PLANNING MALAYSIA:
Journal of the Malaysian Institute of Planners
VOLUME 23 ISSUE 1 (2025), Page 81 – 96

DIGITAL TWIN APPLICATION IN CONSTRUCTION COST MANAGEMENT

Roziha Che Haron[1] and Nurnaqueisha Balqis Muhd Zafir[2]

[1,2]*Kulliyyah of Architecture and Environmental Design,*
UNIVERSITI ISLAM ANTARABANGSA MALAYSIA

Abstract

In line with the current construction revolution, it is time for the construction industry to embrace innovation and technology. This is corresponding with the National Construction Policy 2030 (NCP 2030) that comes out with the aim to digitalize the entire construction industry towards the IR 4.0. The focus is to boost the nation's construction industry's competitiveness and recognition worldwide. The construction industry has undergone a significant transformation in recent years such as BIM, IoT including Digital Twin due to the incorporation of digital technologies. A digital twin is a virtual representation of a physical asset. It is still a relatively new concept in the construction industry, but it offers an innovative method for improving cost management strategies in construction projects. Applications of the digital twin in construction cost management have the potential to revolutionize conventional methods. Therefore, this study seeks to determine the level of understanding of construction industry players on the concept of digital twin applications in construction cost management by providing the concept and to explore the challenges and strategies in implementing the digital twin applications in construction cost management. This research employed a mixed-method approach by means of questionnaire survey and interview for data collection. 35 samples that consist of construction industry players from different organizations participated in this study. The data collected from the survey and interview are analyses through descriptive and content analysis. Overall, the findings find out the understanding of digital twin applications with its challenges and strategies to overcome it. This research contributes to the body of knowledge regarding digital twin applications and construction cost management.

Keywords: construction cost management, challenges, digital twin, strategies

[1] Corresponding Author: roziharon@iium.edu.my

INTRODUCTION

In the early stages of the construction industry, conventional methods like manual progress tracking were used to manage projects. These outdated approaches negatively impacted productivity and quality, largely due to reliance on unskilled manual labor (Santi Edra et al., 2021). With the increasing complexity of projects and the demand for reduced timelines, improved quality, and lower costs (Garcia de Soto et al., 2019; Cristóbal et al., 2018), adopting modern technologies has become essential for maintaining competitiveness.

The Fourth Industrial Revolution (IR 4.0) marks a significant technological leap, with digital twin technology playing a pivotal role. A digital twin involves a digital model, a physical twin, and a connection between them, using real-time data and IoT connectivity (Khajavi et al., 2019). This technology enhances operational efficiency, enabling predictive maintenance and better decision-making. It streamlines traditional construction processes, covering economic conditions, physical environments, and project execution (Reja and Varghese, 2022).

This research focuses on the application of digital twin technology in construction cost management. Cost management spans from initial cost estimation to ensuring project completion within budget and on schedule. Success in construction projects hinges on the balance between cost, time, and quality, where any change in one affects the others (Albtoush et al., 2020). Effective cost management prioritizes efficiency, client satisfaction, and profitability. The study explores how digital twin technology can optimize cost management by improving accuracy, reducing inefficiencies, and ensuring better control throughout the project lifecycle. By leveraging digital twin technology, construction projects can achieve greater alignment with budgets, schedules, and quality standards, ultimately driving project success.

LITERATURE REVIEW

Digitalisation Revolution in Construction Industry

A digital twin is a virtual representation of a physical object or system that simulates its behaviour in real time. In the construction industry, digital twin pertains to a computer-generated replica that incorporates both the design and construction phases offering a full and up-to-date perspective on the project's advancement. A digital twin can be used in project cost management to produce a virtual version of a construction project that can be used to analyse and manage expenses. Khajavi et al., (2019) said the usage of a digital twin for performance is crucial, and it has proven to be successful in terms of cost savings and reliability improvements for capital-intensive equipment such as jet engines. Bademosi et al. (2019) found that these technologies have been associated with improved employee skill development, reduced task redoing, enhanced safety perception, lower labour costs, and improved project deadline outcomes. This is achieved through the integration of simulations with experts' domain knowledge, enabling the use of digital twin in the construction sector. In contrast, Shen (2022) said that the construction sector has historically seen limited uptake of technological advancements in the execution of projects. This phenomenon may be attributed to the prevalent practice of extensive planning and execution in the building industry, sometimes spanning many years.

