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Article

Unveiling the digital horizon: Bridging the realms of digital twinning and construction project management performance

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Abstract: The digitalization of the construction industry is deemed a crucial element in Construction 4.0's vision, attainable through the implementation of digital twinning. It is perceived as a virtual strategy to surmount the constraints linked with traditional construction projects, thereby augmenting their productivity and effectiveness. However, the neglect to investigate the causal relationship between implementation and construction project management performance has resulted from a lack of understanding and awareness regarding the consequences of digital twinning implementation, combined with a shortage of expertise among construction professionals. Consequently, this paper extensively explores the relationship between digital twinning implementation and construction project management performance. The Innovation Diffusion Theory (IDT) is employed to investigate this relationship, utilizing a quantitative research approach through document analysis and questionnaire surveys. Additionally, partial least squares structural equation modeling (PLS-SEM) with SmartPLS software is employed to deduce the relationship. The results underscore that digital twinning implementation significantly improves construction project management performance. Despite recognizing various challenges in digital twinning implementation, when regarded as moderating factors, these challenges do not significantly impact the established causal relationship. Therefore, this investigation aligns with the national push toward the digitalization of the construction sector, highlighting the positive impacts of digital twinning implementation on construction project management performance. Moreover, this study details the impacts of implementing digital twinning from the construction industry's perspective, including positive and negative impacts. Afterwards, this paper addresses the existing research gap, providing a more precise understanding and awareness among construction industry participants, particularly in developing nations.

Keywords: digital twinning; digital twins; Industry 4.0; Construction 4.0; construction project management; innovation diffusion theory (IDT)

1. Introduction

The construction industry is vital to a nation's technological advancement and economic success, encompassing the design, construction, and maintenance of structures (Hussain et al., 2022; Paz et al., 2020). Despite its prominence, the construction industry has continuously struggled with unproductivity and working inefficiency (Andric et al., 2019). Construction 4.0 is being employed to address the existing issues by introducing the technological advancement of Industry 4.0 to digitize and automate the construction processes (Forcael et al., 2020; Olsson et al., 2021). This concept was presented in 2016, emphasizing the utilization of digital data, automation, connection, and access (Nolling, 2016). It aims to enhance productivity and working efficiency in construction projects, which align with global trends. Digital twinning is part of Construction 4.0's vision, which refers to creating a comprehensive digital replica (Digital Twin) of physical assets, objects and processes (Physical Twin) with related cutting-edge technologies (Zuhairi at al., 2020). This concept is popular in numerous industries since it allows real-time data analysis and performance optimization. With the significance of digitalization in the construction industry, many countries have acknowledged digital twinning and released related initiatives to back up the digitalization of the construction industry, such as the U.K., China, and Malaysia. For instance, the Construction Industry Development Board (CIDB) Malaysia has proposed the Construction 4.0 Strategic Plan (2021–2025), and the U.K. has proposed Construction 2025, which encourages the implementation of digital twinning throughout the entire construction projects to combine physical and visual world, along with the transition towards construction digitalization. Hence, the implementation of digital twinning has been considered one of the critical catalysts to drive Construction 4.0 forward through the enhancement of productivity and working efficiency (Lee et al., 2013; Opoku et al., 2021).

However, the construction industry struggles in the implementation of digital twinning due to the lack of sufficient knowledge and awareness among participants (Olsson et al., 2019). The lack of comprehensive education and training in this field also causes uncertainty and hesitancy in the implementation (Nnaji and Karahan, 2020). Besides, the conservative attitude and resistance to changes in this industry further hinder the incorporation of emerging technologies (Matthews et al., 2015). Moreover, the lack of exploration of the impacts of the implementation of digital twining towards construction project management performance in existing research highlights the need for further research. This study aims to identify the impacts of implementing digital twinning and its causal relationship with the performance of construction industry project management in the Malaysian construction industry.

2. Digital twinning

Industry 4.0 has spearheaded digitalization in the manufacturing industry in the past decade. This trend influences the implementation of digital twining, as it merges physical and visual worlds by creating digital representations of physical objects and processes through emerging digital technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), Cloud Computing, and Blockchain. This concept was initially introduced within the context of Project Lifecycle Management (PLM) as a "digital equivalent to a physical product" by Grieves in 2002 and subsequently elaborated upon in 2014 (Grieves and Vickers, 2017). Digital twinning creates comprehensive virtual duplicates (Digital Twins) of tangible objects, systems or procedures (Physical Twins), enabling a complete digital portrayal of their status, properties and functionalities. This concept has received a lot of attention, as it has been listed as No. 4 of the top ten strategic technology trends by Gartner; at the same time, Lockheed Martin has identified it as a revolutionary military technology (Liu et al., 2021). Essentially, digital twinning replicates physical twins in the visual context, allowing real-time monitoring, prediction, and insights into their performance and status (Hassani et al., 2022).

In 2019, Grieves presented an improved understanding of digital twinning, including a standardized framework with three dimensions: Physical Product, Virtual Replica, and Connections. Afterwards, Tao et al. (2019) proposed a more detailed framework with five dimensions: Physical Parts, Virtual Parts, Connections, Databases, and Services, as shown in **Figure 1**. Physical parts are the fundamental of virtual parts, whereas virtual parts are the exact digital representation of physical parts under controllable environment. Connections enable the transmission and management of data through the Internet of Things (IoT). Ultimately, digital twinning is required to provide some services, such as real-time monitoring and controlling of physical twins. Then, those data-derived services the improvement in productivity and working efficiency. This framework explains the processes of data transmission from physical parts to virtual parts to provide services through utilising smart devices, software and related technologies. In short, digital twinning creates virtual representations to reflect the physical reality. This process requires data flow from the physical to virtual parts, although feedback is optional (Jiang et al., 2021).

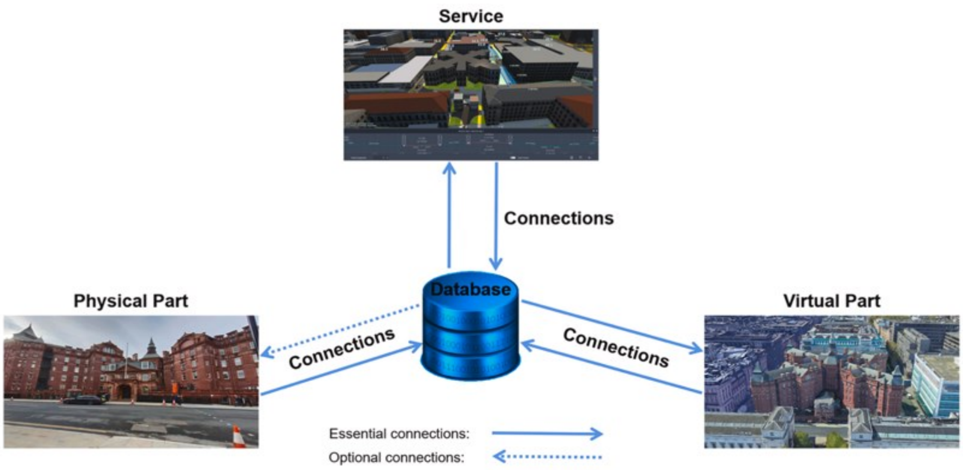

Figure 1. Five-dimensional digital twinning model (Tao et al., 2019).

