. In the first step, duplicate results were excluded from further investigation, and the initial results were reduced to 1423 documents. The titles and abstracts of the publications were then manually screened and assessed for eligibility to retain articles relevant to the research topic by screening the title, abstract, and, additionally, the introduction, of every paper. The final dataset for this study after exclusion included a total of 238 publications, as shown in (Figure 1). A bibliometric analysis was then conducted regarding co-authorship and co-occurrence of related studies. The analysis identified the development of the DTs starting from 2008, and its application and relations with numerous sectors, as illustrated in Figure 2.

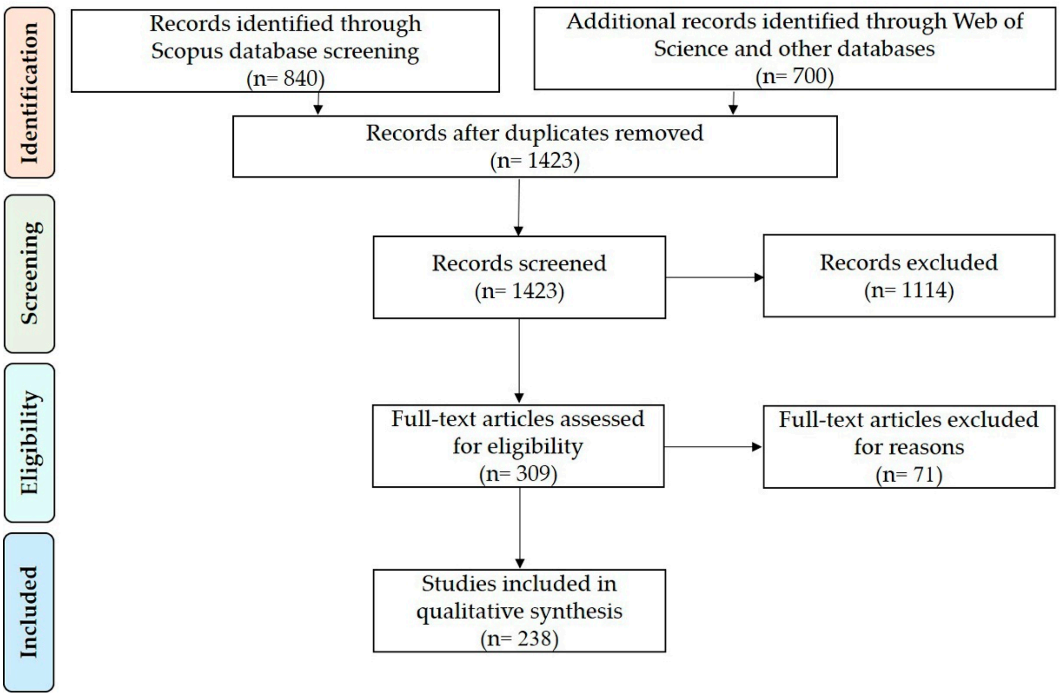

Figure 1. Workflow of selection procedure based on the PRISMA method.

The research approach is divided into several sections after screening and analyzing the previous related literature (Figure 3). Section 3 provides a historical background of the digital revolution and sustainable development. Section 4 then investigates the state-of-the-art concepts and technologies for applying DTs from various perspectives. Section 5 summarizes the DTs platform-based applications and processes in the construction project life cycle phases, as well as reviewing possible applications and related challenges in Section 6. Finally, the current contributions of DTs as well as future challenges are discussed in Section 7.