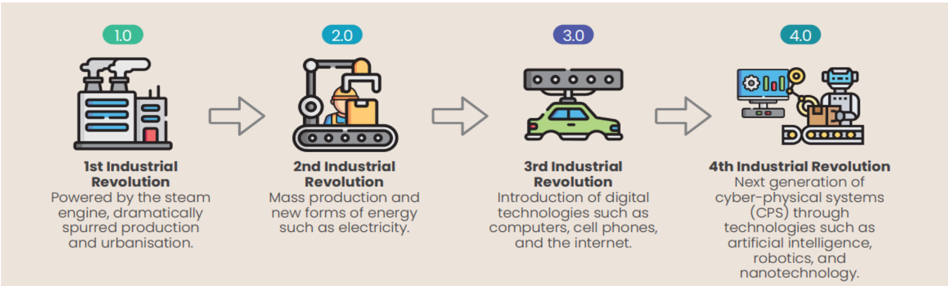

Figure 1: Revolution of Industry
Source: CIDB, 2020

Industrialization has progressed through several key revolutions. Figure 1 illustrates the paradigm shift in the technological revolution. The First Industrial Revolution marked the shift from manual labor to mechanized production. The Second Revolution brought major technological advancements in steel, electricity, communication, and transportation. The Third Revolution transitioned from mechanical to digital technologies, paving the way for the Fourth Industrial Revolution, which enables the digital transformation of industries. This transformation is largely driven by the exponential growth in computational power and the increased accessibility of electronic data (Reischauer, 2018). The COVID-19 pandemic significantly accelerated digitalization, resulting in a marked increase in the use of mobile and cloud computing. According to the McKinsey Global Institute (2020), this surge led to a twofold increase in revenue compared to pre-pandemic projections. This trend is expected to continue as industrialized nations strive to recover economically. Cyber-physical systems, which integrate physical processes with digital technologies, have the potential to save both time and costs, contributing to long-term economic recovery.

Digital Twin

A digital twin is a virtual replica of a physical object that captures and transmits real-time data from the actual asset, creating a digital version. It allows for feedback from the digital world to the physical entity (Madubuike et al., 2022; Fu et al., 2022; Attaran and Celik, 2023). Figure 2 shows how the real space and virtual space are connected by digital twin technology. The technology connects real and virtual spaces, simulating complex processes and behaviors interacting with the environment (Magomadov, 2020). Digital twins can be used in various contexts and are built with data from tools like Building Information Modeling (BIM) and sensor systems. By integrating data through machine learning algorithms, they offer insights across different project phases, enabling real-time monitoring, simulations, and quality assessments.

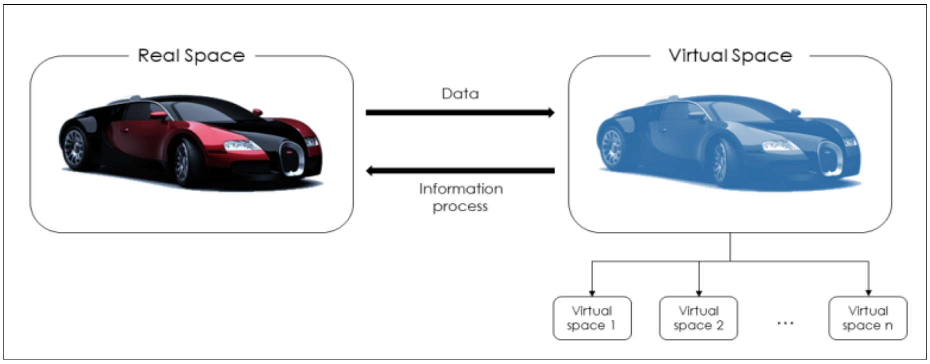

Figure 2: Implementation of Digital Twin
Source: Barricelli et al., 2019

Digital Twin in Construction Industry and Other Sectors

Digital twins enable the simulation and visualization of complex systems, with growing applications in the construction sector. El Jazzar et al. (2020) highlight that digital twin, evolving from Building Information Modeling (BIM), can help transform the construction industry. Liu et al. (2020) note that digital twins could improve safety in construction by integrating AI, sensors, video cameras, and mobile devices to create a comprehensive safety framework. Digital twins allow for real-time monitoring of construction processes and project managers to simulate scheduling scenarios, assess resource utilization, and identify potential conflicts. Lydon et al. (2019) suggest that digital twins can support different construction methods and enhance risk management by modeling various scenarios. By capturing real-time data, digital twins improve decision-making compared to static BIM data, offering better oversight for construction managers, designers, and clients (Tang et al., 2019).