The implementation of digital twinning encompasses a range of technologies, with (Liu et al., 2021) pinpointing crucial elements such as data-related technologies, high-fidelity modelling, and model-based simulation technologies. Data-related technologies form the basis of digital twinning. Digital twinning involves utilizing sensors, scanners, cameras, LiDAR, RFID tags, or similar technologies to gather structured, semi-structured, and unstructured data from physical twins (Opoku et al., 2021; Shanbari et al., 2016). High-fidelity modelling is essential for digital twinning since it involves incorporating acquired data into engineering procedures that convert various data into both geometric and non-geometric information (Douglass, 2014). Additionally, software like Revit, MATLAB, and Simulink aids in the creation of accurate and detailed models. Simulation is an important factor in digital twinning since it allows for immediate and two-way communication between physical and digital twins. This is achieved by using IoT and cloud technologies to share data (Tan et al., 2019).

This study conducts a thorough bibliometric analysis to measure and investigate the current scholarly literature on digital twinning. The study uses the term "Digital Twinning" to get relevant papers from the "ScienceDirect" database, covering all disciplines and publication years, to maintain the accuracy and reliability of the material. The study encompasses a wide range of literature, with a significant sample size of 7169 pieces. Significantly, the keyword search indicates a growing significance of the digital twinning idea, with 7147 articles produced between 2016 and 2023. The trend demonstrates a progressive rise in the concept's prominence, attracting substantial interest in recent years, namely from 2016 onwards, with 5689 articles produced between 2021 and 2023. In addition, the study reveals a total of 5460 papers published in academic journals. This emphasizes the significant role of the academic community in contributing to the discussion on digital twinning, spanning over 666 distinct periodicals.

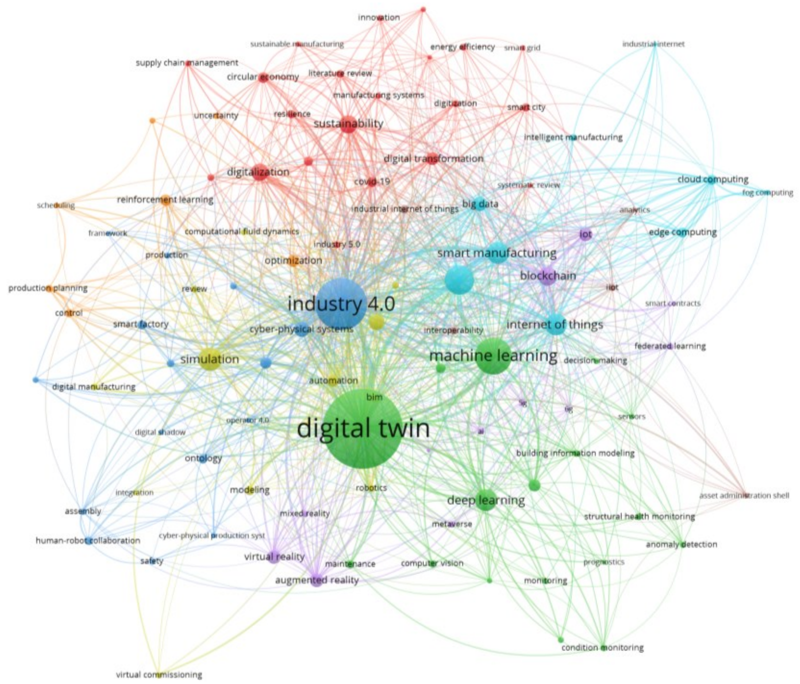

Figure 2. VOSviewer visualization with keyword co-occurrence network.

To understand the current research environment on digital twinning, this study utilizes VOSviewer for bibliometric analysis to identify prominent research topics. Out of the 15,658 keywords initially retrieved from the selected articles, 679 keywords are picked based on a minimum recurrence criterion of 5 and a relevancy set at 100% to assure a direct relationship with digital twinning. **Figure 2** presents the final analysis, identifying the top 100 terms with the highest frequencies. This study helps to identify the main areas of concentration. The major focus of the study on digital twinning has been advancing related technology, exploring the services it may provide, conducting scientific assessments of its application, and examining particular industrial implementations. However, there is a significant lack of study on the effects and cause-and-effect interactions related to construction project management performance. This study addresses and fills the highlighted gap in the present research landscape.

2.1. Positive impacts of the implementation of digital twinning

The increasing agreement on digitization leads to the expectation that the implementation of digital twinning will have significant and positive effects on several industries. This technology is predicted to improve project efficiency and productivity (Tao et al., 2019). This approach gains early success in several industries. It is widely adopted by notable countries such as China, Australia, the United States, the United Kingdom, and Italy, particularly in the building industry. Nevertheless, the use of digital twinning yields diverse outcomes in emerging economies such as Malaysia, New Zealand, and Pakistan (Darko et al., 2020). This paper examines and synthesizes the favourable results of implementing digital twinning in the construction sector, utilizing insights from existing literature on digital twinning implementation across several nations.

2.1.1. Real-time reflection and monitoring

The construction industry has challenges due to its distinctive characteristics, such as the flexibility of project requirements and the participation of different contractors. These challenges necessitate effective on-site communication, monitoring of progress, and prompt reaction to crises (Edirisinghe, 2019; Zhai et al., 2019). Conventional construction project monitoring depends on human observation and documentation, resulting in time-consuming and error-prone procedures. To tackle this difficulty, digital twinning provides real-time monitoring and reflection of physical assets (Sacks et al., 2020; Tao et al., 2018). The constant transmission of monitored data from the physical twin to the digital twin is crucial, as it serves as the foundation for the real-time reflection of the digital twin (Tao et al., 2017). The synchronization guarantees that the digital twin remains very accurate with its physical counterpart, enabling real-time updates on the state of the physical twin (Jiang et al., 2022). In addition to geometric qualities, digital twinning implementation involves capturing inherent physical traits, and rule attributes using 3D representation. This includes representing state evolution, dynamic behavior, functional elements, and performance models (Zhuang et al., 2021). Digital twinning revolutionizes the operation of construction projects by enabling real-time reflection and monitoring.