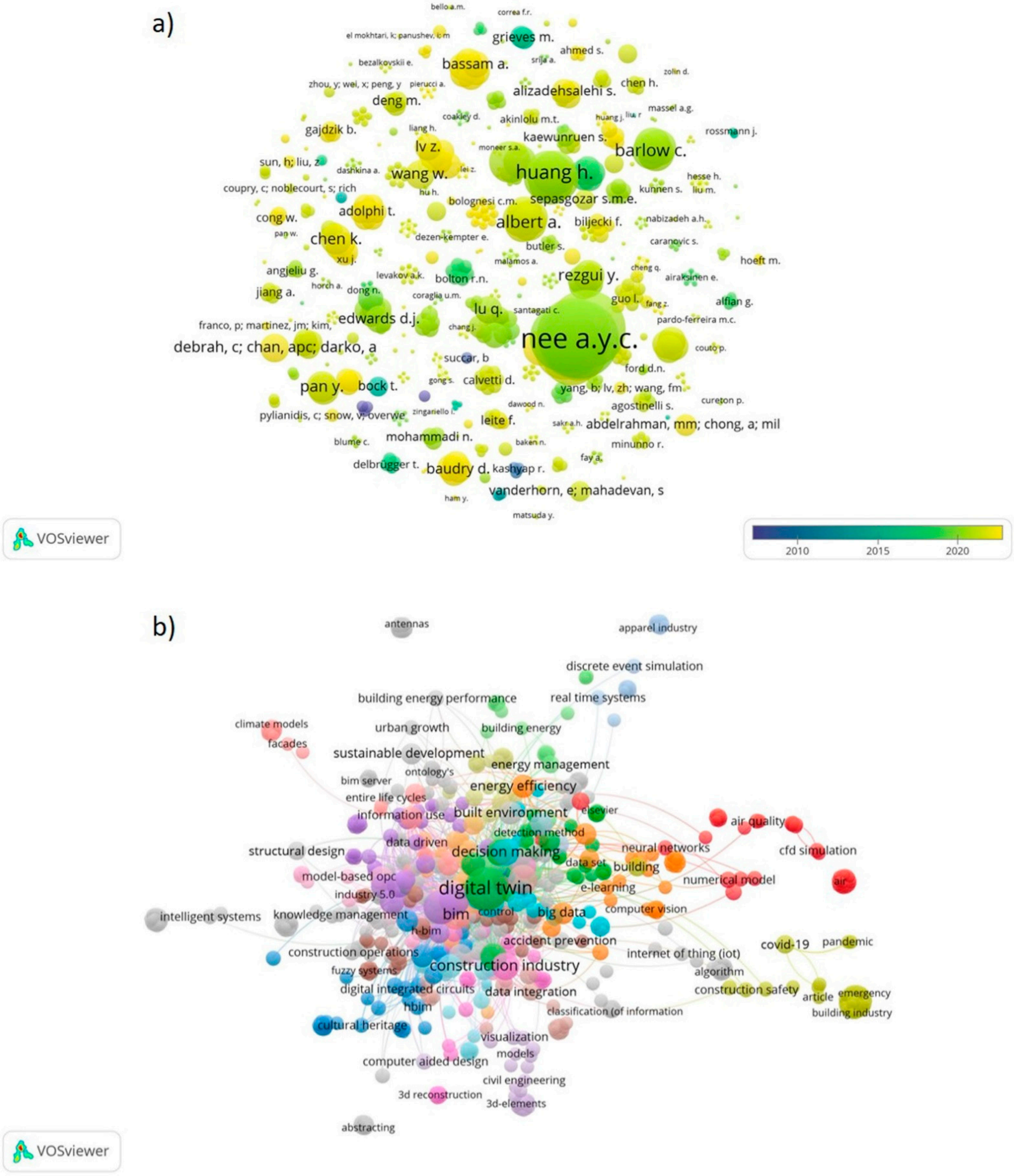

Figure 2. Bibliometric analysis of (**a**) co-authorship, and (**b**) co-occurrence of related studies.

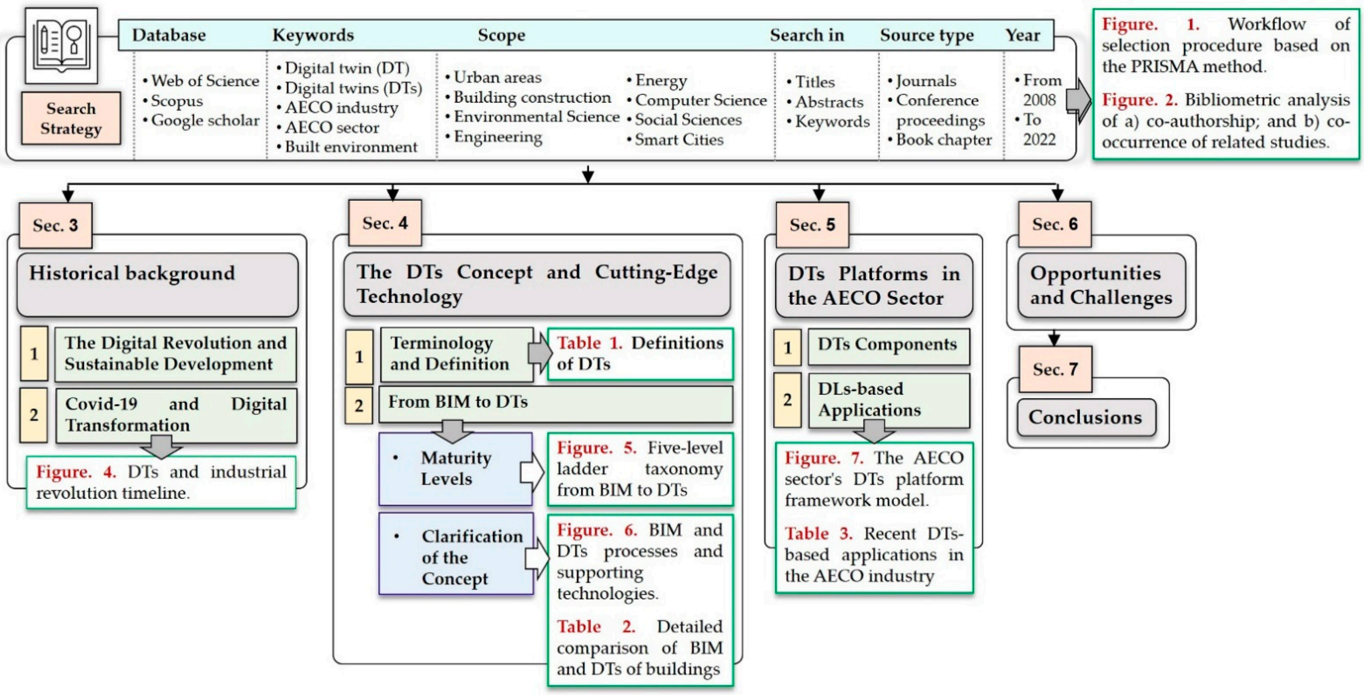

Figure 3. A graphical representation of the methodological framework.

3. Historical Background

This section illustrates how recent technologies and the lessons learned from the COVID-19 pandemic are shaping the future of the AECO industry, as well as their relation to SDGs.

3.1. The Digital Revolution and Sustainable Development

The digital revolution has entered the public discourse in many countries as a possible means of achieving SDGs. For instance, one strategy for sustainable development is to promote multidisciplinary work in the AECO sector by utilizing digital design [14,15]. Since the 2010s, this idea has received increased attention in the AECO academic literature with major improvements in terms of 3D visualization [16,17], building energy simulation [18–21], project management and life cycle assessment [22,23], historic preservation and management [24,25], and parametric design and digital fabrication [26,27]. The emergence of recent plugins of computational fluid dynamics (CFD) has further strengthened the use of digital modeling and numerical investigation to evaluate thermodynamic parameters in indoor and urban spaces [28–31]. This integration of digital approaches can be a solution to the challenges in built environments as well as a help in achieving other SDGs. In this context, physical components in built environments can be designed to be more vibrant, efficient, and resilient if they are modeled, examined, and evaluated before they are constructed [3,32,33].

