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DIGITAL TWIN IN CONSTRUCTION INDUSTRY: A REVIEW ON DEFINITION, APPLICATION AND CHALLENGES OF ADOPTION

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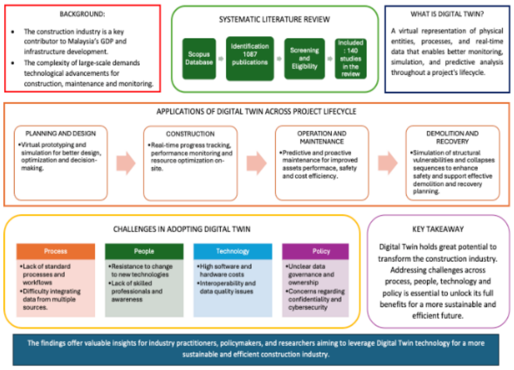
Graphical abstract



Abstract

The construction industry is pivotal in driving Malaysia's Gross Domestic Product (GDP), contributing to economic growth and infrastructure developments. However, with the complexity and large-scale infrastructure projects, there is a growing demand for technological advancements in construction, maintenance and monitoring. Digital Twin (DT) technology, known for its real-time data, predictive analysis, and simulation capabilities, presents a promising solution. A systematic literature review (SLR) was employed, and a total of 1087 publications were retrieved from the Scopus database. After applying inclusion and exclusion criteria, only 140 studies were included for review in this paper. This paper aims to explore the definition, current state of DT applications in the lifecycle phases while highlighting the challenges posed in adopting DT. Digital Twin (DT) is a virtual representation of physical entities, processes, and real-time data that enables better monitoring, simulation, and predictive analysis throughout a project's lifecycle. The application of DT are virtual prototyping and simulation in planning and design stages, real-time progress tracking in construction stage, predictive and proactive maintenance during operation and maintenance and simulation of structural vulnerabilities and collapses sequence in demolition and recovery phases. The study also identifies challenges from four (4) main aspects: process, people, technology and policy. Key challenges include integrating data from multiple sources, resistance to new technologies, high software and hardware cost and concerns regarding confidentiality due to unclear data governance regulations. The findings offer valuable insights for industry practitioners, policymakers, and researchers aiming to leverage Digital Twin technology for a more sustainable and efficient construction industry.

Keywords: Digital Twin, Construction Industry, Definition, Application, Challenges

1.0 INTRODUCTION

The construction industry is a major driver in contributing to Malaysia's economic growth and development. According to Building & Investment (2024), the construction industry's Gross Domestic Profit (GDP) grew by an astounding 17.3% as of the end of September 2024, primarily due to mega infrastructure projects such as Pan Borneo Highway and Sarawak-Sabah Link Road [59]. This has shown the strong recovery from the pandemic-driven fluctuations of the preceding years, with total construction project values reaching RM150.2 billion.

CIDB HQ (2024) claims that the government has set aside a sizeable sum of money for construction, including RM2.8 billion for federal road maintenance and RM27 billion for infrastructure projects in its 2024 budget [7]. These investments aim to improve transportation networks, boost economic growth, and raise living standards by enhancing housing and public infrastructure. Road infrastructure is the foundation of transport networks and is essential to both urban and rural development [65]. The importance of road infrastructure is shown by its vital role in societal functioning, substantial financial investments for countries, and large, developed structures [66]. Transportation networks such as road infrastructure and railways are vital in improving overall mobility and accessibility while facilitating regional connections [12]. However, the complexity and scale of the construction and maintenance of these extensive construction projects necessitate innovative approaches to guarantee work efficiency, cost-effectiveness, long-term durability and enhanced productivity [34; 64].

Cutting-edge technologies like Building Information Modelling (BIM), the Internet of Things (IoT), Digital Twin (DT), and Virtual/Augmented Reality (VR/AR) are rapidly implemented to improve sustainability and efficiency throughout the project lifecycle. These technologies facilitate the digitization of diverse assets, systems, and processes, improving infrastructure management [24] and aligning with the broader Industry 4.0 trend of digital transformation in construction [30]. By leveraging these innovations, construction firms can optimize resource allocation, reduce delays, and improve on-site coordination [47]. For instance, BIM enables 3D simulations for precise planning and visualization, minimizing design and construction errors [22], making data-driven choices for sustainable infrastructure management is made easier by IoT sensors, which enable real-time monitoring and predictive maintenance. [29].

Digital Twin (DT) technology, which creates a virtual entity that mimics the original physical entities and can be used for monitoring, analyzing, testing, and optimizing the physical entities, is particularly novel and advantageous in the construction business [40]. DT can also provide centralized platforms for all stakeholders to access and analyse data collected from sensors that are embedded within the structure [39]. DT facilitates better decision-making, predictive maintenance, and monitoring in real time. Applications for DT are very successful across a range of industries, including civil engineering, healthcare, and smart city sectors [18].

Matchett & Wium (2022) highlighted that DT in road infrastructure receive less attention than buildings and proposed a framework to enhance decision-making in road operations. By integrating dynamic data, DT improve road asset management [61]. In their review of the development, essential methods, and uses of DT, Liu et al. (2020) discovered that DT is employed in manufacturing stages for production control and real-time monitoring, in service for fault detection and predictive maintenance, and in design for redesigning and performance evaluation of the designed objects [62]. When Errandonea et al. (2020) examined DT applications for maintenance, they discovered that by combining real-time information via detectors, satellite imagery, and several other resources, DT present an accurate and current depiction of the state of the road, enabling predictive analytics and enabling maintenance teams to foresee possible problems before they become more serious [63]. DT technology integration is becoming a crucial tool for improving the overall performance and longevity of road infrastructure as it continues to change.

Transport infrastructure is one of the vital components of urban development and faces ongoing challenges related to wear and tear, climate impacts, and increased vehicular loads. The pavement is exposed to severe strains and degradation because of the excessive vehicle load [68]. The most agreed by the construction players for the problems that contribute to adoption of DT in the construction industry are due to the high volume of data obtained during operation, low coordination between stakeholders and cost issues [48]. Furthermore, road infrastructure ages sooner than expected because of the issue of vehicle overloading and a lack of finance, which results in inadequate maintenance [69]. Ageing infrastructure leads to increased maintenance needs, higher repair costs, and potential safety hazards. According to Sehgal (2023), the government plans to spend MYR 17.6 billion (US$ 3.9 billion) on transport infrastructure, specifically to build and upgrade roads and highways and upgrade existing roads, airports, and ports [70]. While the United States spends around USD 12.8 Billion to handle the deteriorating bridge condition every year [71]. This is due to major challenges in managing the data and information needed for effective maintenance of roads, bridges and other infrastructures. All these problems may contribute towards construction problems such as low project quality, project delays, cost overrun and disputes among construction players.

Most of the publications were reviews from other industries, such manufacturing and automotive, because DT is a new technique in the construction sector [30]. Based on Table 1, construction has shown the third highest references in total papers published. This demonstrates that DT are relevant to be further discussed and shown that awareness regarding DT is there and can be implement into the sectors. Because infrastructure projects are inherently complicated, large-scale, and resource-intensive, requiring considerable coordination among various stakeholders and diverse teams, DT should be focused on the construction industry, especially in the context of infrastructure [19]. Digital Twin (DT) can provide unified, real-time, and data rich platform to stimulate, coordinate and manage these complexities effectively. Unlike BIM that mainly used in design and planning stages, DT broadens its scope of application to include design, construction, operation, maintenance, and demolition [4;30]. Furthermore, DT implementation can improve long-term durability, efficiency, and productivity in the construction business, which is also in charge of vital infrastructure systems including roads, bridges, and utilities [23]. As a result, concentrating on DT in the construction sector advances digital transformation in a historically slow-to-adopt innovation sector in both theoretical and practical ways.

Malaysia's construction industry is still in its infancy when it comes to DT technology, despite its potential [67]. In addition, the concept of a DT is still lacking and no consensus between researchers and practitioners on how the DT process and whether the technologies can support design and construction in the context of building and civil infrastructure [35]. Although DT are relatively new to the construction industry, some noteworthy research provides insight into their application and use, particularly in the transportation sector. Consequently, this paper’s topics center on the definition, application and the challenges of adopting DT in the construction sector.