2.1.2. Device diagnostics and prognostics

In the dynamic building industry, characterized by complex projects like large-scale industrial buildings and infrastructure, the advancement of diverse construction equipment is crucial (Darko et al., 2020). Tower cranes, drilling rigs, total stations, and other specialist equipment are essential for carrying out these intricate operations. Nevertheless, the functional duration of such equipment is vulnerable to deterioration and erosion. Equipment malfunctions result in significant expenses and serious repercussions, particularly unexpectedly. The emergence of digital twinning has brought about the implementation of digital twin-driven Prognostics and Health Management (PHM), which serves as the technological basis for autonomously safeguarding equipment conditions. The utilization of real-time data enables the assessment of equipment, identification of faults, prediction of future conditions, and verification of maintenance activities by synchronizing physical and digital twins. Digital twinning allows for real-time synchronization with the physical counterpart, enabling the prediction and precise identification of equipment faults. This capability facilitates the development and evaluation of efficient maintenance methods. This strategy guarantees the efficient operation and durability of the physical equipment (Lim et al., 2020; Zaccaria et al., 2018).

2.1.3. Predictive maintenance

With the growing significance of predictive maintenance in the construction industry, the implementation of digital twinning is gaining interest due to its characterization. Predictive maintenance (PdM) is an approach to predicting and preventing equipment failures based on circumstances, historical data, and specific knowledge. It continually analyses equipment components and forecasts future trends, behaviour patterns and correlations through statistical or machine-learning models. However, conventional PdM approaches struggle with accuracy, reliability, and adaptability (Qi et al., 2021). The implementation of digital twinning is suggested as a remedy to enhance the problem detection, prediction and maintenance decision-making.

A comprehensive digital twinning model includes geometric, physical, functional, and performance components, enabling PdM and problem diagnosis through intelligent real-time data analysis during the entire project lifecycle. Automatic data collection and constant updates are available with the reflection and transmission of real-time data. This enables more accurate and realistic physical simulations (Greif et al., 2020; Opoku et al., 2021; Zhuang et al., 2021). The computing ability of digital twinning enables intelligent application services to optimize data processes for PdM worldwide and reduce the need for human decision-making (Schleich et al., 2017). Those services include design optimization, defect prediction, diagnostics, etc. Therefore, digital twinning advances PdM by modelling equipment conditions and offering intelligent services, resulting in dynamic and comprehensive maintenance programs.

2.1.4. Accelerated risk assessment

The construction industry is renowned for its inherent hazards and ecological obstacles, which may encounter project interruptions due to unforeseeable events such as storms, floods, and debris impacts. Those unforeseeable events may substantially affect project goals, resulting in project delays, extra expenses, or diminished efficiency (Ham et al., 2017). The hazards have been classified into three categories: structural and mechanical failures, functional failures, and ripple effects on infrastructure systems. Early detection and risk assessment of these unforeseeable events are essential for project safety due to potential harm and casualties. (Kamari and Ham, 2022) has argued that the construction industry should emphasize sufficient planning for unpredictable disasters as a long-term goal.

Nevertheless, conventional risk assessment approaches may be error-prone and time-consuming since they generally rely on manual identification and subjective judgment (Han et al., 2006). The implementation of digital twinning revolutionizes this methodology, as it enables real-time monitoring and auto data acquisition using technologies such as UAVs and security cameras. Besides, digital twinning allows the conversion of experts' experiences and historical data into digital format, accelerating the evaluation process (Qi et al., 2021). Thus, the implementation of digital twinning in an imaging-to-simulation framework provides real-time 3D visual monitoring of construction sites, which aids in identifying possible hazards and improving disaster preparedness (Ham et al., 2017). In conclusion, the implementation of digital twinning in risk assessment may assist in successfully managing and reducing environmental and safety hazards in the construction industry.

2.1.5. Collaboration improvement

The construction industry is characterised by various participants and complex activities, which face challenges in team communication and collaboration, thereby affecting productivity and efficiency (Wu et al., 2017). The implementation of digital twinning has emerged as a revolutionary approach, transforming team collaboration and overall efficiency (Bertoni and Bertoni, 2022). Digital twinning addresses this problem by creating a dynamic digital replica of the project, promoting efficient communication and comprehension among all participants, such as architects, engineers, contractors, and clients. The utilisation of IoT, cloud, and blockchain networks enables real-time data exchange, resulting in improved and provisioned transparency and real-time information on the project's progress. In addition, digital twining optimises collaborative problem-solving and construction procedures through its platform, which prompts more efficient cooperation (Semeraro et al., 2021). Therefore, the digital twin of construction progress enables remote cooperation, reduces conflicts, minimises disagreements and improves decision-making, ultimately increasing construction productivity and working efficiency (Soori et al., 2023).

2.1.6. Optimize operation

Current literature in the construction industry mostly uses digital twinning to create digital copies during the design and construction stages of construction projects, focusing on their contribution to project operation and maintenance (Sacks et al., 2020). These digital twins serve as virtual models of structures such as buildings and bridges, keeping a live link with their real counterparts and automatically incorporating any modifications. In contrast to traditional construction procedures, digital twinning consolidates on-site status information into a single project database using multiple monitoring devices. The consolidated database enhances various management tasks, streamlining project operations, minimising on-site accidents, and enhancing overall efficiency (Bi and Huo, 2021). Governmental entities and public clients have increasingly used digital twinning as a fundamental component of information systems. This allows for better-informed and efficient decision-making by evaluating on-site situations thoroughly (Gurevich and Sacks, 2020).

2.1.7. Design and performance improvements

Complete digital twinning covers all stages of construction projects, including planning, design, construction, and operation and maintenance phases (Sai et al., 2020). During the planning phase, digital twinning incorporates extensive physical data into digital twin models, such as terrain, geological information, existing structures, and climatic conditions. This digital twin model allows a comprehensive visualisation and analysis of the projects. Besides, this phase evaluates multiple project plans from economic and technical perspectives in order to select the most appropriate plan within the requirements of the project's quality and participants' interests. Afterwards, the digital twin model incorporates project specifications, component details, geometric characteristics, and historical data of physical twins during the design phase. Thus, the digital twin model is more comprehensive than standard construction models (Rasheed et al., 2020; Zheng et al., 2018). Moreover, digital twinning allows content updates of models during the construction phase, unlike traditional construction projects where design information often becomes outdated (Sun and Liu, 2014). The data collected on-site is immediately processed and converted into the dynamic digital twin model, allowing for ongoing modifications and enhancements based on successed projects. Digital twinning also provides continuing project management through self-evolution and exact operational status simulation even after projects are completed. Hence, this enables the evaluation and improvement of project performance over its entire lifespan (Sai et al., 2020).

2.2. Negative impacts of the implementation of digital twinning

Although the benefits of digital twinning are generally recognized, there is still a lack of comprehensive understanding of the challenges that come with its implementation (Shahat et al., 2021). This study explores potential challenges that may be encountered during the implementation of digital twinning in the construction industry.