Recently, initiatives to make cities smarter have been prompted by important issues including urbanization and rising greenhouse gas emissions. Developments in advanced technologies, including the IoT, big data, AI, cloud and edge computing, wireless sensor networks (WSN), radio frequency identification (RFID), and the fifth-generation cellular network (5G), are providing revolutionary changes in the AECO industry. These cutting-edge technologies facilitate the fusion of the physical and digital worlds, resulting in the creation of DTs. They have recently been used, for example, to switch from conventional building and city operation and maintenance to intelligent, efficient, adaptable, and real-time work management. This highlights a critical need for collaboration between the AECO industry and companies that provide internet-related services and products [12,34–36].

To support the social aspects of SDGs, AI has been integrated into other cutting-edge technical advancements, to shape the future of the AECO industry. In particular, human-centered AI is becoming more common in the replacement of machine-centered AI. This enables architects, engineers, and managers to express their preferences regarding input for technologies that generate concepts, prototypes, and solutions to achieve resilient, safe, and productive results more quickly, as well as sustainable environments at any level within the AECO industry [9,37].

3.2. COVID-19 and Digital Transformation

There will be many more lessons from the COVID-19 pandemic that can be applied to the future of work and our incursion toward Industry 5.0-based technologies. This industrial revolution generates effective processes and rapid improvements in industries and may play a role in expanding the new Society 5.0 model [38–42]. In the past, three industrial revolutions occurred. Recently, we have been experiencing a fourth one, and it is entirely possible that a fifth and sixth one will take place in the coming years. As presented in Figure 4, in 2010, researchers began discussing Industry 4.0, which is already paving the way for subsequent revolutions [43–45].

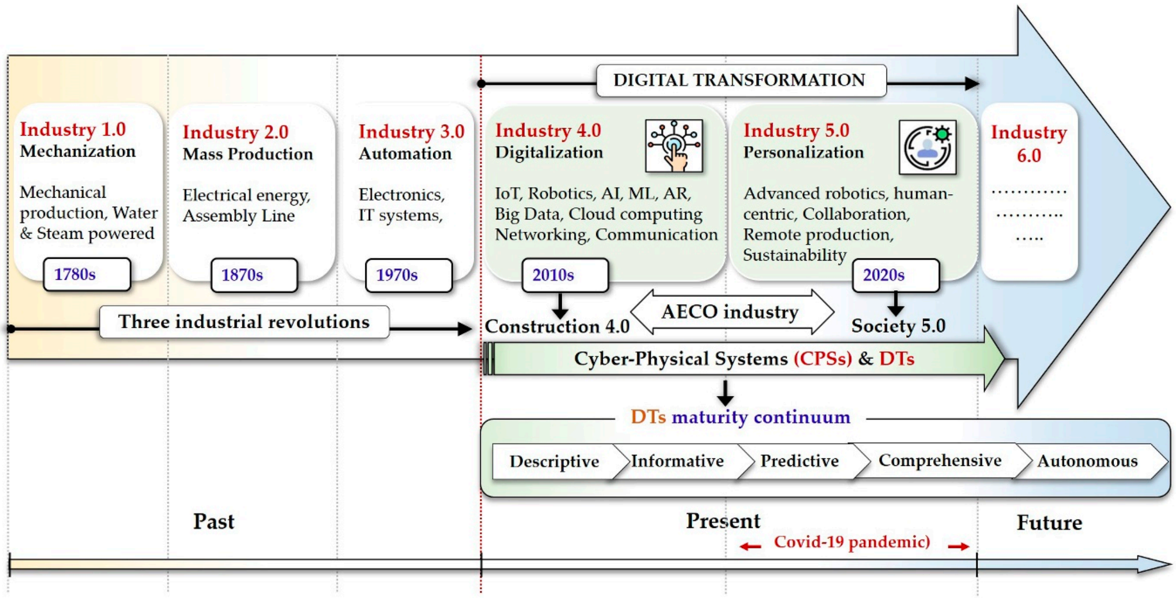

Figure 4. DTs and industrial revolution timeline. Adapted from [42,44].

In the AECO sector, Construction 4.0 is the construction industry's equivalent of Industry 4.0. It is the process of deploying cyber-physical systems (CPSs) and DTs to encourage construction industry digitization in order to achieve more SDGs. In this industry, both CPS and DTs are used to describe cyber–physical integration. However, DTs can be considered a necessary foundation and path to realizing CPSs [3,46,47]. Advanced technologies, tools, and other materials for digital transformation provide a comprehensive overview of material developments, emerging trends, cutting-edge technologies, and strategies in the fields of smart building design, construction, and operation, guiding architects on how to capitalize on the new opportunities brought about by the digital transformation [3,9].

According to [48], the AECO industry suffered several negative consequences during the COVID-19 pandemic. These included material delivery delays, material shortages, permit delays, lower productivity rates, cash flow issues, project suspension, price increases, and potential conflicts and disputes [48]. Furthermore, the spread of COVID-19 highlighted the benefits of remote work, leading AECO specialists to adopt DTs. During such outbreaks, such technologies facilitate socially-distancing work management, as well as virtual employment, which fosters resilience environments in the AECO industry [5,49]. Currently, the government and city managers are looking for ways to use technology to make cities smarter and safer. DTs construct the same digital copy of the smart city during construction [50]. As evidenced by the number of papers published and by the industry leaders investing heavily in the development of DTs technology, the use of DTs in recent literature has increased. This would not be possible without the same level of advancement in Industry 4.0 and Industry 5.0 technologies, which are increasingly becoming key enablers for DTs [41,42].

4. The DTs Concept and Cutting-Edge Technology

This section provides a brief overview of the DTs concept and illustrates how it manifests itself from various perspectives and across multiple technologies.