Construction Cost Management

Herszon (2017) says that cost management is the systematic estimation of costs related to the various activities and endeavours necessary for the successful completion of a project. According to Verbeeten (2011), the scope of cost estimation extends beyond just financial considerations and involves the utilisation of management accounting principles, techniques for gathering and analysing data, and methods of presenting information. The implementation of effective project cost management practises guarantees the successful completion of a project within the allocated budget and in accordance with the predetermined scope. Girma and Alemu, (2018) states that the need of efficiently managing construction costs is widely acknowledged as a crucial element in attaining project success and is a significant task that needs to be done with accuracy. The total cost management process encompasses all stages of development, as depicted in Figure 3. During each step, the execution of cost management activities should be carried out by professionals like Quantity Surveyors (QS) or cost managers.

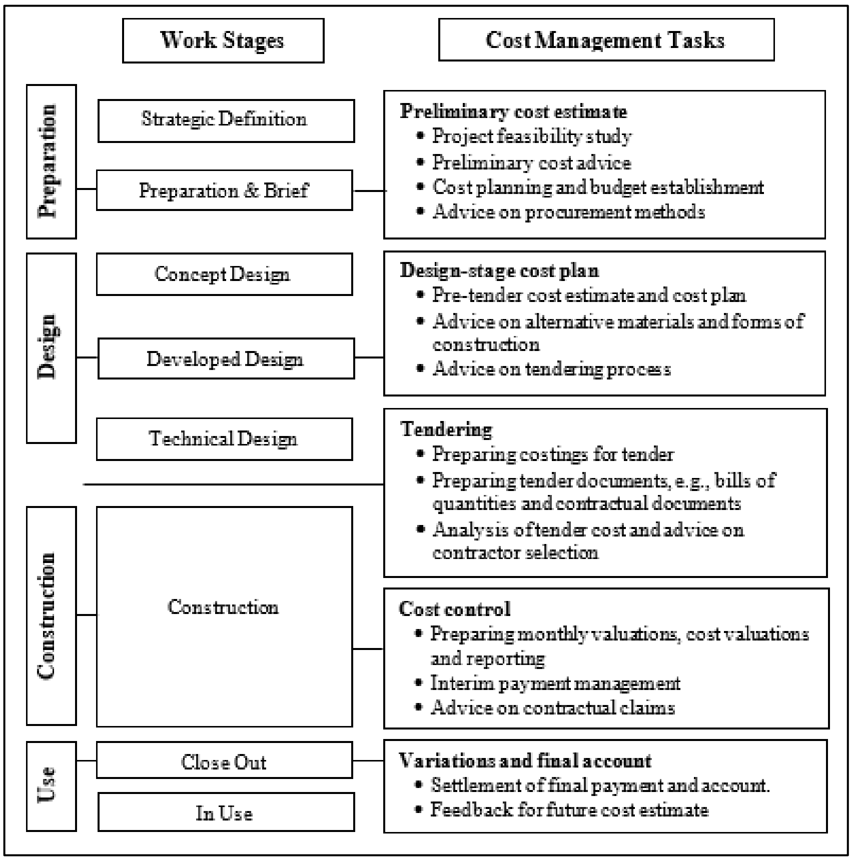

Figure 3: Cost Management Activities by following RIBA Plan of Work
Source: Weisheng et al. 2019

Digital Twin in Construction Cost Management

Challenges and Strategies for Implementing of Digital Twin in Construction Cost Management

Digital twin technology, which creates virtual representations of physical objects or structures, supports informed decision-making in cost estimation, streamlines construction coordination to reduce time, and improves risk management. However, its implementation can face challenges unforeseen by clients, consultants, contractors, and stakeholders. Despite the benefits of digital twins, challenges arise from factors such as knowledge, technology, governance, and economic issues, particularly in Malaysia's construction sector. To overcome these challenges, it is essential to analyze and implement effective strategies, supported by four key enablers: people, integrated technology, governance, and economy.