2.2.1. Data understanding, preparation and usage

The construction industry is naturally data-intensive since a substantial amount of data will be produced over the entire project lifecycle, hence, effective information flow management is critical to the success of construction projects (Jazzar et al., 2020). The implementation of digital twinning has revolutionized traditional construction workflow, which brings a transition from 2D to 3D-object-based information systems. This improvement provides a comprehensive digital representation of information throughout the entire project lifecycle. However, it also raises issues regarding participants' understanding, preparation, and usage of data. This is because of the possible difference in participant comprehension of data substance and purpose (Pereira et al., 2021). Besides, the accuracy and reliability of data are essential during the data preparation phase since any minor errors might result in problems with model synthesis. Data loss, unstructured and irrelevant data, and interoperability issues also complicate the implementation. Furthermore, ensuring compatibility and handling security concerns within the shared data platform of digital twinning is crucial, including access and modification rights (Ammar et al., 2022; Jazzar et al., 2020; Lu et al., 2020; Xu et al., 2020).

2.2.2. Financial uncertainties

Financial issues are crucial in the implementation of digital twinning, as the costs of implementation might vary depending on the complexity of the project. Investment expenses encompass the purchase of software licenses, procurement of commercial data, development of infrastructure, and purchase of essential equipment. Moreover, it is advisable to allocate substantial reserve cash to unexpected events (Attaran and Celik, 2023). Besides, the maintenance of digital twinning infrastructure involves major operational expenses. On the other hand, human resource costs consist of recruiting professionals, implementing training programs, and acquiring expert advice (Lu et al., 2020). Furthermore, construction projects are more complicated and sophisticated than other industries due to their distinctive features, including complex processes, high financial intensity, and extended project durations. Hence, the return on investment (ROI) is inconsistent and uncertain, which makes large-scale implementation challenging (Ammar et al., 2022).

2.2.3. Contractual awareness and knowledge

The insufficiency of current contract systems presents a difficulty in the implementation of digital twinning in the construction sector, specifically with issues of data ownership and interchange (Redmond et al., 2012). Oraee et al. (2019) contend that existing contract systems fail to address data ownership issues due to the unrestricted exchange of information in digital twinning-based construction projects. Furthermore, the lack of explicit instructions about data ownership and the most recent iteration of the digital model becomes apparent once the project is finished and clients request ownership of the model. However, designers can assert ownership of models and argue that the contract does not require them to surrender ownership. Simultaneously, the design team frequently associates the transfer of intellectual property rights with providing 2D models and drawings. Another prevalent problem is the lack of awareness and limited knowledge of legal obligations and liabilities, particularly in developing nations like Malaysia. It is essential to comprehensively comprehend the legal obligations and liabilities awareness among participants in construction projects, which promotes cooperation improvement, data exchanges, and new ideas creation (Ammar et al., 2022).

2.2.4. Organizational structure and processes

The construction industry has difficulties in digitalisation due to its conservative attitude towards changes and low adoption rate of digital technology (Besklubova et al., 2021; Francis and Thomas, 2020). One of the reasons is the traditional construction processes requires collaboration among several organisations, and organisational restructuring is difficult and costly. The financial benefits from obsolete and unproductive processes keep the industry from adopting emerging technologies with uncertainties, notwithstanding the potential for productivity improvement (Redmond et al., 2012). Moreover, another reason is the lack of essential infrastructure and expertise within enterprises. Many participants and organisations lack related knowledge and experience in the implementation of digital twinning, while many companies have not yet been exposed to this concept (Puan, 2019). Meanwhile, many aware organisations, particularly small and medium-sized enterprises (SMEs), lack the necessary infrastructure for implementation due to their difficulties in adapting to changes. Therefore, the lack of comprehensive implementation guidelines and limited knowledge and capability to incorporate emerging technologies into existing workflows are major reasons contributing to the difficulties in the digitalisation of the construction industry (Ammar et al., 2022).

2.2.5. Human capital development

Human resources are another obstacle to the implementation of digital twinning in the construction industry. The implementation of digital twinning requires sufficient knowledge and experience among project participants since construction projects rely on workers. Hence, proper training is necessary for all participants to ensure sufficient knowledge to prioritize and execute projects accurately through the implementation of digital twinning (Ramu et al., 2022). The training is critical to addressing issues related to interoperability, complexity in implementation, and limited understanding of digital technologies, as construction projects significantly depend on skilled labour. Besides, training on social responsibility is also crucial to effectively deal with issues related to the exchange of large amounts of information and data between organizations during the implementation of digital twinning. This training program helps to reduce the risks of personal data and confidential information being exposed or leaked (Oraee et al., 2019). In addition, it is necessary to raise public consciousness and make instruction lucid and comprehensible. Developers of digital twinning technology should target the needs of disadvantaged groups and non-experts to make it more accessible and helpful to a broader range of people (Lei et al., 2023).

2.2.6. Technology development

Current endeavours to promote digitization in the construction industry to enhance project performance are in progress. However, a major obstacle to widespread implementation arises due to the absence of uniform data standards (Greif et al., 2020). The lack of standardized norms, technologies, and procedures for implementing digital twinning across businesses hampers the progress of interactive interfaces and the integration of external systems. Consequently, this obstacle impedes smooth cooperation and communication (Wang et al., 2020). Data integration poses an additional obstacle when information gathered from various devices and stored in different systems, obtained from the physical twin, has difficulties owing to varying data standards. The digital twin paradigm consists of many datasets, necessitating extra work to assure system interoperability. Moreover, the lack of connection and compatibility across various technologies might result in inefficiencies in digital twinning, as the availability of trustworthy data diminishes (Gil, 2020).

3. Construction project management performance

A project is described as a temporary undertaking in the construction industry that involves several players. It has precise goals, a set duration, budgets, and requirements, making it particularly complicated (Demirkesen and Ozorhon, 2017). Construction project management involves strategic planning, efficient organization, and diligent supervision of work to optimize benefits and guarantee the effective completion of a project. Elhaniash and Stevovic (2016) suggested that deficiencies in building projects are frequently ascribed to subpar project management performance, encompassing elements such as insufficient allocation of duties, technical complexities, and site-specific problems. Therefore, it is crucial to investigate the aspects contributing to the success of construction project management performance to ensure project delivery (Adeleke et al., 2019).

Within the construction industry, the term "successful" is defined as achieving predefined objectives, which commonly encompass factors like adherence to time, cost-effectiveness, and high-quality standards (Albtoush et al., 2022). The "Iron Triangle" refers to the three primary criteria used to assess the success and performance of building projects over a significant period. In addition, as construction projects continue to grow and evolve, past research has expanded the criteria to include client satisfaction, management capabilities, environment, safety and health, communication, contract, design, and external factors (Alzahrani and Emsley, 2013; Baccarini, 1999; Cheung et al., 2004; Gledson et al., 2018; Hatem and Salam, 2016; Ling et al., 2004; Liyanage and Villalba-Romero, 2015; Tsiga et al., 2016; Thomas et al., 2002). Thus, this study has utilized the often-cited standards for assessing the effectiveness of construction project management, as identified in previous research. These standards encompass aspects relating to time, cost, quality, contracts, and external influences. **Tables 1–5** display the prevailing success factors within those criteria.