4.1. Terminology and Definition

While the terminology has evolved over time, the basic concept of the DTs models has remained consistent since its inception in 2003. The concept is that a digital informational construct of a physical system can be created as a separate entity. This digital information is a "twin" of the information embedded within the physical system and can be linked to it throughout the system's entire life cycle [10,51]. Researchers from various domains have given various definitions of DTs [11,46]. A brief summary of the literature is provided in Table 1. However, the most widely used definition is that DTs are an integrated multi-physics, multi-scale, probabilistic simulation, enabled by IoT connectivity and real-time advanced data analytics to mimic an IoT system, in order to demonstrate its physical model and performance in real-time [9,42].

Table 1. Definitions of DTs.

Ref.	Definition
[52]	Virtual substitutes for real-world objects are composed of virtual representations and communication capabilities that comprise smart objects that serve as intelligent nodes within the IoT and services
[53]	The simulation of the physical object that predicts the system's future states
[54]	A digital representation of a real-world object that focuses on the object itself
[51]	A collection of virtual information constructs that completely describe a potential or actual physical manufactured product from the micro to the macro geometrical level
[55]	A digital representation of assets, processes, or systems in the built or natural environment that is as accurate as possible
[56]	A linked and synchronized digital replica of physical assets that represents both elements and dynamics
[57]	A simulation-based planning and optimization concept with the potential to transform the AECO industry
[58]	A new engineering model for construction production control that makes use of data streaming and the unique capabilities of multiple site-monitoring systems
[13]	A combined approach based on big data and ML/AI for new forms of modeling and analysis

4.2. From BIM to DTs

The concept of BIM is rapidly evolving as a result of various technological advancements, making it comparable to the preparation of DTs. BIM technology can provide visual 3-dimensional communication for DTs. Furthermore, the proper integration of BIM and IoT technologies can aid in real-time monitoring, which develops a real-time active model for use as a DT application in the AECO industry. This can help with material selection, energy management, and supplier selection decisions. Furthermore, early design decisions regarding project feasibility, energy analysis, and sustainability issues could be informed by BIM and serve as pre-construction guides. Due to the expertise of BIM, it has been the focus of the majority of studies on DTs application in the AECO industry, especially in the first phases of life cycle processes [12,59–61].

4.2.1. Maturity Levels

To illustrate the transition from BIM to DTs, Deng et al. [60] developed a five-level ladder taxonomy, as summarized in Figure 5. In this taxonomy, BIM Level 4+AI exemplifies the use of BIM and AI techniques to improve decision-making and database predictions, whereas Level 5 ideal DTs demonstrate interaction and optimization in the AECO industry's post-BIM era. At the building or city level, this is an essential resource for accurate analyses, efficient operation, real-time decisions, predictive maintenance, and what-if scenario simulation. In terms of flexibility, while some buildings are still built using pre-BIM traditional practices, they can benefit from DTs by being fitted with sensors and using cloud-based analytics tools [9,42,60–62].

BIM technology is primarily used in new construction. However, one of the major challenges to BIM adoption for existing or old buildings that were not built with modeling in mind is obtaining raw and accurate building data and converting it to the BIM model. Based on this challenge, Soliman et al. [63] created a framework that used various data capture techniques for existing buildings and then transformed this captured data into 3D BIM models, allowing it to improve its management processes. Indoor building data was captured using 3D laser scanning techniques, while outdoor building data such as geometric dimensions, material shapes, surfaces, and various shapes were captured using drones equipped with high-definition cameras. The captured data was then converted into a high-resolution 3D model for use and integration with advanced facility management systems and platforms, representing significant progress in this field [63].