Table 1 Total papers published in each sector

No.	Sectors/Fields	References	Total
1	Manufacturing	Singh et al., (2022), Tao et al., (2018), Bottjer et al., (2023), Cimino et al., (2019), Lo et al., (2021), Lucato et al., (2019), Chen et al., (2023), Senna et al., (2023), Colli et al., (2019), Lukhmanov et al., (2022), Liu et al., (2021), Javaid et al., (2023), Enders et al., (2019), Augustine (2020), Jiang et al., (2021), Semeraro et al., (2023), Hu et al., (2022)	17
2	Automative	Deng et al., (2023), Biesinger et al., (2019), Piromalis & Kantaros (2022), Yang et al., (2022), Bhatti et al., (2021), Park & Lee (2021), Chen (2022), Cooke (2021)	8
3	Construction	Singh et al., (2022), Madubuike et al., (2022), Opoku et al. (2021), Kwon et al., (2022), Mendes (2023), Matchett & WIUM (2022), Perera et al., (2022)	7
4	Healthcare	Singh et al., (2022), Fuenmayor et al., (2020)	2
5	Energy	Singh et al., (2022), Islam et al., (2021)	2
6	Aerospace	Negri et al., (2020), Medina et al., (2021)	2
7	Production and Logistics	Muller et al., (2022), Uhlenkamp (2022)	2
8	Maintenance	Errandonea et al., (2020), Liu et al., (2023)	2
9	Smart Cities	Mihaita et al., (2022), Jeddoub et al., (2023)	2
10	Oil & Gas	Wanasinghe et al., (2020)	1
11	IT & Architecture	Weber et al., (2017)	1
12	Environment	Zhai et al. (2022)	1

2.0 METHODOLOGY

Using a Systematic Literature Review (SLR), this study assessed the definition, uses, and difficulties of DT technology as well as its uptake in the construction sector. This approach is used to guarantee thorough coverage of pertinent studies, accuracy, and transparency. The SLR provides a solid basis for expanding the use of Digital Twins in construction industry by minimizing bias, synthesizing existing information, and identifying research gaps through the application of systematic search, screening, and selection criteria [43]. Numerous guidelines are followed by this method, including a thorough examination or presentation of an open approach, repeatability and updateability, and a synopsis and synthesis of the main research issue [6]. In order to increase reporting integrity and document the review process, this study employed methods like Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [27]. The entire process of searching for and screening papers for this study using PRISMA 2020 is depicted in Figure 1. To finish the systematic review, there are three steps involved:

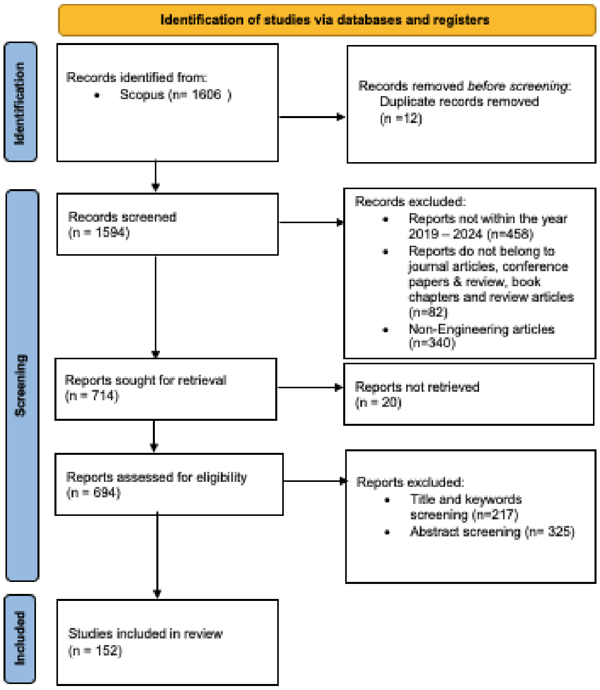


Figure 1 Flowchart of article screening procedure utilizing PRISMA 2020

Stage 1: Identification Stage

Because Scopus has a wider coverage of scientific publications, it was selected as the search engine for this study for this first stage [30];[32]. The Scopus search engine performs better than Web of Science, PubMed, and Google Scholar [11]. A thorough search was carried out using two search components in the Scopus "article title, abstracts, keywords" field. Keywords pertaining to "digital twin," "digital twins," "digital twin technology," or "digital twins (DT)" are included in the first section of the search box. In order to retrieve articles for the second section, the keywords "construction industry" or "construction engineering" and "construction 4.0" were used. Next, the keywords “definition” and “challenges” and “application” were used to retrieved papers that suits for this paper.

As indicated in Table 2, Boolean methods that employ Boolean operators like "AND" or "OR" were employed in this procedure to find and filter the appropriate material. Other technologies, such as BIM in the construction industry, are excluded in this study since it has already been covered in other papers. Thus, the inclusion will be redundant and repetitive. The terminology in this paper was influenced by previous searches using generic phrases. During this stage, inclusion and exclusion criteria were set for future screening processes. 1234 publications in all were obtained via Scopus search queries. After the limitation of the keywords selected, only 607 articles that were recovered. 10 duplicates were eliminated, which resulting in only 597 articles left.

Table 2 Search queries and results

Search Engine	Search Queries	Results
Scopus	(TITLE-ABS-KEY(“digital twin" AND "construction industry" AND definition AND (challenges OR barriers OR limitations) AND (application OR uses cases OR implementation)	1234
	AND (LIMIT-TO (EXACTKEYWORD,"Digital Twin") OR LIMIT-TO (EXACTKEYWORD,"Construction Industry") OR LIMIT-TO (EXACTKEYWORD,"Industry 4.0") OR LIMIT-TO (EXACTKEYWORD,"Digital Twins") OR LIMIT-TO (EXACTKEYWORD,"Construction 4.0") OR LIMIT-TO (EXACTKEYWORD,"Construction") OR LIMIT-TO (EXACTKEYWORD,"Digital Twin (dt)") OR LIMIT-TO (EXACTKEYWORD,"Construction Engineering"))	607
	AND PUBYEAR > 2018 AND PUBYEAR < 2025	420
	AND (LIMIT-TO (LANGUAGE , "English"))	417
	AND (EXCLUDE (DOCTYPE , "sh"))	416

Stage 2: Screening and Reviewing Stage

The papers that were found in the Scopus database using the search query were filtered and examined at this point. Table 3 displayed the criteria for being included or excluded. First, the year of publication is a requirement for inclusion in this systematic review. The selection year would be in the period of 5 years as it is essential to ensure its relevance and accuracy and aligned with the current academic and industry standards [14]. Thus, the publication was retrieved from year 2019 to 2024. Only 1 article that did not fit into the categories of journal articles, conference papers, book chapters, or review articles were eliminated, while about 187 items were published outside of the year 2019-2024.

Table 3 Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
● Journal papers that are accessible through the Scopus database	● Duplicated articles
● Review articles that are accessible through the Scopus database	● Articles unavailable for online retrieval
● Articles from year 2019 to 2024	● Non-Engineering articles
● Articles clarifying the definition of DT	● Irrelevant research that includes other technologies
● Articles studying the application of DT within construction sector	● Irrelevant research that does not include the definition, application and challenges of DT
● Articles studying the challenges of DT implementation	

After the filtration based on the year, non-English publications were removed. A total of 3 articles were written in other subject areas such as Chinese, Italian and Persian. From this exclusion, only 406 paper was obtained as it were published in English. After examining the remaining articles for access, 20 were removed since their entire texts could not be obtained. Only about 788 publications can be assessed for their eligibility to be included in this paper.

The next step for the screening stage is to review the remaining article by title, keywords and abstract. 227 papers in total were removed since the keywords used do not match the theme of this paper which “digital twin” and “construction industry”. The remaining 365 papers were continued for abstract screening. Consequently, only 196 papers could be considered in this publication.

Stage 3: Categorization stage

In order to accomplish the goals of this paper—which include presenting (i) the definition, (ii) its applications, and (iii) the challenges encountered in adopting DT technology in each article—the remaining 196 articles were divided into multiple sections in this step.

2.1 Results

This section illustrates the findings from the collection of articles from the 2019–2024 interval using the Scopus database, based on the inclusion and exclusion criteria.

2.1.1 Articles per year

140 papers were selected for this review study based on the preliminary evaluation of the articles in the prior section. The distribution of publications about DT in the construction sector from 2019 to 2024 is depicted in Figure 2. While other industries have seen advancements in the usage of DT, such as manufacturing [40] and automotive [3], the number of articles retrieved shows a steady and significant increase over the five-year period, proving the increasing interest in and possible implementation of DT in the construction industry.