RESEARCH METHODOLOGY

This study uses questionnaires and interviews to collect data from construction industry participants, both directly and indirectly involved in the construction process. Questionnaires, which include both closed and open-ended questions, are distributed via email, Google Forms, and social media platforms like LinkedIn, targeting 70 respondents. The data is analyzed using the Statistical Package for the Social Sciences (SPSS), with frequency distribution and central tendency measurements to identify key patterns. A Likert scale is used to gauge the extent of agreement with digital twin applications in construction cost management, categorized into low, medium, or high based on mean values. Additionally, four experienced respondents are interviewed to provide insights on challenges and strategies for implementing digital twin technology. Content analysis is employed to examine and categorize responses from the interviews.

ANALYSIS AND DISCUSSION

Questionnaire Survey

The first part of the questionnaire is to know the level of understanding and agreement of respondents on the concept of digital twin applications in construction cost management. This section aims to achieve the main objectives.

Table 1: Result of Digital Twin Application in Construction Cost Management

Digital Twin Application in Construction Cost Management	Mean
Analysis and Optimization - Digital twins can be used to analysis by simulating and evaluating cost projection in virtual environments, this is to avoid loss, cost overruns, minimise the risk and helps in decision making.	3.8857
Real-Time Cost Tracking - Digital twins allow real-time tracking and costing of construction projects through the use of sensors, Internet of Things (IoT) and project management tools to track labour productivity, materials and equipment used for projects.	3.8571
Risk Management - Digital twins facilitates construction project manager in risk management related to cost, i.e.: risk identification, risk mitigation, risk allocation etc.	3.8571
Cost Estimation - Digital twins facilitate accurate cost estimation using data provided from architectural and engineering designs, material, labour and machinery rates and others.	3.8000
Lifecycle Cost Analysis - Digital twins analyse the lifecycle of a building, including maintenance, operational, energy consumption, and cost data for cost management.	3.7714

The analysis of Table 1 shows that all concepts of digital twin application in construction cost management received high scores, with mean values above 3.50. The majority of respondents agreed that digital twin technology helps with analysis, optimization, and cost projection in virtual environments, minimizing risks and cost overruns (mean value of 3.89). The lowest mean value, 3.77, relates to digital twins analyzing a building's lifecycle, including maintenance, operations, energy consumption, and cost data. The research also aims to identify the challenges faced by Malaysian industry players in adopting digital twin technology for cost management and to recommend efficient strategies for overcoming these challenges. Respondents shared their opinions using a Likert scale, with a focus on identifying obstacles and potential solutions. Although digital twins are widely used in aerospace, manufacturing, and industrial engineering, their implementation in construction remains limited (Madubuike et al., 2022). Respondents strongly agreed that digital twins integrate multiple software types, facilitating the creation of virtual models and linking them to real-world objects. This aligns with Madubuike et al.'s (2022) research, which emphasizes that digital twins optimize services and operations through data from the Internet of Things (IoT) and physical assets.

Table 2: Result of Challenges and Strategies of Digital Twin Application in Construction Cost Management

Challenges	Mean	Strategies	Mean
Lack of experience with Digital Twin application in construction industry	4.3714	Providing training to industry players of Digital Twin application	4.3143
Lack of government incentives i.e.: training centre	4.3143	Enhanced skills programme for Digital Twin technology application in construction	4.3143
Lack of knowledge of Digital Twin technology	4.2857	Create a blueprint for digital twins to give clear standard approach	4.2571
Lack of Digital Twin experts	4.2571	Government to infuse emerging technologies in construction practices	4.2571
Lack of awareness regarding Digital Twin technology	4.2286	Strengthen partnerships between the public and private sectors to joint venture in the implementation of digital twin technology	4.2286
Lack of confidence in successfully implementing Digital Twin technology	4.2000	Educate and giving awareness on the implementation of Digital Twin technology	4.2000
Limited Digital Twin technology implementation in construction project	4.2000	Partnering with a trusted provider to avoid making cost mistakes	4.2000
Poor collaboration among construction players in incorporating new technology	4.1714	Government to developing a privacy policy to secure the data information and privacy	4.2000
Lack of investor in technology application that includes Digital Twin application	4.1714	Government to enforce rules that the usage of data must be in accordance with privacy policy	4.1714
Lack of training provided related to Digital Twin	4.1429	Government to analyse and strengthen existing legislation, rules, and standards to create a comprehensive digital construction environment.	4.1714
Lack of government support i.e.: funding	4.1429	Increase local stakeholders' expertise through knowledge transfer by collaboration with international organisations.	4.1429