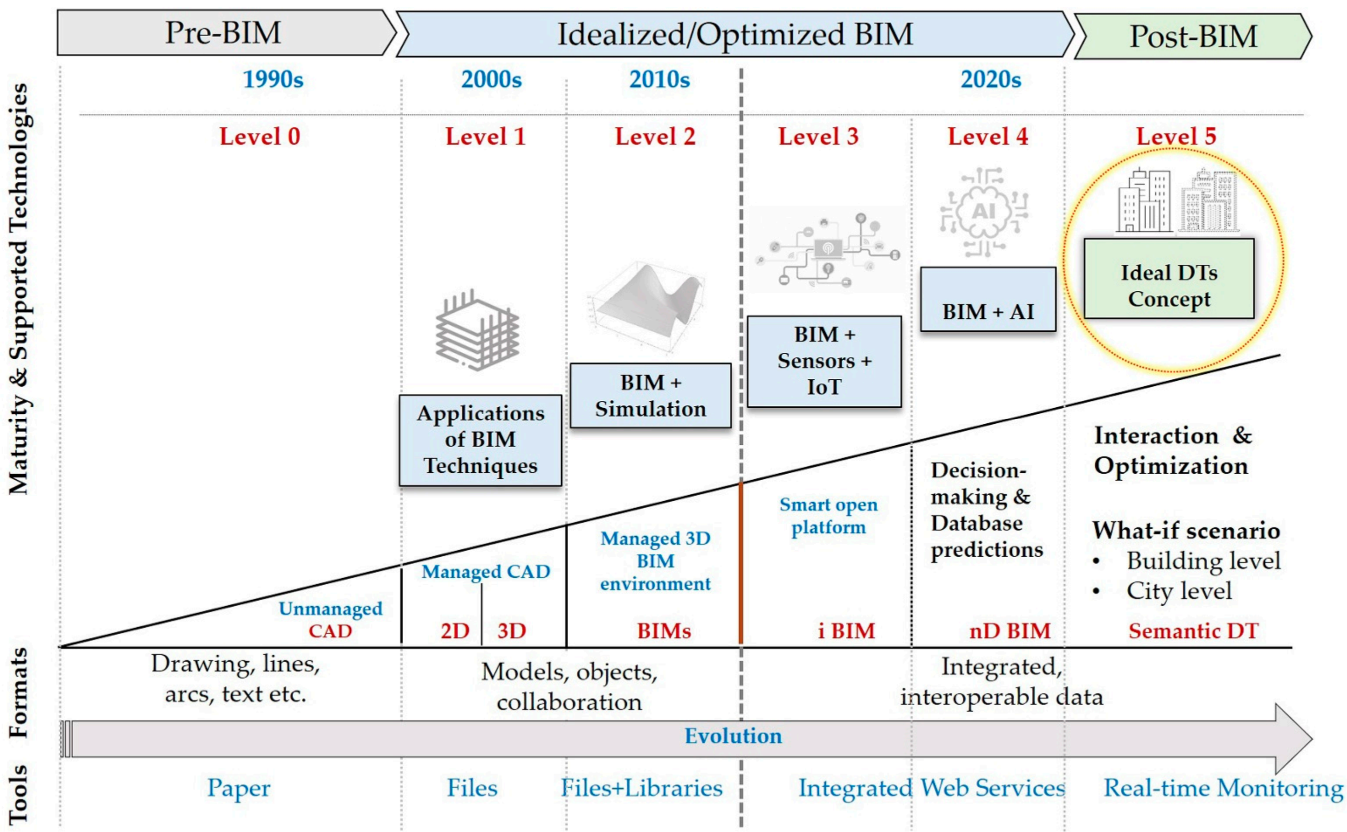

Figure 5. Five-level ladder taxonomy from BIM to DTs. Adapted from [6,60,64].

4.2.2. Clarification of the Concept

DTs are a rapidly evolving technology with a wide range of successful applications. While the applications have grown to include the AECO sector, some research has confused DTs with other concepts, such as BIM. DTs can be termed as a living and dynamic version, forming the output of the BIM process used to create virtual models, as illustrated in Figure 6. These DTs can then evolve, supported by real-time data and ML algorithms. The concepts of BIM and DTs can be compared in detail, based on many characteristics (see Table 2). Though both BIM and DTs vary in nature, they are proving to be a gain for the AECO industry by enabling buildings to become smart and dynamic [6,46,61].

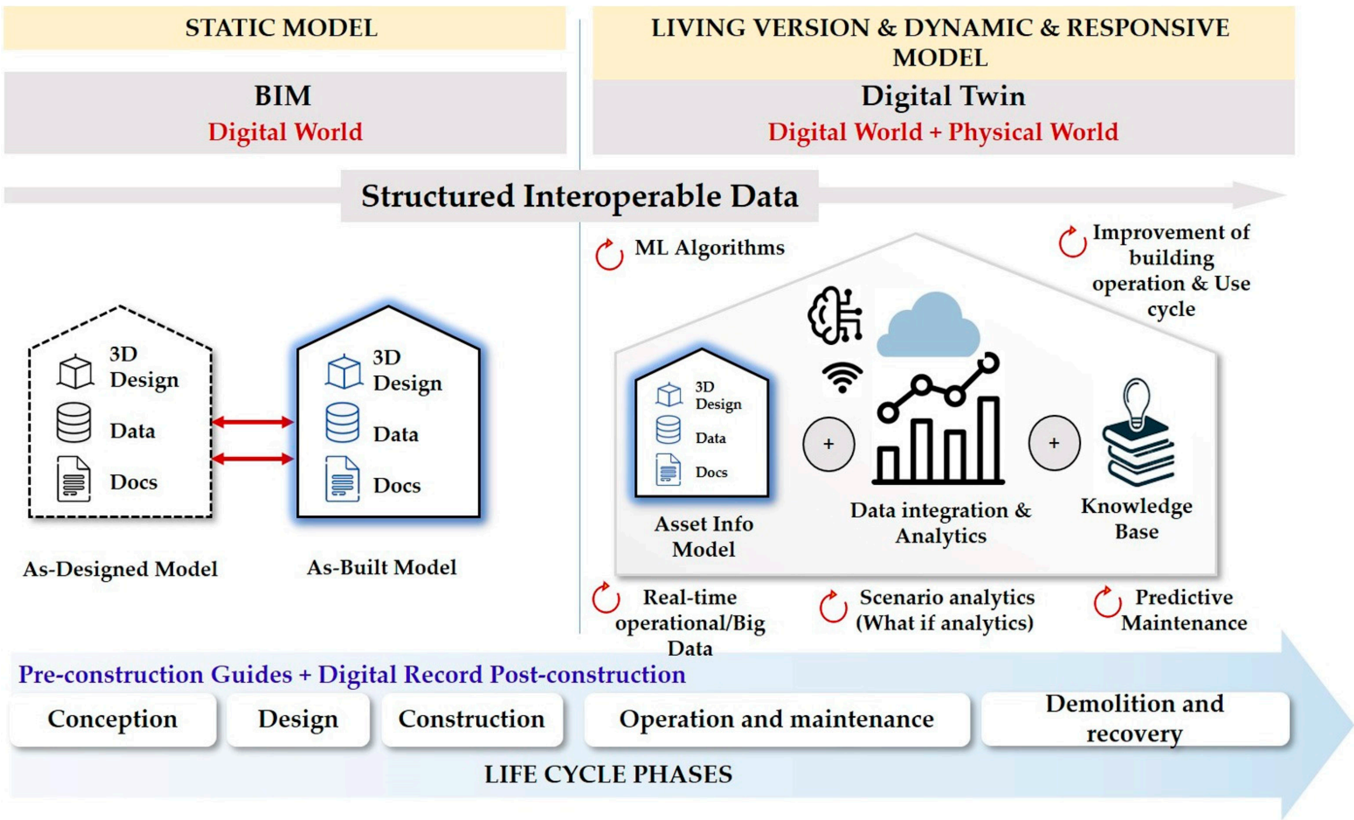

Figure 6. BIM and DTs processes and supporting technologies. Adapted from [61].