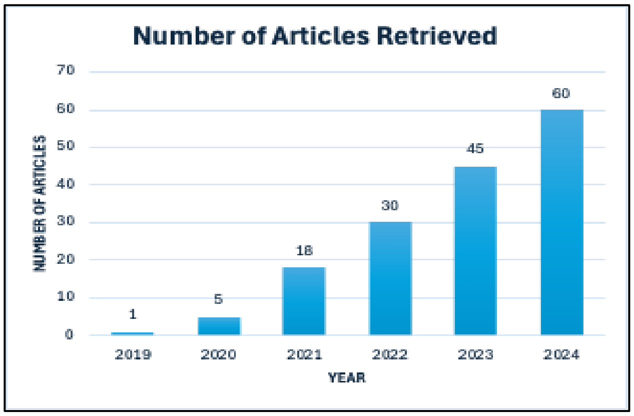


Figure 2 Total articles published annually in the Scopus database

Since DT are still in their infancy, only four articles were recovered in 2019; by 2020, that number of articles have increased to seven. The notable increase between the year 2021 until 2023 indicate that most practitioners have the awareness about these technologies since BIM is one of the digital advancements that have been employed before DT and have promising benefits towards the construction industry. Thus, the peak growth in the year 2024 can be concluded as the construction players has an increasing interest in adopting these technologies. However, the maturity on these technologies is still nascent and need for future research.

2.1.2 Types and Publisher Of Acquired Articles

The reviewed articles come from a variety of document types, including 72 articles, 20 conference proceedings, 4 book chapters, and 62 review papers and 1 book. As illustrated in Figure 3, an extensive review of all these documents is conducted to comprehend the use of DT within the construction sector.

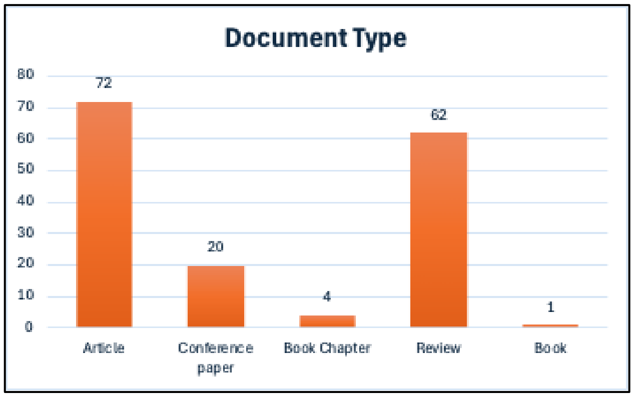


Figure 3 Document types retrieved for review(Image Errors)

Figure 4 shows the sources of journals for the articles that were reviewed in this study. The highest number of publications come from research journals from various backgrounds, such as Building Engineering, Cleaner Production, Design and Built Environment, Engineering, Design and Technology, Information Technology, Infrastructure Intelligence and Resilience, Infrastructure, Policy and Development, and Intelligent Manufacturing, with 27 articles involved.

2.1.3 Citation Analysis

The top ten most mentioned publications that were found throughout this investigation are displayed in Figure 5. Citation analysis demonstrates the significance and impact of the chosen publications and indicates that DT twin technology has demonstrated a promising influence for further research, namely in the construction sector. With over 700 citations, Boje et al. [4] are the most cited research papers found in this investigation, followed by a paper by Opoku et al. [30], which has 414 citations. This depicts that both papers in the earlier year have brought substantial benefits to the field.

3.0 RESULTS AND DISCUSSION

This section discussed the articles' results regarding the definition, use, and difficulties of DT in the construction industry.

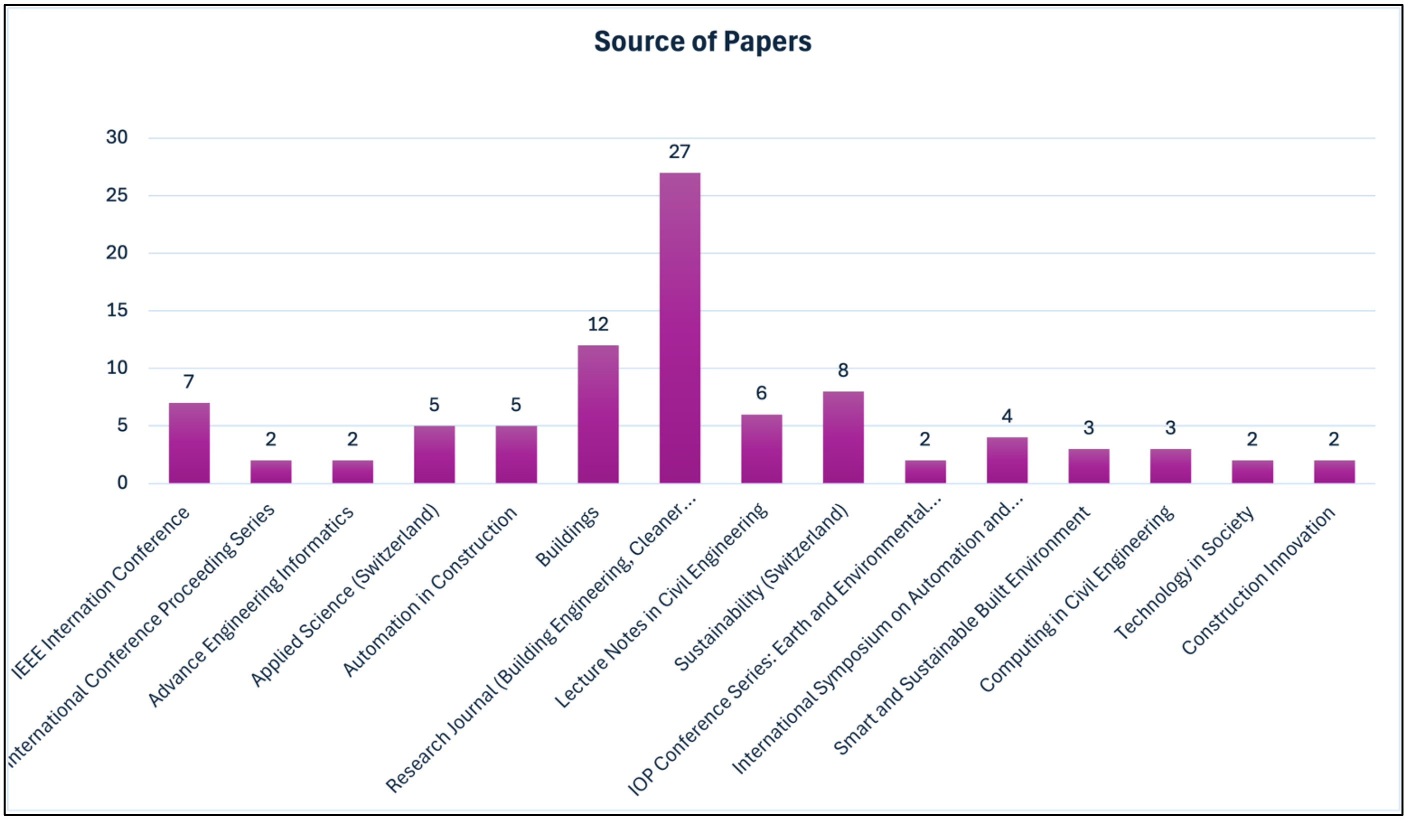


Figure 4 Source of published papers

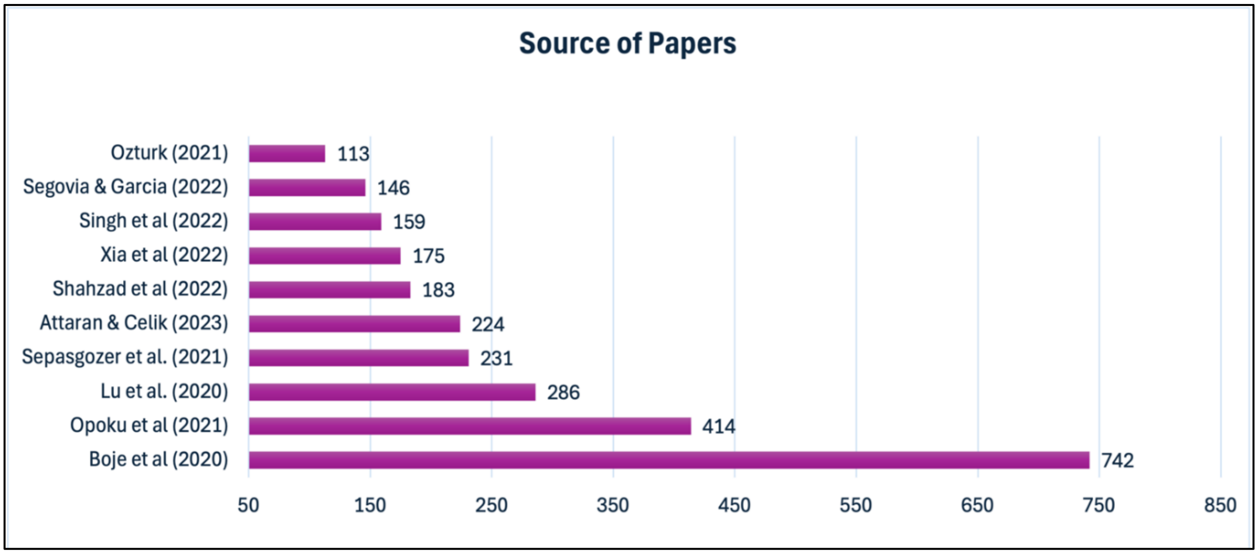


Figure 5 Most cited papers from retrieved papers

3.1 Definition of Digital Twin (DT)

Recent publications are mostly focusing on the application, but theoretical considerations are still important [60]. The definition of DT is various and does not fix to one as it is different based on the author and the fields discovered. According to Fuller et al. (2020), the lack of standardization and misconceptions with definition of Digital Twin are needed to be address to ensure its future developments [13].