Table 1. Summary of reviewed articles on the construction project management performance criteria of Quality-related Factors.

Quality-related Factors	**Sources**							
Conformance to norms and standards	Gudiene et al. (2013)	Larsen et al. (2015)	Mahamid, (2016)	Neyestani, (2016)	Oke et al. (2017)	Slawomir et al. (2020)	Riaz et al. (2023)	Albtoush et al. (2022)
Employee capability training	Gudiene et al. (2013)	Neyestani, (2016)	Yu et al. (2019)	Slawomir et al. (2020)	Gunduz and Almuajebh, (2020)	Riaz et al. (2023)		
No defects in the project (Proper supervision)	Neyestani, (2016)	Oke et al. (2017)	Slawomir et al. (2020)	Gunduz and Almuajebh, (2020)	Albtoush et al. (2022)			
Good and reasonable planning	Larsen et al. (2015)	Oke et al. (2017)	Yu et al. (2019)	Slawomir et al. (2020)	Gunduz and Almuajebh, (2020)			
No change in material (Design changes)	Larsen et al. (2015)	Mahamid, (2016)	Oke et al. (2017)	Albtoush et al. (2022)				
Employee involvement	Yu et al. (2019)	Slawomir et al. (2020)	Gunduz and Almuajebh, (2020)	Riaz et al. (2023)				

Table 2. Summary of reviewed articles on the construction project management performance criteria of cost-related Factors.

Cost-related Factors	Sources							
Financial stability and adequate funding	Gudiene et al. (2013)	Larsen et al. (2015)	Mahamid, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Seddeeq et al. (2019)	Riaz et al. (2023)	Albtoush et al. (2022)
Accurate bill of quantities	Neyestani, (2016)	Mahamid, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Seddeeq et al. (2019)	Riaz et al. (2023)	Albtoush et al. (2022)	
Accuracy of preliminary cost estimate	Larsen et al. (2015)	Neyestani, (2016)	Mahamid, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Seddeeq et al. (2019)	Albtoush et al. (2022)	
Proper documentation	Gudiene et al. (2013)	Larsen et al. (2015)	Mahamid, (2016)	Aljohani et al. (2017)	Seddeeq et al. (2019)			
No frequently reworks	Neyestani, (2016)	Mahamid, (2016)	Aljohani et al. (2017)	Seddeeq et al. (2019)	Nabi and El-adaway, (2021)			
Proper collaboration and communication among all stakeholders	Neyestani, (2016)	Chandrasekaran and Murugasan, (2017)	Seddeeq et al. (2019)	Nabi and El-adaway, (2021)	Riaz et al. (2023)			

Table 3. Summary of reviewed articles on the construction project management performance criteria of time-related factors.

Time-related Factors	Sources							
No frequent changes of order	Larsen et al. (2015)	Neyestani, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Samuel et al. (2017)	Seddeeq et al. (2019)	Nabi and El-adaway, (2021)	Albtoush et al. (2022)
Accuracy of preliminary time estimate	Larsen et al. (2015)	Neyestani, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Samuel et al. (2017)	Albtoush et al. (2022)		
Reduce of rework	Neyestani, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Seddeeq et al. (2019)	Nabi and El-adaway, (2021)			
Project completion date	Neyestani, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Samuel et al. (2017)	Albtoush et al. (2022)			
Reduce duration of information flow among all parties	Neyestani, (2016)	Aljohani et al. (2017)	Chandrasekaran and Murugasan, (2017)	Samuel et al. (2017)	Seddeeq et al. (2019)			

Table 4. Summary of reviewed articles on the construction project management performance criteria of Contractual-related Factors.

Contractual-related Factors	Sources				
No disputes in projects	Larsen et al. (2015)	Samuel et al. (2017)	Tiew, (2022)	Gurgun and Koc, (2022)	Albtoush et al. (2022)
The value of bid bond	Cakmak and Cakmak, (2014)	Samuel et al. (2017)	Chandrasekaran and Murugasan, (2017)	Gurgun and Koc, (2022)	Albtoush et al. (2022)
No defects in contracts	Cakmak and Cakmak, (2014)	Larsen et al. (2015)	Samuel et al. (2017)	Chandrasekaran and Murugasan, (2017)	Tiew, (2022)
Awareness of legal responsibility	Cakmak and Cakmak, (2014)	Chandrasekaran and Murugasan, (2017)	Tiew, (2022)	Gurgun and Koc, (2022)	
Adherence to contract conditions	Cakmak and Cakmak, (2014)	Chandrasekaran and Murugasan, (2017)	Tiew, (2022)	Gurgun and Koc, (2022)	

Table 5. Summary of reviewed articles on the construction project management performance criteria of external-related factors.

External-related Factors	Sources					
Project location	Gudiene et al. (2013)	Qiang et al. (2015)	Mahamid, (2016)	Samuel et al. (2017)	Gunduz and (Almuajebh, 2020)	Albtoush et al. (2022)
Political complexities, security and stability	Gudiene et al. (2013)	Qiang et al. (2015)	Samuel et al. (2017)	Aljohani et al. (2017)	Gunduz and (Almuajebh, 2020)	
Weather conditions	Gudiene et al. (2013)	Larsen et al. (2015)	Mahamid, (2016)	Samuel et al. (2017)	Aljohani et al. (2017)	
Social and cultural impacts	Gudiene et al. (2013)	Qiang et al. (2015)	Aljohani et al. (2017)	Gunduz and Almuajebh, (2020)		
Project complexity	Qiang et al. (2015)	Mahamid, (2016)	Samuel et al. (2017)	Gunduz and Almuajebh, (2020)		

Research model

This study focuses on identifying the implementation of digital twinning in the construction industry, particularly emphasizing the acceptance procedure and individual attitudes towards innovation. The paper proposes a research methodology that combines the Innovation Diffusion Theory (IDT) and construction project management performance criteria to assess the causal connection between the implementation of digital twinning and construction project management performance. The framework, backed by the IDT model, evaluates relative benefits, complexity, compatibility, trialability, and observability to measure the readiness of potential adopters. Furthermore, the performance criteria for construction project management include quality, cost, time, contract, and external-related factors. **Figure 3** illustrates the research model, which consists of these aspects and acknowledges the challenges in implementing digital twinning as moderators in the connection. Subsequently, this study utilizes partial least square structural equation modelling (PLS-SEM) to examine the identified components and their influence on construction project management performance.