Table 2. Detailed comparison of BIM and DTs of buildings, adapted from [12,13,46,60,61,65].

Dimension	BIM	DTs Concept
Origin	Charles Eastman in the mid-1970s	Michael Grieves in 2003
Components	Virtual models typically built onsite. They contain both geometric and semantic information about the building elements.	Five parts: physical part, virtual part, connections, data, and services. It not only looks like the building model but also behaves just like the real building.
Physical part	Optional -does not emphasize the existence of the physical counterpart -can denote something that does not exist or has not been constructed	Compulsory -emphasizes the existence of the physical counterpart -must promptly reflect the physical counterpart's current state

Table 2. *Cont.*

Dimension	BIM	DTs Concept
Virtual part	Compulsory	Compulsory
Real time	It is not designed for real-time operational responses; however, BIM supports reactive measures.	It focuses on real-time data, giving an extensive picture of the building in real time, thereby supporting proactivity.
Maturity continuum	Prescriptive	Descriptive
Characteristic	Static model	Dynamic and responsive model
Main focus	Buildings and tools (software)	People and their behavior patterns
Main purpose	Collaboration and visualization during the design and construction phases	Operations and maintenance of the building, making it a live building
Application focus	Interoperability of stakeholders, design visualization and consistency, clash detection, lean construction, time and cost estimation	Predictive maintenance, occupant comfort enhancement, resource consumption efficiency, what-if analysis, closed-loop design
Main enabling technologies	Detailed 3D model, common data environment, industry foundation class, construction operations building information exchange	3D model, WSN, data analytics, AI, ML, cloud and edge computing
Tool/Software	Autodesk Revit, EnergyPlus, MicroStation, ArchiCAD, Open source BIMserver, Grevit	Predix, Dasher 360, Intelligent Communities Lifecycle, The Building Minds, Ecodomus
Users	Architects, engineers, constructors, AEC, and facility managers	Architects, facility managers

5. DTs Platforms in the AECO Sector

This section summarizes the emerging applications of DTs in the AECO sector, focusing on building life cycle phases. The cycle consists of many phases, namely, conception, design, construction, operation, maintenance, demolition, and recovery. Each phase can be separated into superimposed information layers that necessitate sufficient information exchange strategies for interoperability. Therefore, to achieve efficient information updates and exchanges throughout a building's life cycle, significant effort must be invested [60,66]. Stakeholders must make numerous decisions throughout the building's life cycle. Because of the rapid advancements in computing, data science, and AI technology, DTs enable these technologies to be leveraged, and create new opportunities to run what-if scenario analyses and nD simulations to learn from data and aid in decision-making. What-if scenarios and nD simulations are critical management techniques for assessing risks, forecasting outcomes, performance, and challenges, and acting proactively, particularly in the post-pandemic AECO Industry [67].

5.1. DTs Components

The concept of DTs is a collection of modules that work in tandem to monitor, learn, and optimize the overall system operation. This concept's implementation necessitates the development of new processes, methods, and platforms that interact with one another [68]. According to Kritzinger et al. [69], a digital twin is a fully integrated data flow between an existing physical object and a digital model. In this case, the digital model could also serve as a controlling instance of the physical object. A change in the state of the physical object causes a change in the state of the digital model, and vice versa [49].

Tao et al. [57] proposed that DTs have five components: (a) the physical part; (b) the virtual model that mirrors the physical part in a controlled setup; (c) the connections that enable data transfer and control; (d) real-time and optimization services such as simulation, decision-making, monitoring, and control of the physical object; and (e) data that drives the services to improve system convenience, reliability, and productivity. The key elements of DTs are the data that connect the physical and digital worlds through the bidirectional dynamic interaction of physical objects and virtual models [70].

5.2. DTs-based Applications

Fundamental to the combination concept, the DTs model of a smart city is not a single monolithic model; rather, it is built on a hierarchical architecture and includes a network of sub-DTs. These models are linked and built on data that can learn and update from multiple sources to represent and predict the current and future conditions of their physical counterparts correspondingly and promptly [11]. Sensors, 3D laser scanning, and other data capture techniques will be installed in the DTs platform, as shown in Figure 7, to collect a variety of data. The information and data contained within the DTs can be collected and transferred by various sensor networks to create real-time monitoring, which frequently includes climate data, energy demand, occupancy, carbon emissions, and footprint, monitored air quality data, and so on [13].