In a 2012 publication, the National Aeronautics and Space Administration (NASA) was initially introduced the phrase "Digital Twin" (DT). According to NASA, a digital twin is a probabilistic, multi-physics, multi-scale simulation of a system or vehicle that mimics the life of its corresponding flying twin by utilizing the finest physical models, sensor updates, fleet history, etc. [37]. Understanding the term helps improve one's comprehension of the technology. Nonetheless, it revolves on the terms "digital model", "digital twin", and "digital replica". Table 4 illustrates the definitions of DT used by different authors.

Table 4 Definition of DT

No	Author/Year	Definition
1.	Shafto et al. (2012)[37]	A digital twin is a probabilistic, multiphysics, multi-scale simulation of a system or vehicle that mimics the life of its corresponding flying twin by utilizing the finest physical models, sensor updates, fleet history, and other accessible data.
2.	Tuegel et al. (2012)[42]	DT is responsible for creating high-fidelity models, digital environments, and loads for life prediction and aircraft structural modelling.
3.	Grieves and Vickers (2016)[15]	a collection of digital data that, from the microatomic level to the macro geometrical level, completely characterizes a possible or real physical manufactured product.
4.	Vatn (2018) [17]	A digital twin is an actual, controllable, and decision-making digital duplicate of physical assets, systems, and procedures.
5.	Tchana et al. (2019) [41]	The relationship and coordination between the information in the virtual product and the data pertaining to the actual goods.
6.	Sacks et al. (2020) [35]	A novel approach to production management, Digital Twin Construction (DTC) uses a range of artificially intelligent functions and site monitoring technology to offer precise status updates and to proactively assess and optimize current design, planning, and production.
7.	Delgado & Oyedele (2021) [8]	The three parts of DT are the physical component, the virtual model, data analysis and how it is connected to the physical component through technologies such as Internet of Things (IoT).
8.	Jiang et al. (2021) [18]	The five components of DT are the physical component that serves as the foundation for the virtual components, the virtual component that replicates the physical component in a controlled environment, the connections that allow data transfer and control, the services that are offered, including simulation, and the data that powers the services to improve the system's dependability and efficiency.
9.	Botín-Sanabria et al. (2022) [5]	A digital version of a real thing or procedure that which can collect information from the real world to illustrate, support, and encourage the actions of the physical twin both currently and in the future.
10.	Opoku et al. (2022) [31]	DT is a real-time display of a partially or fully completed building or structure that is designed to capture the fundamental characteristics of the structure or building it portrays.

Digital twin (DT) are defined as digital copies of real items or workflows that are updated in actual time with data to analyze, stimulate, and optimize performance [40]. DT are primarily advantageous as they can lower hazards and increase operational efficiency by offering precise models and predictions prior to making actual adjustments [40]. By establishing a connection between the virtual and real worlds, DT are enabling more intelligent, sustainable practices and transforming enterprises.

3.2 Application of Digital Twin in the Construction Industry

The construction industry's lifecycle phases comprise several stages, including design and planning, construction, operation and maintenance, demolition and deconstruction. The different stages of the construction industry's lifecycle demonstrate the use of the newly developed DT [8]. The percentage of articles about DT at various stages is displayed in Figure 6. Thus, this section will discuss the application of DT in each of these stages.

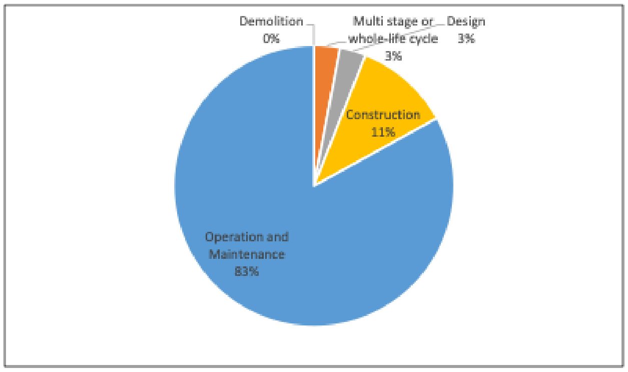


Figure 6 The proportion of articles about digital twin in different stages (Adopted from Zhang et al., 2023)

3.2.1 Application of Digital Twin In Planning And Design Stages

The planning and design stages are the first stage that needs to be done in a construction project's lifecycles. During these stages, architects and engineers develop conceptual, schematic and detailed designs for the construction projects. Tools such as Building Information Modelling (BIM) and Digital Twin (DT) play a significant role in performing budgeting, scheduling, and risk assessment at this stage. Eastman et al., (2019) emphasize that integrating BIM and DT in the design stage improves coordination and error detection [9]. DT offer a dynamic, data-driven presentation of a construction project prior to the start of actual work by combining Building Information Modelling, the Internet of Things (IoT), and Artificial Intelligence (AI) [30]. This enables designers, architects, and engineers to visualize and optimize designs within a virtual environment, minimizing errors and enhancing productivity.

Virtual prototyping and simulation are two of the main ways that DT are used during the design phase. Traditional methods rely heavily on static 2D and 3D models, which inadequately represent the details of actual construction. However, DT provide real-time, interactive 3D models that are continuously updated based on data inputs, which then allow performance testing, clash detection and environmental impact assessment [26]. A complex construction project requires seamless collaboration between a number of disciplines, including architecture, structural engineering, and mechanical, electrical, and plumbing (MEP) systems.

DT combine multidisciplinary design data and employ AI-powered clash detection algorithms to find discrepancies [35]. Project teams can reduce the need for expensive on-site adjustments, improving project efficiency and cutting down on material waste by proactively resolving conflicts in the digital environment. For example, Jiang et al., (2021) demonstrated how a DT model in a high-rise office building project helped identify over 300 design conflicts, leading to a 15% reduction in rework costs [18]. DT allow for real-time design validation, enabling engineers to test multiple scenarios before the actual construction begins [4].

DT adoption has been made easier by the integration of BIM, which makes it possible to create and maintain digital models with asset-specific data [30]. By enabling data to be updated, changed, and verified against actual conditions, BIM improves stakeholder collaboration. In this context, DT are created by combining Wireless Sensor Networks (WSN) with BIM to create a dynamic, real-time model [21].

Furthermore, by offering a shared, cloud-based platform that allows architects, engineers, and clients to engage with the changing design model in real-time, DT promote stakeholder collaboration [43]. This enhances decision-making, communication, and project transparency, minimizing misunderstandings and guaranteeing that all project participants are on the same page from the start. In his paper, Boje et al. (2020) also highlights how DT-enabled semantic construction models improve information flow between architects and engineers, reducing design conflicts [4].

As for sustainability aspects, Rafsanjani & Nabizadeh (2023) stated that DT helps in optimizing material selection and energy efficiency simulations for sustainable design [34]. For instance, Arowoiya et al. (2024) shows DT model was utilized to optimize the design of the HVAC system in a smart hospital project in Germany, which resulted in a 20% reduction in energy consumption even before construction began [2]. DT make it possible to create sustainable and energy-efficient buildings by combining real-time climate data with material performance data analysis.

DT also allow planners to stimulate city layouts, test infrastructure resilience and manage resources more effectively. For example, The City of Zurich used DT to optimize urban planning decisions for transport and housing developments [36]. Sacks et al. (2020) stated that DT provide predictive analytics to stimulate potential risks in project execution and propose solutions [35]. For instance, a bridge project in the UK used DT to test its structural integrity under various environmental conditions and found that the system led to a 40% reduction in manual inspection and improved maintenance scheduling, which then extended the bridge service's life [46].

3.2.2 Application of Digital Twin In Construction Stage

In a construction project's lifecycle, the construction stage is crucial. This is where the actual or the finished object were construct and mistake or clashing at this stage are very prominent due to the lack of communication or supervision between the stakeholders. Digital Twin (DT), in contrast to conventional construction monitoring techniques, offer a real-time virtual model of the project that is updated continuously as physical progress is made. This enables stakeholders to monitor progress, anticipate hazards and optimize processes [26].