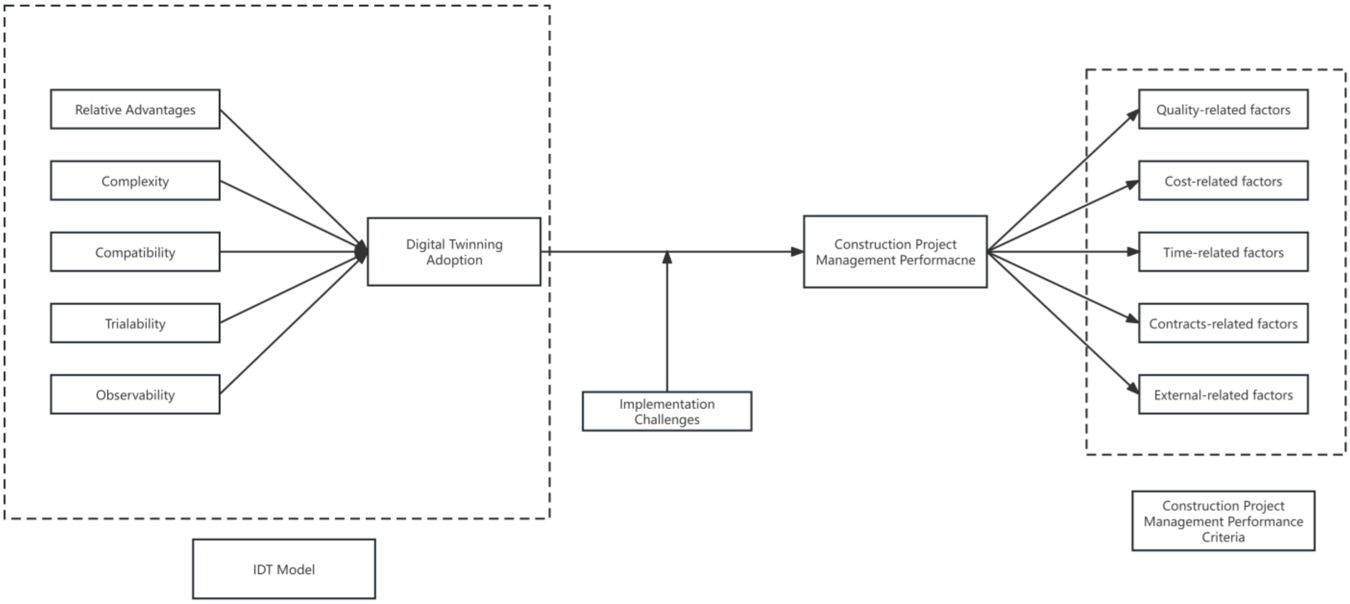

Figure 3. Research model.

4. Research methodology

This study effort uses the quantitative research approach, including data collection through an extensive literature review, questionnaire survey, and data analysis using SmartPLS 4.0 software. Questionnaire surveys are administered using purposive sampling to ensure that respondents are specifically selected individuals from the Malaysian construction industry. Additionally, 66 valid replies were obtained out of 210 questionnaires sent, resulting in a response rate of 31.4%. The sample size exceeds the minimum acceptable threshold (Kock and Hadaya, 2018) and is comparable to the study published by Hwang et al. (2020). Therefore, the Partial Least Squares Structural Equation Model (PLS-SEM) is used for data analysis. PLS-SEM is considered one of the most suitable methods for analysing data with a small sample size, low theoretical background, high importance on prediction accuracy, and absence of predefined model parameters.

The preliminary analysis is performed using IBM SPSS Statistic 28.0 software, providing a comprehensive summary, analysis, and interpretation of the processed and refined data. The initial study results indicate that the most reliable participants are Civil and Structural Engineers, Project Engineers, and Cost Engineers, accounting for 30.6%, 7.4%, and 6.5%, respectively. Additionally, the main group of eligible participants consists of individuals with either less than five years or more than five years but less than ten years of work experience (33.3% and 33.3%). Furthermore, 10.6% of eligible participants possess over two decades of professional experience. On the other hand, the density of respondent's locations is mainly focused on Sarawak (64.8%), Kuala Lumpur (8.3%), Selangor (8.3%), Sabah (4.6%), Johor (2.8%) and Penang (2.8%).

5. Results and discussion

Figure 4 depicts the PLS-SEM measurement model, a hierarchical component model (HCM) comprising two higher-order and ten lower-order constructs. To assess this method, the two-stage technique, which involves using both the repeated indicators approach and latent variable scores analysis, is implemented (Hair et al., 2019). **Figure 5** displays the PLS-SEM measurement model with latent variable scores analysis. It has been completed based on the latent variable scores preserved from the PLS-SEM model with lower-order constructs (LOCs). Next, the measurement model is evaluated based on five criteria: indicator loadings, indicator multicollinearity, construct reliability, convergent validity, and discriminant validity. The summary findings for assessing the measurement model, as shown in **Table 6**, reveal a reasonable level of reliability for construct dependability, with the lowest value of Cronbach's Alpha at 0.651. The confirmation of convergent validity is based on the composite reliability values exceeding 0.6. Furthermore, the presence of multicollinearity in the indicators is confirmed by the maximum VIF value of 2.752, which is below the criterion of 3. In addition, discriminant validity is assessed by the Heterotrait-Monotrait ratio of correlations (HTMT). The findings in **Table 7** demonstrate that the HTMT value for the measurement model is much below the 0.85 limits, thus confirming discriminant validity. However, three indicators are removed from the analysis because their indicator loadings are insufficient, measuring below 0.4.