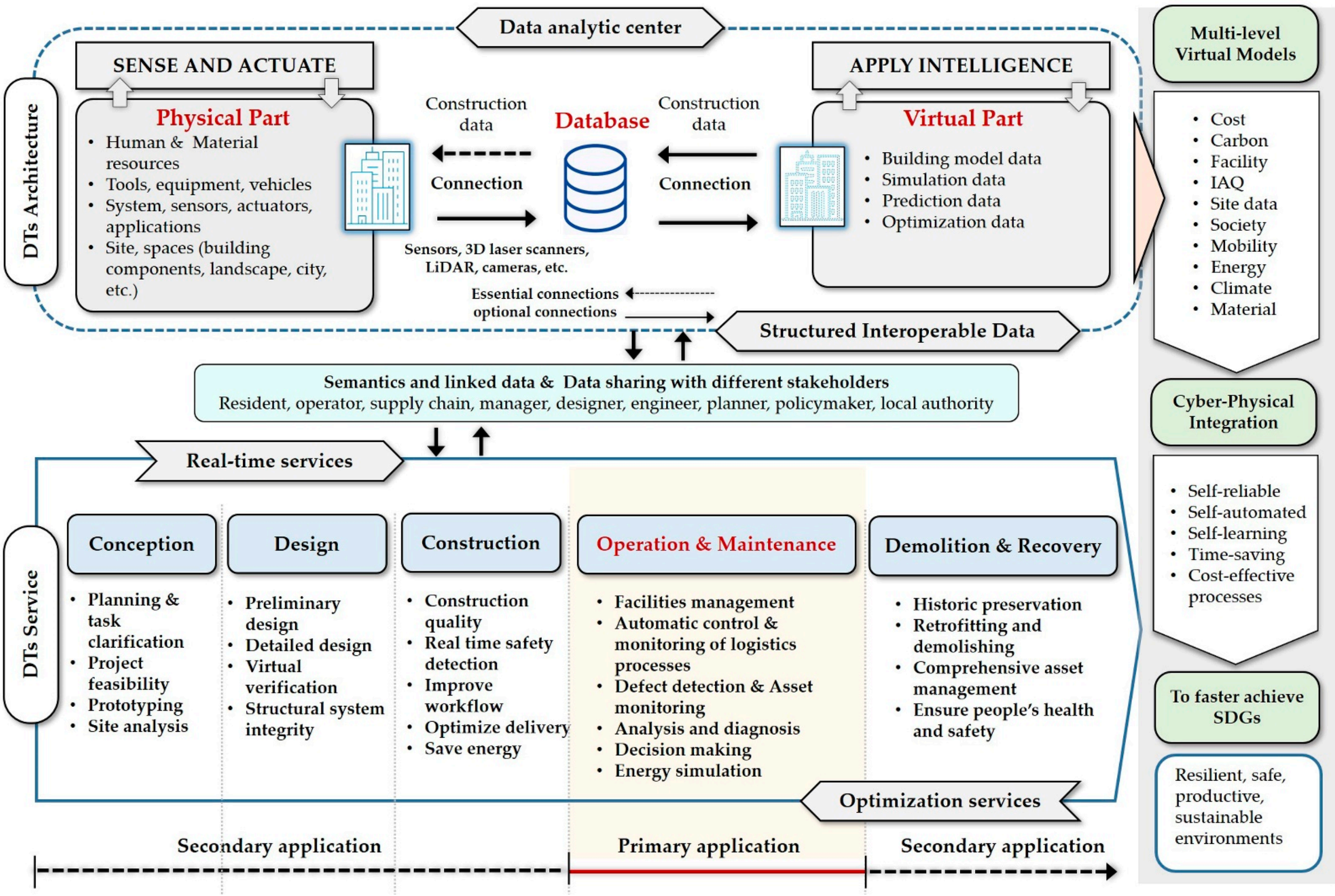

Figure 7. The AECO sector's DTs platform framework model. Adapted from [6,46].

Real-time data are collected and transferred to a data analytic center in Ideal DTs, where they are analyzed along with their complex systems for either prediction or optimization for several sustainability objectives. These data will be analyzed further and used in actions/decisions with various stakeholders for operations. For example, the vast majority of energy data are used to improve energy self-consumption, maximize economic benefits, reduce carbon emissions, and so on. Some of these data can be interpreted for maintaining Indoor Air Quality (IAQ) levels in specific buildings, as a virtual model provides an additional opportunity for analytical insights. The possibilities of generated heat and noise maps can assist city planners in creating a more comfortable and cooler living environment for residents. Given the characteristics of dynamic information, enormous potential also exists in the social dimension. [59,71–73].

In addition, employees were forced to work remotely and maintain social distance when sharing space with others due to the COVID-19 pandemic. This shift may have an impact on future project design, as more emphasis is placed on the optimal use of space to meet end-user needs and new preferences. Future designs can be simulated in a digital environment to predict specific parameters such as occupant comfort, occupant use of oxygen, lighting access, and acoustic insulations, using data collected on how occupants use their space, whether in their units or to maintain social distance in offices, and through DTs. In the event of a future pandemic, digital twins could be an effective strategy [67].

In the AECO sector, the life cycle of a physical structure includes major phases. Within the conception, design, and construction phases, architects, engineers, and managers are in charge of comprehending the relationship between design and construction and managing these components as a whole. This necessitates managing numerous tasks at the same time. In the last life cycle phases, every aspect of the structure should be monitored in real-time to optimize operation and maintenance, identify possible improvements, detect potential problems, and ensure people's health and safety [9]. Most DTs applications in the AECO industry, according to the literature, are focused on a single phase. Researchers were preoccupied with the initial phases, while ignoring the use of the DTs concept during demolition and recovery. The majority of the literature on DTs application focuses on the use of BIM models during the first phases of the object [12]. Table 3 summarizes a short example from the literature.

Table 3. Recent DTs-based applications in the AECO industry.

Ref.	Application
[74]	Develops an integrated system to capture information and knowledge of building maintenance operations during and after maintenance, to understand how a building deteriorates and to support preventive/corrective maintenance decisions.
[64]	Develops a theoretical framework for the HBIM approach in historic preservation and management
[75]	Transforms D BIM into nD BIM by incorporating IoT-enabled tools for prefabricated construction
[76]	Investigates the role of big data in the physical, social, and cyberspaces of cities in order to build smart cities
[77]	Conducts a practical investigation into the process of developing and collaborating with the new UCL Campus's DTs
[11]	Provides a comprehensive examination of the definitions and developments of DTs, as well as their applications in the AECO sector
[78]	Based on city virtualization and DTs, provides predictive insights into a city's smarter performance and growth
[6]	Examines BIM's many applications and limitations, as well as the importance of construction DTs in the construction industry
[79]	Presents the application of a computational procedure to assist DTs in the construction process
[80]	Develops and implements AECO's DT, VR, AR, and BIM technologies
[81]	Presents the topic of cybersecurity for DTs in the built environment
[60]	Conducts research on the evolution of BIM to DTs in built environment applications
[82]	Identifies relevant gaps, challenges, and future work on DL-based safety management applications in the AECO industry
[83]	Presents a hybrid approach that combines physics-based and machine learning methods to create a DT for the existing built environment.
[61]	Applies information from a practical investigation, in which more than 25,000 sensor reading instances were collected, analyzed, and used to create and test a limited digital twin of an office building facade element.
[63]	Creates a framework for generating a BIM model for existing buildings, using a variety of data-capture techniques and then integrating the BIM model with a web-based building management system.