One of the most impactful applications of DT is real-time progress tracking, DT with the help of other technologies such as IoT-enabled sensors, drones, and BIM, can create a 3D live model of the construction site which then allows managers to monitor the real-time progress and changes on-site against the project timeline [35]. Rafsanjani and Nabizadeh (2023) demonstrated that using DT in a large-scale infrastructure project reduced construction delays by 25% by providing real-time updates and improving coordination among stakeholders [34].

The majority of research, according to Opoku et al. (2021), concentrated on utilizing DT to assess the integrity of the structural system during a project's construction phase [30]. DT have been used to study the integrity of the structural system, according to Angjeliu, Coronelli, and Gradani (2020), who developed a model used for simulation for DT applications in old masonry buildings [1]. The study discovered that, especially in intricate areas of masonry buildings, DT can be used to comprehend structural actions and can be updated continuously based on the knowledge gained. This can help ensure that when force is applied to the buildings, the objects' structural system will not fail. In addition, AI-driven DT models analyze worker movements, environmental conditions, and structural integrity to identify high-risk areas [4]. For example, Opoku et al., (2021) shows that a construction project that used DT safety simulations can reduce by 30% workplace injuries due to real-time alerts and emergency response planning [30].

Furthermore, in the event that the design drawings are unavailable, DT can work to produce as-built drawings [25]. As-built drawings are produced after a project is finished and can help stakeholders keep track of the maintenance and operating phases. With sufficient project details, DT can assist with the volume of data required to improve quality, reduce construction costs, and enable effective stakeholder management [30]. Numerous resources, such as labour, materials, and machinery, are used on construction sites; these resources must be distributed effectively to prevent delays and cost overruns. DT-based predictive maintenance keeps equipment running by anticipating possible problems before they arise, avoiding expensive malfunctions and downtime [18].

Manual inspections, which can be tedious and prone to mistakes, are the foundation of traditional on-site inspection techniques. Thus, by integrating DTs computer vision and AI-powered image recognition, it can automatically scan construction sites for structural defects, misalignments or material inconsistencies [26]. This early detection can prevent from costly reworks and enhances construction quality.

3.2.3 Application Of Digital Twin In Operation And Maintenance Stage

The structure moves into its operational and upkeep stage after construction is finished and it is made available to the public. DT provide a centralized platform for stakeholders to access and analyze data collected from sensors embedded in the infrastructure [38]. Because of the proactive maintenance techniques made possible by this connectivity, stakeholders may detect and resolve problems before they become more serious, reducing downtime and increasing operational effectiveness.

Lu et al. (2021) illustrates the usage of DT with photographs and CAD models for existing structures through a case study involving a section of an office block. This suggests that during a building's operating phase, operations and maintenance with DT's assistance are a successful approach [23]. In a smart office building, for instance, Jiang et al. (2021) showed that a maintenance system enabled by a DT decreased HVAC system failures by 30%, resulting in significant cost savings and enhanced occupant comfort [18]. DT in operation and maintenance have many advantages in defect detection, asset monitoring, decision-making, analysis and diagnosis, retrofitting, and destruction [18]. The primary feature is defect detection, where it uses point clouds and images to identify as-builts flaws and design variations. Callcut et al. (2021), for instance, disclosed that DT was used in the overhead transmission line (OTL) trial inspection and predicted 112 flaws in the 2.34km length of OTL, whereas only three defects were previously found during the human inspection [58]. This shows that DT can be helpful in detecting defects before they are used or opened to the public, preventing further problems from occurring.

DT also enables informed decision-making and resource allocation. Physical components can be represented by DT in the virtual world, and decisions can be made using DT [18]. According to Zhong et al. (2023), the use of DT improves the capacity for wise decision-making during maintenance [57]. The equipment's precise fault threshold allows for the autonomous decision-making of the system to be configured in the simulation environment [57]. This allows for the realisation of intelligent decision-making through prediction based on real-time data.

Structural health monitoring is another area where DT have proven useful. Integrity and safety of structures such as bridges, tunnels and buildings are important as they are exposed for public use daily. Thus, DT are used for continuous monitoring and detection of early signs of structural deterioration by integration of IoT-based vibration, temperature and stress sensors, allowing for timely intervention before major failures occur [44]. For example, Kaewunruen et al., (2022) shows that the European railway bridge employed a DT to track stress and material degradation, thus improving its operational safety and longevity [19]. Overall, DT can be used to reliability of assets, promote teamwork, and expedite maintenance processes in the construction sector.

3.2.4 Application of Digital Twin In Demolition And Recovery Stage

Researchers frequently overlook this stage, also known as the retire phase [56]. The construction sector disregards the use of DT technology since structural information is usually lost at this point [30]. Demolition has been known for its resource-intensive process, often leading to material waste, environmental hazards and unoptimized deconstruction strategies. Thus, using DT can stimulate the mechanical behavior of the buildings, assessing structural vulnerabilities, potential collapse sequences and the safest dismantling approaches [20]. Ellul et al. (2024) demonstrates how location-enabled DT were implemented to enhance demolition safety and deconstruction planning for high-rise buildings in London [10]. DT stimulated the blast scenarios to predict structural collapse sequences, ensuring safer and more controlled demolition processes, reducing accidental collapse by 30%, minimizing safety risks for workers and surrounding structures.

DT also supports circular economy practices by tracking and cataloging building materials that can be reused, recycled and repurposed [16]. Valuable materials such as concrete, steel and glass can be extracted with minimal waste as DT assist in selective deconstruction by analyzing the composition and condition of the materials. A study found that a DT-assisted deconstruction of a large commercial building in Germany led to a 40% reduction in landfill waste by optimizing recovery processes. Next, the process of dismantling buildings often leads to dust emissions, noise pollution and CO2 release. DTs can integrate real-time environmental monitoring to track air quality, noise levels and carbon footprint during demolition activities [46]. It can help planners to choose the least environmentally damaging approach, improving sustainability and regulatory compliance by stimulating various deconstruction scenarios. And lastly, one the deconstruction Is done, DTs can assess the soil conditions, underground utilities and environmental factors to guide future construction or land rehabilitation process [45]. For instance, smart city redevelopment in Amsterdam, where DT was used to evaluate the site readiness for new infrastructure, reduced redevelopment time by 20% [33].

Table 5 shows the summary of the application of Digital Twin throughout the construction's lifecycle stages.

Table 5 Summary of the application of DT throughout the lifecycle stages

Lifecycle Stage	Key Applications	Benefits / Outcomes	References
Planning & Design	- Virtual prototyping & simulation (real-time 3D models) - AI-powered clash detection - BIM + IoT + AI integration - Cloud-based collaboration platforms - Sustainability optimization (material, energy, HVAC) - Urban & infrastructure resilience testing	- Improved design visualization & optimization - Reduced rework costs (15% in high-rise case) - Enhanced stakeholder collaboration & communication - Energy savings (20% in smart hospital) - Reduced manual inspection (40% in UK bridge)	Eastman et al., (2019); Opoku et al.,(2021); Jiang et al., (2021); Tuhaise et al., (2023); Rafsanjani & Nabizadeh, (2023); Arowoiya et al., (2024); Boje et al., (2020)
Construction	- Real-time progress tracking (IoT, drones, BIM) - Structural integrity simulation (masonry, bridges) - Safety simulation (AI-driven alerts) - As-built drawing generation - Predictive maintenance of equipment - Automated defect detection (computer vision, AI)	- Reduced delays by 25% (large infra project) - Decreased workplace injuries by 30% - Improved construction quality & reduced rework - Lower cost overruns via resource optimization - Enhanced safety & defect detection accuracy	Opoku et al., (2021); Rafsanjani & Nabizadeh, (2023); Angjeliu et al., (2020); Sacks et al., (2020), Opoku et al., (2020);
Operation & Maintenance	- Real-time monitoring (IoT sensors) - Predictive & proactive maintenance - Defect detection (point clouds, CAD) - Asset condition monitoring (HVAC, bridges) - Decision-making support (AI & simulations) - Structural health monitoring (bridges, tunnels)	- 30% fewer HVAC failures (smart office) - Early defect detection (112 flaws vs 3 by humans in OTL) - Improved operational safety & longevity of bridges - Cost savings via predictive maintenance - Intelligent decision-making with real-time data	Lu et al., (2021); Jiang et al., (2021); Callcut et al., (2021); Kaewunruen et al., (2022); Zhong et al., (2023) Tao et al., (2018);
Demolition & Recovery	- Simulation of structural vulnerabilities & collapse sequences - Safer dismantling approaches - Circular economy practices (tracking reusable materials) - Real-time environmental monitoring (dust, CO_2, noise) - Site readiness assessment for redevelopment	- Safer demolition (30% fewer accidental collapses) - 40% reduction in landfill waste (Germany project) - Improved sustainability & compliance - Faster redevelopment (20% reduction in Amsterdam project) - Optimized material recovery (concrete, steel, glass)	Ellul et al., 2024; Sivarethinamohan & Reddy (2024); Ye et al., (2021); Afzal et al., (2023); Liu et al., (2020); Kaewunruen et al., (2021)

3.2.5 Summary Of Findings On Digital Twin Application In Various Lifecycle Phases

In conclusion, the construction industry is greatly influenced by DT at various stages of an object's existence. All phases demonstrate that DT are useful in real-time processes. In design phases, DT are useful in improving design stages by enhancing visualization, simulation, coordination and sustainability. DT adoption is essential in boosting construction projects' accuracy, efficiency and environmental effect as the sectors shift towards more data driven and automated processes.