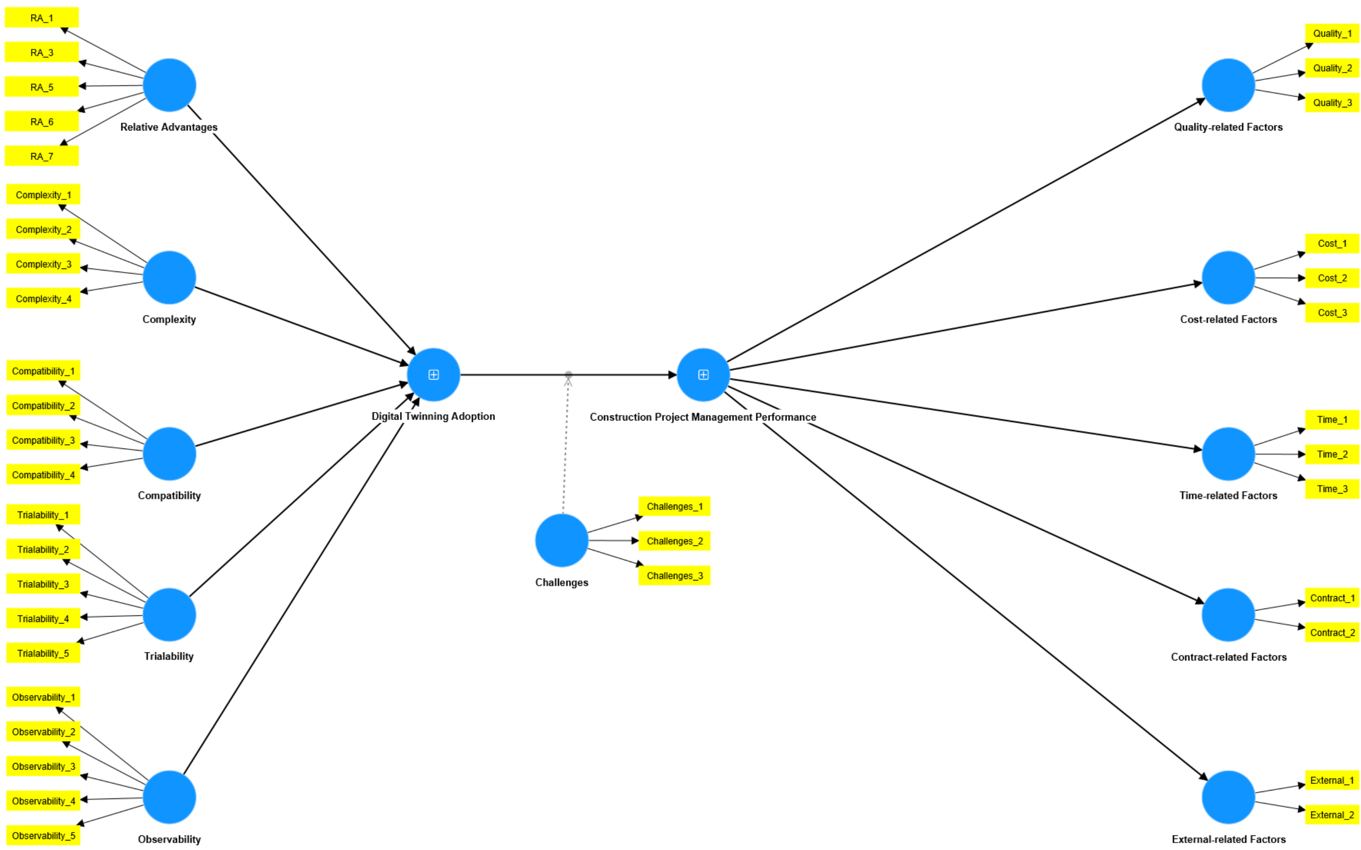

Figure 4. PLS-SEM measurement model.

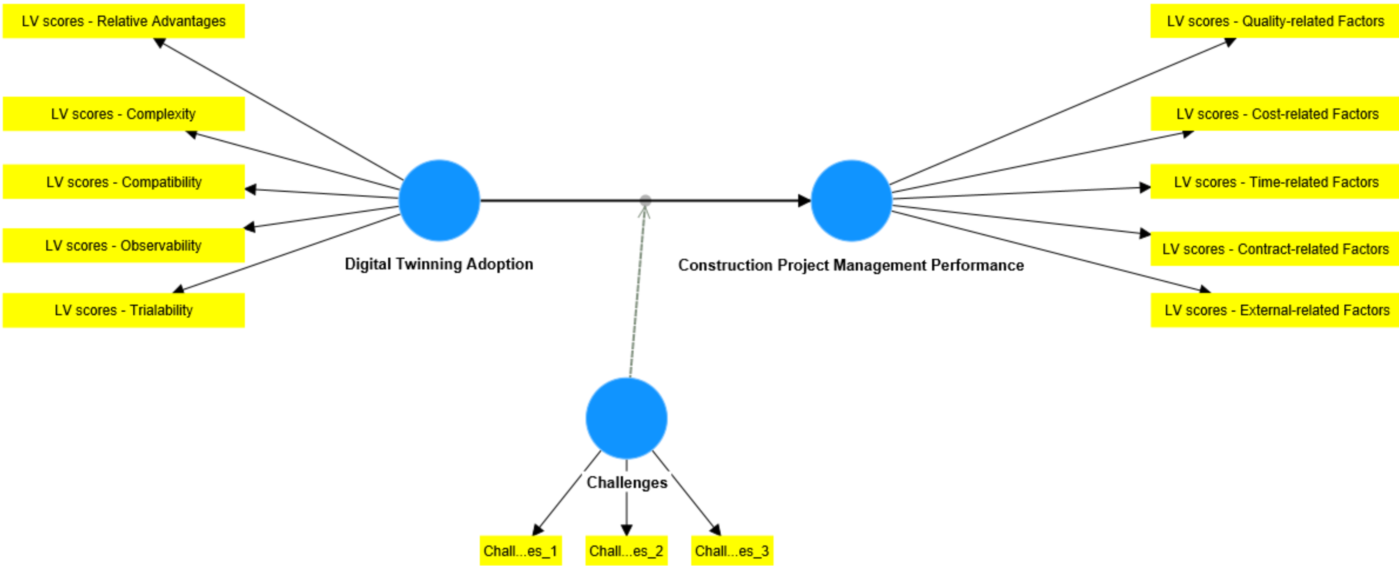

Figure 5. PLS-SEM measurement with latent variable scores analysis.

Table 6. Results summary for evaluation of PLS-SEM measurement model.

Indicators	Indicator Loading	VIF	Cronbach's Alpha	Composite Reliability	AVE	*t* Value	*p* Value
LV Scores—Relative Advantages	0.712	1.487	0.800	0.715	0.516	3.140	0.002*
LV Scores—Complexity	0.286	1.598	0.800	0.715	0.516	1.141	0.254
LV Scores—Compatibility	−0.210	1.553	0.800	0.715	0.516	0.825	0.410
LV Scores—Trialability	0.422	2.752	0.800	0.715	0.516	2.089	0.037*
LV Scores—Observability	0.293	2.284	0.800	0.715	0.516	1.288	0.198
LV Scores—Quality-related Factors	0.830	1.680	0.684	0.730	0.439	7.654	0.000*
LV Scores—Cost-related Factors	0.464	1.335	0.684	0.730	0.439	2.485	0.013*
LV Scores—Time -related Factors	0.764	1.683	0.684	0.730	0.439	5.949	0.000*
LV Scores—Contract -related Factors	0.672	1.469	0.684	0.730	0.439	5.035	0.000*
LV Scores—External -related Factors	0.553	1.297	0.684	0.730	0.439	2.460	0.014*
Challenges_1	0.633	1.288	0.651	0.720	0.564	2.021	0.043*
Challenges_2	0.805	1.403	0.651	0.720	0.564	3.533	0.000*
Challenges_3	0.825	1.213	0.651	0.720	0.564	3.232	0.001*

Table 7. HTMT results summary for PLS-SEM measurement model.