Challenges	Mean	Strategies	Mean
High cost of Digital Twin implementation	4.1429	Develop understanding of using Augmented Reality (AR) as it helps to give information about the visualisation of digital twin	4.1429
Digital twin is a new technology in construction industry	4.0571	Governments to provide funding to support research and development of digital twin technologies	4.1143
Resistance to change to the new technology	4.0571	Use and improve the integration of the current data platform for construction data sharing	4.0857
No clear blueprint to use Digital Twin	4.0571	Benchmarking programme to identify technological gaps with the Construction 4.0 leading countries.	4.0857
Require higher financial obligations	4.0571		
Unreadiness of financial institution to fund in Digital Twin technology	4.0286		
Readiness of stakeholders in adopting Industry Revolution 4.0 (IR 4.0)	3.8857		
Complexity of data sharing	3.8857		
Readiness of stakeholders in IT investment	3.8571		
Complicated use of Digital Twin technology	3.8571		
Lack of information security and data privacy	3.7143		
Legal and ethical issues	3.6571		

.

Table 2 shows that the challenges associated with digital twin application in construction cost management have high mean scores, with all challenges exceeding a moderate level of 3.50. The most significant challenge, with a mean of 4.37, is the lack of experience with digital twin technology in the construction industry. The least significant challenge, with a mean of 3.66, relates to legal and ethical issues. For strategies, the mean scores range from 4.31 to 4.09, indicating strong support for strategies promoting digital twin adoption. The highest-rated strategy is providing training and enhancing skills for industry players, with a mean score of 4.31. The lowest-rated strategy is conducting benchmarking programs with leading Construction 4.0 countries, scoring 4.09. The top challenges include lack of experience, government incentives, knowledge, experts, awareness, and confidence in implementing digital twin technology. These challenges align with findings by Santi Edra et al. (2021), highlighting issues like limited talent, lack of training, and resistance to change. The most significant challenges relate to knowledge and governance. Regarding strategies, all received mean scores above 4.00, indicating strong support. The highest-ranked strategy is providing training for industry players, with the government identified as a key enabler. Research by Mazumder et al. (2023) emphasizes the importance of training and upgrading skills to fully leverage digital twin technology, suggesting that universities could incorporate digital tools into relevant courses to prepare future professionals for the construction industry's digital transformation.

Interview

In order to strengthen the research objectives, semi-structure interview is also conducted after questionnaire survey is done. The targeted respondents are construction industry players that had involve in construction process directly or not. The names of the interviewees were abbreviated as Respondent 1 (R1), Respondent 2 (R2), Respondent 3 (R3), and Respondent 4 (R4) that are contractor, executive in contract, quantity surveyor and researcher respectively.

Table 3: Result of Digital Twin Application in Construction Cost Management

Concept	No. of Respondents Agree
Digital twins provide accurate cost estimates by utilizing data from architectural models, engineering designs, material quantities, and labour rates.	R1, R2, R3, R4
Digital twins enable real-time monitoring and accounting of construction project costs, incorporating sensors, IoT devices, and project management systems to track labour productivity, material consumption, and equipment usage.	R1, R2, R3
Digital twins enable scenario analysis by simulating and evaluating cost scenarios in virtual environments, enabling stakeholders to optimize cost management strategies and make cost-conscious decisions.	R1, R2, R3
Digital twins help construction project managers identify and manage cost-related risks, develop risk mitigation strategies, and allocate contingency budgets by analysing historical data.	R1, R2, R3
Digital twins analyse building lifecycle, integrating maintenance, operational, energy, and cost data for cost optimization.	R1, R2, R3

The Table 3 shows that respondents R1, R2, and R3 agreed with all statements regarding digital twin application in construction cost management. However, R4 did not provide an answer, as they believe the technology is complex and requires more research before implementation. During interviews, participants initially expressed confusion about the term "digital twin." However, after receiving a detailed explanation from the researcher about its definition and practical applications, they realized they had encountered similar technology before, but in a different context. Their responses were based on theoretical knowledge, and they found it difficult to provide practical answers without further experience.