3.3 Challenges Of Digital Twin Adoption

Although DT adoption shows multiple benefits in the lifecycle phases, there are still challenges that cause the slow adoption into the construction industry. There are four main capabilities for a successful Architecture, Engineering, Construction, and Operation (AECO) organizations to produce DT: People, Technology, Process and Policy [48]. Thus, this paper will discuss the challenges based on the four categories.

3.3.1 People's Aspect

People aspect is one of a significant effect in adoption of DT. Manpower is an important role as it is in every situation, such as in designing or creating the drawings using 2D or 3D models, constructing, oversee and maintaining the object. According to Opoku et al. (2020); Love & Matthews (2019), many professionals in the industry are unfamiliar with new technologies and systems for structuring new systems, thus disinterested with DT concepts and benefits [31, 22]. The resistance to change as they are more comfortable with the older way of documentation are causing the reluctancy of the professionals to switch from 2D to 3D [49].

Next, a skill gap in the construction workforce prevents successful adoption as they frequently lack the necessary technical skills to develop, manage and utilize DT efficiently [46]. This problem is made worse to the shortage of specialized training courses, which hinders employees from developing the skills necessary for the adoption DT [50]. Senna (2023) reported that almost all businesses struggle to find skilled workers with formal training in I4.0 technologies [51]. Furthermore, the collaborative nature of DT necessitates strong interdisciplinary coordination; however, many constructions teams face communication challenge and different work culture that limits construction teams face communication challenges and different work cultures that limit digital integration and knowledge sharing [52]. Without proper awareness, training and engagement, organizations may face internal resistance from employees, which then slows down the integration of DT into the construction industry.

3.3.2 Process' Aspect

Implementation of new technologies requires a smooth process to come out with the best products. However, setbacks in the process are a common problem due to workflow complexity and fragmentation. The lack of standardized processes for DT implementation phases, leads to inconsistencies in data integration and interoperability across various project phases [30]. One of the reasons for the construction industry's slow embrace of DT, which covers activities including data compilation, storage, and exchange, is the challenge of handling extremely precise information [49].

Interoperability between systems is necessary for the efficient use of data integration from various sources, including Building Information Modelling (BIM), Geographic Information Systems (GIS), and Internet of Things (IoT) sensors. Software compatibility, for instance, can cause delays and make the design process slower and more challenging. However, different formats, standards, and software can impose challenges in adopting DT technologies [13]. Therefore, standardized procedures are crucial for successfully integrating DT in the construction sector.

3.3.3 Technology Aspect

As for technology, it involves the costs, hardware, network and software levels to employ DT. The setup and implementation of DT technology can be expensive, involving significant investment in software, hardware, and skilled personnel. According to Sacks et al. (2020), implementing a DT system necessitates significant upfront investments for the installation of IoT sensors, integration platforms, and data analytic systems [35]. The intricacy of developing a DT model for major projects like infrastructure might make DT adoption difficult and resource-intensive for small to mid-sized businesses. Stakeholders believed that the execution of DT was complicated and were hesitant about investing money on them until there were solid business justifications and established advantages that showed their worth and return on investment [54].

DT relies heavily on real-time data from physical assets, which makes data privacy and cybersecurity to become increasingly important. As DT needs to communicate with cloud-based platforms, there is a greater chance of data breaches or illegal access to private data [40]. Gaining confidence in DT systems requires addressing these security issues prior to implementation, particularly for larger infrastructure projects like manufacturing, roads, bridges, and railroads. The precision and competent of real-time data gathered on-site from physical assets determine how effective DT technologies are. The dependability of the DT can be compromised by inaccurate or insufficient data from IoT sensors and other monitoring systems, which can lead to faulty forecasts and simulations [40]. To guarantee a successful DT deployment, high-quality data collection and management are essential.

3.3.4 Policy's Aspect

A policy in the construction industry also encourages an organization to become more flexible in its transition from conventional working systems to the creation of DT technologies [48]. Uncertainty in data governance laws makes it difficult to assign accountability for data protection, storage, and ethical use, raising concerns about confidentiality and liability [55]. The lack of a common regulatory framework that establishes standards for data interchange, security protocols, and DT deployment in many industries is one of the challenges in DT adoption [30].

Large-scale infrastructure projects become inefficient when organizations struggle with interoperability problems and inconsistent needs due to a lack of standardized policies. to overcome these policy-related obstacles, stakeholders, lawmakers, and academic institutions must work together to create detailed, legally enforceable regulations that encourage the safe and uniform use of DT in the building sector. For example, Public Works Department (2022), in its roadmap, has outlined Jabatan Kerja Raya (JKR)'s strategy for implementing the mandatory BIM adoption across public infrastructure projects [50]. Therefore, to bid on the project and comply with the governance incentives, organizations will have to adjust to the DT adoption.

4.0 CONCLUSION

In summary, this study looked at the definition, applications, and challenges of DT in the construction sector at every stage of their existence. To find articles on the subject, a systematic literature review using Scopus has been used in this paper. According to the literature assessment, the growing number of articles each year indicates that stakeholders are interested in deploying DT, which are a promising and emerging technology. Using real-time data, a DT is a virtual copy of a physical asset that mimics its behavior and functioning. Nevertheless, there is not a consensus definition for DT as of yet. Every step of growth has seen the use of DT in the construction industry. The primary uses for DT are real-time monitoring, clash detection, structural system integrity, sustainability practices and logistics. The applications demonstrate how the DT could revolutionize the construction sector by converting it into an automated and data-driven sector. Four perspectives which are people, process, technology and policy, have also been used to analyze the difficulties in implementing DT. All these challenges can be tackled with proper guidelines for the stakeholders. Future studies should focus on evaluating practitioners' levels of digital maturity adoption. This is to avoid spending money on resources before the technologies are ready to be used because of their high initial cost. In order to help practitioners better understand the areas in which DT can be used, additional research should concentrate on using of DT at every stage, as Building Information Modelling (BIM) has been widely used in the design stage.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

[1] Angjeliu, G., Coronelli, D., and Cardani, G. 2020. Development of the simulation model for Digital Twin applications in historical masonry buildings: The integration between numerical and experimental reality. *Computers & Structures*, 238: 106282. DOI: https://doi.org/10.1016/j.compstruc.2020.106282

[2] Arowoiya, V. A., Moehler, R., and Fang, Y. 2023. Digital Twin Technology for Thermal Comfort and Energy Efficiency in Buildings: A State-of-the-Art and future directions. Energy and Built Environment. 5(5): 641-656. DOI: https://doi.org/10.1016/j.enbenv.2023.05.004

[3] Biesinger, F., Meike, D., Kraß, B., and Weyrich, M. 2019. A digital twin for production planning based on cyber-physical systems: A Case Study for a Cyber-Physical System-Based Creation of a Digital Twin. *Procedia CIRP*. 79: 355-360. DOI: https://doi.org/10.1016/j.procir.2019.02.087

[4] Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. 2020. Towards a Semantic Construction Digital Twin: Directions for Future Research. *Automation in Construction*. 114: 103179. DOI: https://doi.org/10.1016/j.autcon.2020.103179

[5] Botín Sanabria, D. M., Mihaita, A.-S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., and Lozoya-Santos, J. de J. 2022. Digital Twin Technology Challenges and Applications: A Comprehensive Review. *Remote Sensing*. 14(6): 1335. DOI: https://doi.org/10.3390/rs14061335

[6] Briner, R. B., and Denyer, D. *Systematic Review and Evidence Synthesis as a Practice and Scholarship Tool*. 2012. United States: Oxford University Press. 112-129. Retrieved date: 2025, February 7. DOI: https://doi.org/10.1093/oxfordhb/9780199763986.013.0007

[7] CIDB. 2023, November 20. *Economic Impact of Madani Framework and Budget 2024 on the Construction Industry*. Malaysia: Construction Industry Development Board (CIDB). https://www.cidb.gov.my/eng/economic-impact-of-madani-framework-and-budget-2024-on-the-construction-industry/ Retrieved date: 2025, February 7