	Challenges	Construction Project Management Performance	Challenges × Digital Twinning Adoption
Challenges			
Construction Project Management Performance	0.40.1		
Digital Twinning Adoption	0.247	0.491	
Challenges × Digital Twinning Adoption	0.307	0.114	0.118

The evaluation of the structural model occurs after confirming the correctness of the measurement model. The structural model is evaluated using four criteria: collinearity across predictor components, coefficient of determination (R^2), effect size (f^2), blindfolding (Q^2), and the relevance of the route coefficient. The findings displayed in **Table 8** indicate that the VIF value of 1.682 is the highest, indicating successful completion of the collinearity test. The R^2 value of 0.263 suggests a modest coefficient of determination, while the greatest Q^2 value of 0.085 indicates that the predictive significance was accepted. Additionally, all values are above 0. The effect sizes for the route models are moderate to large, with values of 0.259, 0.096, and 0.004. The path coefficient analysis reveals a statistically significant and positive correlation between the implementation of digital twinning and the performance of construction project management. The study finds that challenges have a small but statistically significant positive correlation with construction project management performance. However, the combination of challenges and digital twinning adoption does not indicate a meaningful association with project management performance.

Table 8. Results summary for evaluation of PLS-SEM structural model.

Indicators	VIF	R^2	Q^2			
LV Scores—Relative Advantages	1.415		0.000			
LV Scores—Trialability	1.415		0.000			
LV Scores—Quality-related Factors	1.680	0.263	0.085			
LV Scores—Cost-related Factors	1.335	0.263	0.085			
LV Scores—Time -related Factors	1.682	0.263	0.085			
LV Scores—Contract -related Factors	1.467	0.263	0.085			
LV Scores—External -related Factors	1.294	0.263	0.085			
Challenges_1	1.288		0.000			
Challenges_2	1.403		0.000			
Challenges_3	1.213		0.000			
Path Model	**Path Coefficient**	f^2	***t* Value**	***p* Value**	**Significant Level**	**90% Confidence Level**
Digital twinning adoption → Construction project management performance	0.417	0.234	3.854	0.000	***	0.625
Challenges → Construction project management performance	0.274	0.095	2.004	0.045	**	0.466
Challenges x Digital twinning adoption → Construction project management performance	−0.021	0.001	0.186	0.853	NS	0.128

* Notes: * ($p > 0.100$), ** ($p < 0.050$), *** ($p < 0.001$), NS = Not Significant.

The study indicates that the challenges faced during the implementation of digital twinning do not diminish its beneficial effects on the performance of construction project management. The issues arising from limits in capacity, circumstances, and facilities, such as a lack of understanding of contractual obligations, inadequate equipment, and insufficient knowledge of technology, may be addressed through suitable solutions and mitigation programs (Ammar et al., 2022; Greif et al., 2020; Lei et al., 2023; Oraee et al., 2019; Ramu et al., 2022; Redmond et al., 2012; Wang et al., 2020). Therefore, most users who adopt digital twinning to improve construction project management performance are likely to believe that the advantages of its implementation are more than the challenges faced throughout the process. Furthermore, another significant determinant is the effect of pertinent legislation, rules, and governmental endeavours. When government organizations require the implementation of digital twinning in construction projects, regardless of the problems experienced by project parties, the implementation becomes obligatory. An example of this is the Integrated Digital Delivery (IDD) project of Singapore's Building and Construction Authority (BCA), which has a vital role in enforcing the adoption of digital twinning. This effort compels players to tackle challenges in the construction industry successfully. Starting in 2023, as per the program, all new public sector projects with a contract value above $10 million must have Integrated Digital Delivery (IDD). Hence, it is evident that the legal and policy framework plays a crucial role in influencing the execution of digital twinning in the construction industry. This necessitates project participants to tackle and overcome any challenges that may arise during the implementation process in the construction sector efficiently.

6. Conclusion

In summary, the impact of implementing digital twinning in the construction industry is thoroughly investigated in this study, uncovering seven positive and six negative impacts, as well as five performance criteria for construction project management. SmartPLS software is employed to thoroughly examine the causal connection between the adoption of digital twinning and the performance of construction project management. The findings indicate a strongly significant positive association. The challenges faced during the procedure do not greatly reduce the beneficial relationship between the adoption of digital twinning and the performance of construction project management. The results highlight the significant beneficial effect of digital twinning on project management in the construction industry, underlining its ability to improve overall performance despite the inherent hurdles in its implementation.

The study makes substantial contributions in several aspects. Firstly, it aligns with the national goals of digitalizing the construction sector, showcasing that the use of digital twinning may improve the performance of construction project management, thereby promoting the wider digital transformation of the construction industry. The study presents a detailed causal model to explain this connection, highlighting the capacity of digitalization to enhance the industry's competitiveness and sustainability, therefore directly contributing to overall economic growth. Furthermore, the study provides significant insights for the construction sector and diverse organizations by giving a comprehensive analysis of the good and negative consequences linked to the implementation of digital twinning. The offered recommendations are a dependable source of information for the industry's move towards digitization, with the anticipation that this change would result in notable improvements in productivity and efficiency. This innovation has the capacity to transform operational approaches in the construction field, offering valuable knowledge for construction companies, government bodies, and private research institutions. As a result, it will significantly impact the future direction of the construction industry and establish crucial groundwork for the advancement of intelligent construction. Finally, the research focuses on a crucial area that has not been studied before, examining the impact of digital twinning adoption on construction project management performance. This not only enhances comprehension for stakeholders in the construction sector but also promotes awareness regarding the application of digital twinning, especially in developing countries, imparting crucial knowledge to industry stakeholders.

7. Limitation and future works

This study recognizes certain limitations due to the restrictions imposed by time and budgetary constraints. The implications of implementing digital twinning and the criteria for evaluating construction project management performance are mostly obtained from a comprehensive literature analysis. However, it is important to note that the research deadline may result in certain dimensions being overlooked. Difficulties with the trustworthiness of data obtained from a questionnaire survey that uses a Likert scale are acknowledged. The possibility of variety in how respondents understand the questions is recognized, along with the limitation of just focusing on the Malaysian construction sector. Another restriction impacting the generalizability of findings is the very small sample size. To overcome these constraints, PLS-SEM modelling analysis, which is well-suited for efficiently managing lower sample numbers, is employed.

Potential areas for future investigation are proposed in the paper, such as integrating supplementary factors to develop a more comprehensive model, employing qualitative analysis to strengthen the dependability of findings, and expanding similar research to other nations to include any changes in the sector. These suggestions aim to enhance comprehension of the application of digital twinning and provide practical insights to aid the construction industry by addressing theoretical and practical knowledge gaps.

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