6. Opportunities and Challenges

While the COVID-19 pandemic slowed most industries worldwide for several months, it hastened the adoption of DTs technologies to help government officials, businesses, and residents better prepare for future similar health crises, as well as better visualize and correlate analytics across multiple sectors to rapidly assess and implement economic recovery plans for affected cities [50]. As a result, the COVID-19 pandemic has significantly accelerated the adoption of DTs that have the potential to optimize disaster management strategies [81]. However, as with any new concept, DTs present both opportunities and challenges [48].

Based on SDGs, the AECO industry has sought approaches and methods to optimize resource utilization, lower project costs, increase productivity, improve safety, and shorten project delivery time. DTs can be used to learn about and propose new scenarios before constructing buildings or planning smart cities. Such learning advantages are based on DTs' capability for simulation, monitoring, life cycle assessment, sensing, optimization, and prediction, which increases system resilience [42,84,85].

As shown in the developed and proposed DTs platform framework model (Figure 7), DTs provide a revolutionary means of accelerating societal sustainability in terms of energy transition, circular economy, and climate change [13,51]. In response, DTs have been developed and gained prominence as ground-breaking technological developments for utilizing spatiotemporal data to digitally construct and visualize in real-time all characteristics, information, aspects, and activities, even in complex projects, without the need for costly and time-consuming physical onsite tracking. These technological advancements enable data-driven project management, operation, and maintenance, which improves the work efficiency of architects, engineers, managers, and industry workers [9,11,86].

According to [87], DTs are critical to paving the way for the development of additional contingency plans and of a new working strategy for a pandemic-induced reduction in human contact [86]. As a result, applying DTs to smart city construction has recently become a research hotspot [2,88,89]. DTs provide an unrivaled solution for mapping, managing, and mitigating the COVID-19 pandemic. A 3D visual model-based DT of an infected city is the ideal platform for aggregating and distributing information at scale during a crisis, such as the current virus outbreak [50]. However, from a practical standpoint, DTs present significant technical, societal, and operational challenges, including a) the availability of technology and the complexity of supporting systems, b) a lack of common data standards, tools, and skilled human resources, c) complex environment modeling, d) data security and ownership, and e) the need for systemic cultural change. As a result, when applied to a project, DTs require a higher initial investment; however, their inclusion provides a potentially significant return on investment throughout the life cycle [12,89–92].

Finally, while the DTs paradigm has the potential to provide significant benefits to the built environment as a whole, cities are difficult to model because they are complex combinations of dynamically interacting infrastructures and populations, subject to highly variable external influences such as atmospheric, hydrologic, socioeconomic, and other factors [88]. Another significant challenge for researchers and scientists in this context is that DTs, in particular, necessitate dynamic, connected web-based environments that integrate IoT, BIM, and AI to deliver human-centered smarter work. This is especially true for DTs and human-centered AI, which are both essential components of a smart AECO industry.

As a result, implementing new Industry 5.0 technologies may aid in overcoming some of these challenges. Humans and robots work more collaboratively in Industry 5.0. As a result, there is an urgent need to humanize the industry while also addressing issues of sustainability and resilience. Such fusions of DTs, AI, and human-centered approaches will shape the AECO industry's future and open up numerous research opportunities [9,37]. These difficulties indicate that the use of DTs in the built environment is still in its early stages, and more research on current cutting-edge technologies is needed to develop a future research agenda [60].

In conclusion, the study developed and proposed theoretical models that examine the evolution of DTs in the context of BIM, cutting-edge technologies, platforms, and applications throughout the project's life cycle phases. This study demonstrates DTs' high potential as a comprehensive approach to planning, managing, predicting, and optimizing AECO projects that will achieve more SDGs. The research findings, however, are based on a theoretical approach that has not been tested in practice. The framework of the study serves as a starting point for future quantitative studies. Future studies incorporating different stakeholder perspectives, such as interviews and existing case studies, will be required to validate the theoretical frameworks from various perspectives. As a result, the road to developing more comprehensive models is still evolving.

7. Conclusions

DTs are gaining popularity in our built environment, both academically and industrially. As a result, this research looked at how DTs are evolving from the BIM paradigm to support better decision-making in the smart AECO sector.

This paper provides an overview of the DTs concept, as well as cutting-edge technologies, platforms, and applications used throughout the project life cycle phases. The DTs platform provides a comprehensive approach for precise analyses, effective operation, real-time decisions, predictive maintenance, and what-if scenario simulation at the building or city level. Despite the obvious benefits of DTs in achieving SDGs, several technical, societal, and operational challenges must be addressed to achieve the overall development of this technology.

Regarding theoretical contributions, the study develops and proposes conceptual models that examine the evolution of DTs, cutting-edge technologies, platforms, and applications throughout the project's life cycle phases. It demonstrates how existing AI, IoT, and computer science knowledge can provide insights into the AECO sector. This science enables the easy, efficient, effective, and accurate exchange of data and information, regardless of time or place, resulting in significant benefits for collaboration with various stakeholders, particularly in the post-pandemic AECO industry. However, the research findings are entirely theoretical. The approach and findings provide an intriguing catalyst for future practical research into the application of human-centered approaches to effective communication in real-world scenarios. A more in-depth investigation is required, which should include some empirical evidence, such as interviews and case studies.

Author Contributions: N.A.M.: conceptualization; investigation; methodology; resources; visualization; writing original draft; writing review and editing. A.M.H.: investigation; methodology; resources; writing review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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