Table 4: Result of Challenges and Strategies of Digital Twin Application in Construction Cost Management

Challenges	No. of Respondents	Strategies	No. of Respondents
Reluctance of players	R1, R2, R3, R4	Enhance awareness	R1, R2, R3
Lack awareness	R1, R2, R3, R4	Initiatives from government	R1, R2
Funding/Money issues	R1, R2, R4	Financial incentive from government	R3
Ecosystem – the IT facilities and software	R3, R4	Collaboration with expertise	R3
Lack of knowledge	R2, R3	Training	R3
Lack of expertise	R1, R4	Enforce guidelines and policies	R4
Industry players still use traditional method	R1, R2	Build the capacity	R4
Long Return of Investment (ROI)	R1, R2		
Server – connection/internet	R3		
No demand for new technology	R2		

The interviews revealed that the main challenges in adopting digital twin technology for construction cost management are related to knowledge, technology, governance, and economics. Key issues include a lack of awareness and reluctance among industry players, which aligns with the questionnaire findings. Respondents noted that limited knowledge and awareness of digital twin technology hinder its application in Malaysia's construction sector. Additionally, reluctance to adopt new technologies poses a significant barrier. Funding for the necessary hardware and software also remains a challenge. Successful implementation of digital twin technology requires overcoming these barriers through technological innovation, organizational commitment, and effective change management. The majority of interviewees emphasized the importance of increasing awareness and knowledge to address these challenges. They suggested that awareness could be raised by governmental bodies, universities, and industry stakeholders. Respondents highlighted the government's crucial role in promoting awareness, offering incentives, and providing training before requiring the adoption of new technology in construction projects, as outlined by CIDB (2020).

CONCLUSION

This research successfully achieved its aim and objectives using a mixed-method approach for data collection. The study concludes that the application of digital twin technology in construction cost management within the Malaysian construction industry is currently low. A majority of respondents lack awareness and knowledge about digital twin technology. However, they recognize the challenges hindering its adoption in the industry and fully agree with the recommended strategies to overcome these challenges. The key challenges identified relate to knowledge gaps, including a lack of awareness, confidence, and hesitance to adopt the technology, as well as cost concerns. The questionnaire findings also highlight the need for government and large organizations to provide training programs to industry players to facilitate the adoption of digital twin technology. For future research, it is recommended to explore the perspectives of IT experts on their readiness to adopt digital twin technology in the Malaysian construction industry. Further research in this area could improve understanding and raise awareness of digital twin technology.

ACKNOWLEDGEMENTS

This study is funded under KAED Research Grant (KAED-RG24-008-0008), provided by International Islamic University Malaysia. The researchers would also like to thank all respondents for their contributions in this research.

REFERENCES

Albtoush, A. M. F., Doh, S. I., Rahman, A. R. B. A., & Albtoush, J. A. (2020). Factors effecting the cost management in construction projects. *International Journal of Civil Engineering and Technology*, *11*(1). https://doi.org/10.34218/ijciet.11.1.2020.011

Attaran, M., & Celik, B. G. (2023). Digital twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, *6*, 100165. https://doi.org/10.1016/j.dajour.2023.100165

Augustine, P. (2020). Chapter four - The industry use cases for the digital twin idea. In *Advances in Computers, The Digital Twin Paradigm for Smarter Systems and Environments: The Industry Use Cases*. Editors. P. Raj and P. Evangeline (Elsevier). 79–105.

Bademosi, F., Blinn, N., & Issa, R. R. A. (2019). Use of augmented reality technology to enhance comprehension of construction assemblies. *Journal of Information Technology in Construction*, *24*, 58–79.

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access*, *7*, 167653–167671. https://doi.org/10.1109/access.2019.2953499

CIDB, 2020. *Construction 4.0 Strategic Plan (2021-2025)*

Cristóbal, J., Carral, L., Diaz, E., Fraguela, J., & Iglesias, G. (2018). Complexity and project management: A general overview. *Complexity*, *2018*, 1–10. https://doi.org/10.1155/2018/4891286

De-graft, J. O., Perera, S. Osei-Kyei, R. Rashidi, M. Bamdad, K. & Famakinwa, T. (2023) Barriers to the adoption of digital twin in the construction industry: A literature review. *Informatics*, *10*, 14. https://doi.org/10.3390/informatics10010014

De-graft, J. O., 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 2022*, *12*, 113.

El Jazzar, M., Piskernik, M. and Nassereddine, H. (2020) Digital twin in construction: An empirical analysis.