[8] Delgado, J. M., and Oyedele, L. 2021. Digital Twins for the built environment: learning from conceptual and process models in manufacturing. *Advanced Engineering Informatics*. 49: 101332. DOI: https://doi.org/10.1016/j.aei.2021.101332

[9] Eastman, C. M., P. Teicholz, Sacks, R., and Liston, K. *BIM Handbook: A Guide to Building Information Modeling For Owners*. 2011. United States: John Wiley & Sons, Inc. 10(2): 93-282. Retrieved date: 2023, December 24. https://www.benardmakaa.com/wp-content/uploads/2021/11/BIM-Handbook_-A-Guide-to-Building-Information-Modeling-for-Owners-Designers-Engineers-Contractors-and-Facility-Managers-Wiley-2018.pdf

[10] Ellul, C., Hamilton, N., Pieri, A., and Floros, G. (2024). Exploring Data for Construction Digital Twins: Building Health and Safety and Progress Monitoring Twins Using the Unreal Gaming Engine. *Buildings*. 14(7): 2216-2216. DOI: https://doi.org/10.3390/buildings14072216

[11] Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., and Pappas, G. 2008. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and Weaknesses. *The FASEB Journal*. 22(2): 338-342. DOI: https://doi.org/10.1096/fj.07-9492lsf

[12] Frangopol, D. M., and Bocchini, P. 2011. Resilience As Optimization Criterion for the Rehabilitation of Bridges Belonging to a Transportation Network Subject to Earthquake. *Structures Congress 2011*. 1802-1811. DOI: https://doi.org/10.1061/41171(401)178

[13] Fuller, A., Fan, Z., Day, C., and Barlow, C. 2020. Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*. 8: 108952-108971. DOI: https://doi.org/10.1109/access.2020.2998358

[14] Grant, M. J., and Booth, A. 2009. A Typology of reviews: an Analysis of 14 Review Types and Associated Methodologies. *Health Information & Libraries Journal*. 26(2): 91-108. DOI: https://doi.org/10.1111/j.1471-1842.2009.00848.x

[15] Grieves, M., and Vickers, J. 2016. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. *Transdisciplinary Perspectives on Complex Systems*. 85-113. DOI: https://doi.org/10.1007/978-3-319-38756-7_4

[16] Hielscher, T., Khalil, S., Virgona, N., and S.A. Hadigheh. 2023. A neural network based digital twin model for the structural health monitoring of reinforced concrete bridges. *Structures*. 57: 105248-105248. DOI: https://doi.org/10.1016/j.istruc.2023.105248

[17] J. Vatn. Industry 4.0 and real-time synchronization of operation and maintenance. 2018. Norway: Taylor & Francis. 681-686. DOI: https://doi.org/10.1201/9781351174664-84 Retrieved date: 2025, February 7

[18] Jiang, F., Ma, L., Broyd, T., and Chen, K. 2021. Digital twin and its implementations in the civil engineering sector. *Automation in Construction*. 130: 103838. DOI: https://doi.org/10.1016/j.autcon.2021.103838

[19] Kaewunruen, S. *Rail Infrastructure Resilience*. 2022. San Diego: Woodhead Publishing. DOI: https://doi.org/10.1016/c2019-0-01267-8 Retrieved date: 2024, April 20

[20] Kaewunruen, S., Sresakoolchai, J., and Lin, Y. 2021. Digital twins for managing railway maintenance and resilience. *Open Research Europe*. 1: 91. DOI: https://doi.org/10.12688/openreseurope.13806.2

[21] Lin, Y.-C., and Cheung, W.-F. 2020. Developing WSN/BIM-Based Environmental Monitoring Management System for Parking Garages in Smart Cities. *Journal of Management in Engineering*. 36(3):

04020012. DOI: https://doi.org/10.1061/(asce)me.1943-5479.0000760

[22] Love, P. E. D., and Matthews, J. 2019. The "how" of benefits management for digital technology: From engineering to asset management. *Automation in Construction*. 107(1): 102930. DOI: https://doi.org/10.1016/j.autcon.2019.102930

[23] Lu, Y., Liu, Z., and Min, Q. 2021. A digital twin-enabled value stream mapping approach for production process reengineering in SMEs. *International Journal of Computer Integrated Manufacturing*. 34(7-8): 764-782. DOI: https://doi.org/10.1080/0951192x.2021.1872099

[24] Mabkhot, M., Al-Ahmari, A., Salah, B., and Alkhalefah, H. 2018. Requirements of the Smart Factory System: A Survey and Perspective. *Machines*. 6(2): 23. DOI: https://doi.org/10.3390/machines6020023

[25] Macchi, M., Roda, I., Negri, E., and Fumagalli, L. 2018. Exploring the role of Digital Twin for Asset Lifecycle Management. *IFAC-PapersOnLine*. 51(11): 790-795. DOI: https://doi.org/10.1016/j.ifacol.2018.08.415

[26] Madubuike, O. C., and Anumba, C. J. 2023. Digital Twin-Based Health Care Facilities Management. Journal of Computing in Civil Engineering. 37(2): 1-11. DOI: https://doi.org/10.1061/jccee5.cpeng-4842

[27] Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: the PRISMA Statement. *PLoS Medicine*. 6(7): e1000097. DOI: https://doi.org/10.1371/journal.pmed.1000097

[28] Negri, E., Fumagalli, L., and Macchi, M. 2017. A Review of the Roles of Digital Twin in CPS-based Production Systems. *Procedia Manufacturing*. 11: 939-948. DOI: https://doi.org/10.1016/j.promfg.2017.07.198

[29] Opoku, A., and Ahmed, V. 2014. Embracing sustainability practices in UK construction organizations. *Built Environment Project and Asset Management*. 4(1): 90-107. DOI: https://doi.org/10.1108/bepam-02-2013-0001

[30] Opoku, D.-G. J., Perera, S., Osei-Kyei, R., and Rashidi, M. 2021. Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*. 40(1): 102726. DOI: https://doi.org/10.1016/j.jobe.2021.102726

[31] Opoku, D.-G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., and Bamdad, K. 2022. Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review. *Buildings.* 12(2): 113. DOI: https://doi.org/10.3390/buildings12020113

[32] Osei-Kyei, R., and Chan, A. P. C. 2015. Review of studies on the Critical Success Factors for Public-Private Partnership (PPP) projects from 1990 to 2013. *International Journal of Project Management*. 33(6): 1335-1346. DOI: https://doi.org/10.1016/j.ijproman.2015.02.008

[33] R. Sivarethinamohan, and Reddy, R. S. 2024. *Digital Twin for Smart City Resilience and Solutions*. 605-619. DOI: https://doi.org/10.1002/9781394303564.ch25

[34] Rafsanjani, H. N., and Nabizadeh, A. H. 2023. Towards Digital Architecture, Engineering, and Construction (AEC) Industry through Virtual Design and Construction (VDC) and Digital Twin. *Energy and Built Environment*. 4(2): 169-178. DOI: https://doi.org/10.1016/j.enbenv.2021.10.004

[35] Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. 2020. Construction with digital twin information systems. *Data-Centric Engineering*. 1(1): e14. DOI: https://doi.org/10.1017/dce.2020.16

[36] Schrotter, G., and Hürzeler, C. 2020. The Digital Twin of the City of Zurich for Urban Planning. PFG - Journal of Photogrammetry, *Remote Sensing and Geoinformation Science*. 88(1): 99-112. DOI: https://doi.org/10.1007/s41064-020-00092-2

[37] Shafto, M., Conroy, M., Doyle, R., Glassgen, E., Kemp, C., and LeMoigne, J. *NASA Technology Roadmap: Modeling, Simulation, Information Technology and Processing Roadmap.* 2010. Washington, D.C.: National Aeronautics and Space Administration (NASA). 11: 1-32 https://www.lpi.usra.edu/sbag/goals/capability_inputs/2015_Tech_11_modeling_simulation.pdf Retrieved date: 2023, August 11

[38] Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., and Sui, F. 2018. Digital twin-driven product design, manufacturing and service with big data. The *International Journal of Advanced Manufacturing Technology*. 94(9-12): 3563-3576. DOI: https://doi.org/10.1007/s00170-017-0233-1

[39] Tao, F., Zhang, C., Qi, Q., and Zhang, H. 2022. Digital twin maturity model. *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems (CIMS).* 28(5): 1267-1281. DOI: https://doi.org/10.13196/j.cims.2022.05.001

[40] Tao, F., Zhang, H., Liu, A., and Nee, A. Y. C. 2019. Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*. 15(4): 2405-2415. DOI: https://doi.org/10.1109/tii.2018.2873186

[41] Tchana, Y., Ducellier, G., and Remy, S. 2019. Designing a unique Digital Twin for linear infrastructures lifecycle management. *Procedia CIRP*. 84: 545-549. DOI: https://doi.org/10.1016/j.procir.2019.04.176

[42] Tuegel, E. 2012. The Airframe Digital Twin: Some Challenges to Realization. *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference.* 1(53): 1-11. DOI: https://doi.org/10.2514/6.2012-1812

[43] Tuhaise, V. V., Handibry, J., and Abanda, F. H. 2023. Technologies for Digital Twin Applications in Construction. *Automation in Construction*. 152: 104931-104931. DOI: https://doi.org/10.1016/j.autcon.2023.104931

[44] Vuoto, A., Funari, M. F., and Lourenço, P. B. 2023. On the Use of the Digital Twin Concept for the Structural Integrity Protection of Architectural Heritage. *Infrastructures*. 8(5): 86-86. DOI: https://doi.org/10.3390/infrastructures8050086

[45] Ye, C., Kuok, S.-C., Butler, L. J., and Middleton, C. R. 2021. Implementing bridge model updating for operation and maintenance purposes: examination based on UK practitioners' views. *Structure and Infrastructure Engineering*. 18(12): 1638-1657. DOI: https://doi.org/10.1080/15732479.2021.1914115

[46] Afzal, M., Yi, R., Shoaib, M., Muhammad Faisal Ayyub, Lavinia Chiara Tagliabue, Bilal, M., Ghafoor, H., and Manta, O. 2023. Delving into the Digital Twin Developments and Applications in the Construction Industry: A PRISMA Approach. *Sustainability*. 15(23): 16436-16436. DOI: https://doi.org/10.3390/su152316436

[47] Bunjaridh, Y., A. Rahman, R., and Mohamed Yusof, L. 2024. Digitalizing Construction - Key Organizational Capabilities for Digital Twin Production. Malaysia: Construction Industry Development Board (CIDB). https://smart.cidb.gov.my/article/digitalizing-construction-key-organizational-capabilities-for-digital-twin-production-385 Retrieved date: 2023, July 27

[48] Mendes, N. 2023. BIM and Digital Twins in Infrastructure Projects: An overview from the Transportation Professional's Perspective. *LSU Scholarly Repository.* 5842. DOI: https://doi.org/10.31390/gradschool_theses.5842

[49] Heaton, J., Parlikad, A. K., and Schooling, J. 2019. A Building Information Modelling approach to the alignment of organisational objectives to Asset Information Requirements. *Automation in Construction.* 104: 14-26. DOI: https://doi.org/10.1016/j.autcon.2019.03.022

[50] Public Work Department (JKR). *Department of Public Works Strategic Plan 2021-2025.* 2022. Malaysia: Department of Public Works of Malaysia (Jabatan Kerja Raya / JKR) *Global BIM Network*. https://globalbim.org/info-collection/department-of-public-works-strategic-plan-2021-2025/ Retrieved date: 2025, February 7

[51] Senna, P., Cristina, B. A., Jaime, B. R., and Américo, A. 2023. Development of a digital maturity model for Industry 4.0 based on the technology-organization-environment framework. *Computers & Industrial Engineering.* 185: 109645-109645. DOI: https://doi.org/10.1016/j.cie.2023.109645

[52] Qi, Q., Sui, F., Liu, A., Tao, F., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Y., and Nee, A. Y. C. 2018. Digital twin-driven product design framework. *International Journal of Production Research*. 57(12): 3935-3953. DOI: https://doi.org/10.1080/00207543.2018.1443229

[53] Shahzad, M., Shafiq, M. T., Douglas, D., and Kassem, M. 2022. Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. *Buildings*. 12(2): 120.DOI: https://doi.org/10.3390/buildings12020120

[54] Xu, Y., Sun, Y., Liu, X., and Zheng, Y. (2019). A Digital-Twin-Assisted Fault Diagnosis Using Deep Transfer Learning. *IEEE Access*. 7: 19990-19999. DOI: https://doi.org/10.1109/access.2018.2890566

[55] Opoku, D.-G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Bamdad, K., and Famakinwa, T. 2023. Barriers to the Adoption of Digital Twin in the Construction Industry: A Literature Review. *Informatics 2023*. 10(1): 14. DOI: https://doi.org/10.3390/informatics10010014

[56] Liu, M., Fang, S., Dong, H., and Xu, C. 2020. Review of Digital Twin about concepts, technologies, and Industrial Applications. *Journal of Manufacturing Systems.* 58: 346-361. DOI: https://doi.org/10.1016/j.jmsy.2020.06.017

[57] Zhong, D., Xia, Z., Zhu, Y., and Duan, J. 2023. Overview of predictive maintenance based on digital twin technology. *Heliyon*, 9(4): e14534. DOI: https://doi.org/10.1016/j.heliyon.2023.e14534

[58] Callcut, M., Cerceau Agliozzo, J.-P., Varga, L., and McMillan, L. (2021a). Digital Twins in Civil Infrastructure Systems. Sustainability, 13(20), 11549. DOI: https://doi.org/10.3390/su132011549

[59] BizAdmin. 2024, October 22. *Malaysia Construction Sector Achieve Remarkable Growth in 2024.* Malaysia: Building & Investment. https://b-i.info/malaysia-construction-sector-achieve-remarkable-growth-in-2024/ Retrieved date: 2025, January 15

[60] Uhlenkamp, J.-F., Hauge, J. B., Broda, E., Lutjen, M., Freitag, M., and Thoben, K.-D. 2022. Digital Twins: A Maturity Model for Their Classification and Evaluation. *IEEE Access*. 10: 69605–69635. DOI: https://doi.org/10.1109/access.2022.3186353.

[61] Matchett, R., and Wium, J. 2017. Digital Twins For Road Infrastructure. *40th Southern African Transport Conference (SATC)*. 1-13. DOI:https://www.semanticscholar.org/paper/Digital-Twins-For-Road-Infrastructure-Matchett-Wium/5f830f1eae12f146d7a2693233ab0a78c79790d7

[62] Liu, M., Fang, S., Dong, H., and Xu, C. 2020. Review of Digital Twin about concepts, technologies, and Industrial Applications. *Journal of Manufacturing Systems*. 58: 346-361. DOI: https://doi.org/10.1016/j.jmsy.2020.06.017

[63] Errandonea, I., Beltrán, S., and Arrizabalaga, S. 2020. Digital Twin for maintenance: A literature review. *Computers in Industry*. 123: 103316. DOI: https://doi.org/10.1016/j.compind.2020.103316

[64] Yitmen, I., and Alizadehsalehi, S. *Towards a Digital Twin-based Smart Built Environment.* 2021. Florida: Taylor & Francis. 21–44. Retrieved date: 2024, July 22. DOI: https://doi.org/10.1201/9781003017547-2

[65] Costin, A., Adibfar, A., Hu, H., and Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. *Automation in Construction*, *94*, 257–281. DOI: https://doi.org/10.1016/j.autcon.2018.07.00

[66] Sanfilippo, F., Thorstensen, R. T., Jha, A., Jiang, Z., and Robbersmyr, K. G. 2022. A perspective review on digital twins for roads, bridges, and civil infrastructures. *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*. 1-6. DOI: https://doi.org/10.1109/iceccme55909.2022.9988693

[67] Waqar, A., Othman, I., Almujibah, H., Khan, M. B., Alotaibi, S., and Elhassan, A. A. M. 2023. Factors Influencing Adoption of Digital Twin Advanced Technologies for Smart City Development: Evidence from Malaysia. *Buildings*. 13(3): 775. DOI: https://doi.org/10.3390/buildings13030775

[68] Intan, N. A. S., and Doh , S. I. 2021. Factors Influencing Road Damage in Developing Countries. *International Journal of Management Science and Engineering Research*. 06(02). DOI: https://www.ijerm.com/vol/Volume-06-Issue-02 Retrieved date: 2023, August 27

[69] Ismail, A., Razelan, I. S. M., Yusof, L. M., Zulkiple, A., and Masri, K. A. 2021. An Overview of Pavement Maintenance Management Strategies in Malaysia. *IOP Conference Series: Earth and Environmental Science*, 682(1): 012042. DOI: https://doi.org/10.1088/1755-1315/682/1/012042

[70] Sehgal, S. 2023, March 9. *Malaysia’s government eyes high spending*. Malaysia: FrontierView. https://frontierview.com/insights/malaysias-government-eyes-high-spending/ Retrieved date: 2025, September 2

[71] Lu, R., and Brilakis, I. 2019. Digital twinning of existing reinforced concrete bridges from labelled point clusters. *Automation in Construction*. 105: 102837. DOI: https://doi.org/10.1016/j.autcon.2019.102837