El Saddik, A. (2018). Digital twins: the convergence of multimedia technologies. *IEEE MultiMedia*, *25*(2), 87–92. https://doi.org/10.1109/mmul.2018.023121167

Fu, Y., Zhu, G., Zhu, M., & Xuan, F. (2022). Digital twin for integration of design-manufacturing-maintenance: An overview. *Chinese Journal of Mechanical Engineering*, *35*(1). https://doi.org/10.1186/s10033-022-00760-x

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: enabling technologies, challenges and open research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/access.2020.2998358

García de Soto, B., Agustí-Juan, I., Joss, S., & Hunhevicz, J.J. (2019). Implications of construction 4.0 to the workforce and organizational structures. *International Journal of Construction Management*, *22*, 205 - 217.

Girma, A. & Alemu, M.G., 2018. Improving project cost management practice and profitability of domestic contractors in Vadodara. *Journal of Emerging Technologies and Innovative Research*, *5*(5).

Grieves, M. (2014) Digital twin: Manufacturing excellence through virtual factory replication. *White Paper*, 2014: 1-7.

Herszon L (2017) *The complexity of projects: an adaptive model to incorporate complexity dimensions into the cost estimation process*. University of Huddersfeld, Hud

Hosamo H. H., Nielsen H. K., Alnmr A. N., Svennevig P. R. and Svidt K. (2022), A review of the digital twin technology for fault detection in buildings. *Front. Built Environ*. *8*:1013196.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C. and Holmström, J. (2019) Digital twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access 2019*, *7*, 147406–147419

Kor, M., Yitmen, I., & Alizadehsalehi, S. (2022). An investigation for integration of deep learning and digital twins towards construction 4.0. *Smart and Sustainable Built Environment*, *12*(3), 461–487. https://doi.org/10.1108/sasbe-08-2021-0148

Lau, S. E. N., Zakaria, R., Aminudin, E., Chai, C. S., Abidin, N. I., Roslan, A. F., Hamid, Z. A., Zain, M. Z. M., & Lou, E. (2019). Review: Identification of roadmap of fourth construction industrial revolution. *IOP Conference Series*, *615*(1), 012029. https://doi.org/10.1088/1757-899x/615/1/012029

Liu, G.; Yang, H.; Fu, Y.; Mao, C.; Xu, P.; Hong, J.; Li, R. (2020) Cyber-physical system-based real-time monitoring and visualization of greenhouse gas emissions of prefabricated construction. *J. Clean. Prod*. *2020*, *246*

Lydon, G. P., Caranovic, S., Hischier, I. and Schlueter, A. (2019) Coupled simulation of thermally active building systems to support a digital twin. *Energy and Buildings 202*

Magomadov, V. S. (2020). The digital twin technology and its role in manufacturing. *IOP Conference Series*, *862*(3), 032080. https://doi.org/10.1088/1757-899x/862/3/032080

Mazumder, A., Sahed, M., Tasneem, Z., Das, P., Badal, F. R., Ali, M. W., Ahamed, M. H., Abhi, S., Sarker, S., Das, S. K., Hasan, M., Islam, M., & Islam, M. R. (2023). Towards next generation digital twin in robotics: Trends, scopes, challenges, and future. *Heliyon*, *9*(2), e13359. https://doi.org/10.1016/j.heliyon.2023.e13359

Mckinsey Global Institute (2020) *How COVID-19 has pushed companies over the technology tipping point—and transformed business forever*

Melissa Li, W. L., Wong, S. Y. and Ding, C. S. (2022) Challenges of industrial revolution 4.0: quantity surveying students' perspectives. *Engineering, Construction and Architectural Management*

Nagy, O., Papp, I., & Szabó, R. Z. (2021). Construction 4.0 organisational level challenges and solutions. *Sustainability*, *13*(21), 12321. https://doi.org/10.3390/su132112321

Naoum, S. (2013). *Dissertation Research and Writing for Construction Students*

National Construction Policy 2030 (NCP 2030)

Nikmehr, B., Hosseini, M. R., Martek, I., Zavadskas, E. K., & Antucheviciene, J. (2021). Digitalization as a strategic means of achieving sustainable efficiencies in construction management: A critical review. *Sustainability*, *13*(9), 5040. https://doi.org/10.3390/su13095040

Madubuike O. C., Chimay J. Anumba, Rana Khallaf 2022 A Review of Digital Twin Applications in Construction. *Journal of Information Technology in Construction*. 145-172. 10.36680/j.itcon.2022.008

Ramasubramanian, A. K., Mathew, R., Kelly, M., Hargaden, V., & Papakostas, N. (2022). Digital twin for human–robot collaboration in manufacturing: Review and outlook. *Applied Sciences*, *12*(10), 4811. https://doi.org/10.3390/app12104811

Reinbold, A., Lappalainen, E., Seppänen, O., Peltokorpi, A., & Singh, V. (2022) Current challenges in the adoption of digital visual management at construction sites: Exploratory case studies. *Sustainability*, *14*, 14395. https://doi.org/10.3390/su142114395

Reischauer, G. (2018) Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing. *Technological Forecasting and Social Change*, *132*, 26–33

Reja, V. K. and Varghese, K. (2022) Digital Twin Applications for Construction Project Management.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. (2020). Construction with digital twin information systems. *Cambridge University Press. Data-Centric Engineering*.

Salem, T., & Dragomir, M. (2022). Options for and challenges of employing digital twins in construction management. *Applied Sciences*, *12*(6), 2928. https://doi.org/10.3390/app12062928

Santi Edra, N. L., Aminudin, E., Zakaria, R., Chai, C. S., Abidin, N. I., Ahmad, R., Hamid, Z. A., Zain, M. Z. M., Lou, E., & Shaharuddin, A. B. (2019). Revolutionizing the future of the construction industry: Strategizing and redefining challenges. *WIT Transactions on the Built Environment*. https://doi.org/10.2495/bim190101

Santi Edra, N. L., Aminudin, E., Zakaria, R., Chai, C. S., Roslan, A. F., Hamid, Z. A., Zain, M. Z. M., Maaz, Z. N., & Ahamad, A. H. (2021). Talent as a spearhead of construction 4.0 transformation: Analysis of their challenges. *IOP Conference Series*, *1200*(1), 012025. https://doi.org/10.1088/1757-899x/1200/1/012025

Seo, H.; Yun, W.-S. Digital Twin-Based Assessment Framework for Energy Savings in University Classroom Lighting. *Buildings 2022*, *12*, 544.

Sepasgozar, S. M. E. (2020). Digital technology utilisation decisions for facilitating the implementation of Industry 4.0 technologies. *Construction Innovation: Information, Process, Management*, *21*(3), 476–489. https://doi.org/10.1108/ci-02-2020-0020

Shen, W. (2022). Application of BIM and Internet of things technology in material management of construction projects. *Advances in Materials Science and Engineering*, *2022*, 1–11. https://doi.org/10.1155/2022/5381252

Statsenko, L., Samaraweera, A., Bakhshi, J., & Chileshe, N. (2022) Construction 4.0 technologies and applications: a systematic literature review of trends and potential areas for development *Construction Innovation*

Tang, S., Shelden, D.R., Eastman, C.M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the Internet of Things (IoT) devices integration: Present status and future trends. *Automation Construction 101* 127–139

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C., & Nee, A. Y. C. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935–3953. https://doi.org/10.1080/00207543.2018.1443229

Tao, F., Zhang, H., Liu, A. and Nee, A.Y. (2018) Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform*. *2018*, *15*, 2405–2415.

Taofeeq, D. M. (2020). Emerging challenges and sustainability of industry 4.0 era in the Malaysian construction industry. *International Journal of Recent Technology and Engineering*, *9*(1), 1627–1634. https://doi.org/10.35940/ijrte.a2564.059120

Tuhaise, V.V., Tah, J.H.M., & Abanda, F.H. (2023) Technologies for digital twin applications in construction. *Automation in Construction*

Turner, C., Oyekan, J., Stergioulas, L. K., & Griffin, D. (2021). Utilizing Industry 4.0 on the construction Site: Challenges and opportunities. *IEEE Transactions on Industrial Informatics*, *17*(2), 746–756. https://doi.org/10.1109/tii.2020.3002197

Verbeeten, F.H.M. (2011) Public sector cost management practices in The Netherlands. *International Journal of Public Sector Management 24*(6), 492–506

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

Weisheng, L., Chi, C. L., and Tung, T. (2019). *BIM and Big Data for Construction Cost Management*. Routledge.

Received: 6th July 2024. Accepted: 23rd October 2024

