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EVALUATION OF THE BENEFITS OF THE IMPLEMENTATION OF DIGITAL TWINS IN SUSTAINABLE CONSTRUCTION PROJECTS

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ABSTRACT

Digital twin technology has emerged as a promising tool for enhancing sustainability in construction projects by providing a virtual representation of physical assets and processes. This research explores the benefits of implementing digital twins to drive sustainable construction projects. Through a review of the literature and a survey, the findings show that digital twin technologies provide significant benefits in the implementation of sustainable construction projects. Particularly, they allow faster internal decisions, improve communication, and enhance productivity. Furthermore, digital twins' implementation promotes employee innovation, engagement, and project team trust and minimises project risks. While certain benefits are more noticeable than others, digital twins contribute positively to project outcomes, demonstrating their importance in sustainable construction management. The findings also provide insights into the challenges and opportunities associated with the adoption and integration of digital twin technology in sustainable construction management, paving the way for future research.

Keywords: *Digitisation; Productivity; Sustainable Construction Management; Information.*

1. INTRODUCTION

The construction sector stands pivotal in the reduction of carbon emissions. The creation of virtual replicas of physical assets with digital twin technology will enable real-time monitoring and analysis, which has the potential to improve the performance and productivity of the construction sector. In recent years, the construction sector has undergone a paradigm shift towards sustainable methods, spurred by rising awareness of environmental concerns, resource restrictions, and the urgency to minimise the impacts of climate change (Olanrewaju, et al., 2019). As stakeholders work to meet ambitious sustainability goals, emerging technologies have emerged as significant tools for

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improving the productivity and performance of construction sector. Among these technologies, digital twins have received substantial attention for their potential to enhance the processes and strategies by which construction projects are planned, developed, built, and operated (Bartlett, 2020; Madubuike et al., 2022). Digital twins are now being used more frequently in the construction sector to improve project outcomes, optimise resource utilisation, and reduce environmental consequences (Bartlett, 2020). Digital twins integrate advanced sensors, data analytics, and simulation technologies, allowing stakeholders to visualise, analyse, and optimise many elements of building projects, from design and planning to operation and maintenance phases. There is already significant research that has demonstrated the benefits of digital twins in construction (Bartlett, 2020; Madubuike et al., 2022; Su et al., 2023), but there is less research on the benefits of adopting and integrating digital twins in sustainable construction. Further, research on the benefits of digital twins in construction is fragmented and based on a literature review. However, there is the potential for a clear understanding of the positive impact of technology in the delivery of sustainable construction projects. It is argued that the benefits of digital twin in conventional construction projects may not be applicable to sustainable construction projects because the requirements of sustainable construction are different from the requirements of traditional construction (Olanrewaju, 2022). Against this backdrop, this study seeks to investigate the benefits of adopting digital twins in the delivery of sustainable construction projects. The article stressed the place of digital twins in the procurement of sustainable construction projects and particularly the impact of digital twins on productivity, performance, communication, engagement, and efficiencies.

2. BACKGROUND AND THEORETICAL FRAMEWORK

The construction sector, which has a long history of conservatism, is one of the least mechanised and digitalised, with data retained on paper documents. However, as the construction sector's unpredictability and challenges increase, construction companies are turning to digital construction to promote productivity, collaboration, and competitiveness. Contractors, architects, engineers, and suppliers are increasingly interacting and collaborating digitally, from video-calling site meetings to digital order fulfilment (Bartlett, 2020). Demand for digital collaboration, wearables, BIM 3D printing, artificial intelligence, and modular building has increased dramatically (Obando, 2021). A survey predicted that the need for construction technologies would rise by more than 70%, and more than 60% of respondents stated they had hired new employees specifically to focus on new technologies (Brown, 2022). According to a recent survey, digital construction is used for a variety of purposes, including increasing productivity (77%), reducing risk/safety improvement (73%), saving money (67%), addressing skill shortages (51%), gaining confidence in project delivery time (37%), and shortening project duration (32%). Construction technologies are defined as those that have a particular use in the construction sector. There are several construction-oriented tools, software, and technologies available to help reduce or eliminate process-related difficulties and improve project delivery, performance, and profit margins (Azhar, 2017; Bartlett, 2020). Construction companies face intense pressure to increase productivity, profit margins, client satisfaction, and risk reduction through greater collaboration and communication, which is possible with construction technologies (Gambatese & Hallowell, 2011). Bartlett (2020) presented the construction technologies industry map that provides connectivity among the technologies. Digital twin is one of the prominent technologies whose application and adoption are gaining popularity. Similarly, Olanrewaju et al. (2024) develop a framework for the relationship among the latest construction technologies. The relationship or connectivity is important because it represents the relationship of data, processes, activities, and workflow among projects and organisations. Companies used construction technologies to reduce unnecessary procedures and activities, as well as low productivity caused by a lack of collaboration, communication, repetitive duties, and trust. Construction technologies include a diverse set of equipment, procedures, and materials used in planning, designing, constructing, and operating structures and infrastructure. Building information modelling, 3D printing, robotics and automation, augmented and virtual reality, drones, the Internet of Things, and digital twins are some of the most prominent construction technologies. Construction digital twins refer to the fabrication of virtual counterparts of physical structures or infrastructure. These digital representations use real-time data from sensors, IoT devices, and other sources to provide a complete picture of the project's state, performance, and behaviour during its entire lifecycle. Construction digital twins allow stakeholders to visualise, simulate, and analyse different parts of a project, such as design, construction, operation, and maintenance. They help to improve decision-making, collaboration among project teams, and resource utilisation.

A "digital twin" has been defined as a "digital representation of a physical object or system" (Grieves & Vickers, 2016) that can be used to simulate and analyse the behaviours of construction projects in a virtual environment. A digital twin is dynamic, as opposed to a static 3D replica. Even after the construction is finished, it continues to change and update itself as more information is available. A digital twin's real-time project data enables advanced monitoring and management from an operational standpoint, enabling design-centric smart planning and optimised design. The operation of digital twins for a building involves the seamless integration of data, modelling, simulation, monitoring, analysis, and decision support processes to optimise performance, enhance sustainability, and improve the overall operation and management of the building throughout its lifecycle. The mechanism for the operation of digital twins in a building involves several key components and processes. A digital twin can be developed for part of a building, a complete building, or groups of buildings. A digital building can be developed for a city, factories, or land. Construction digital twins are sometimes referred to as data twins, virtual models, or the next generation of built drawings. Construction digital twin can be created using data from design, construction, and operation of construction projects. The application and uses of construction digital twin is extensive, including validation of design, evaluation of constructability and maintenance and operation of the projects. It often created from using data from various sources including, BIM, sensors, survey, drones, laser scanning, mobile mappings. All these data are used to create point clouds, which are crucial parts of the fundamentals of digital twin (Stojanovic et al., 2018; Xue et al., 2020). Figure 1 display the mechanism for the operation of the digital twin technologies for building projects. Several studies have been conducted on the use of construction twins (Hou et al., 2021; Jiang, 2021; Lee and Lee, 2021; Sack et al., 2020; and Zhang et al., 2021). However, despite the potential benefits of digital construction twins, their implementation and adoption in the construction sector remain limited. Unlike a digital model or a simulation, a digital twin is responsive and continues to evolve as more data is provided to the twin. Digital twins are customised to a specific project.

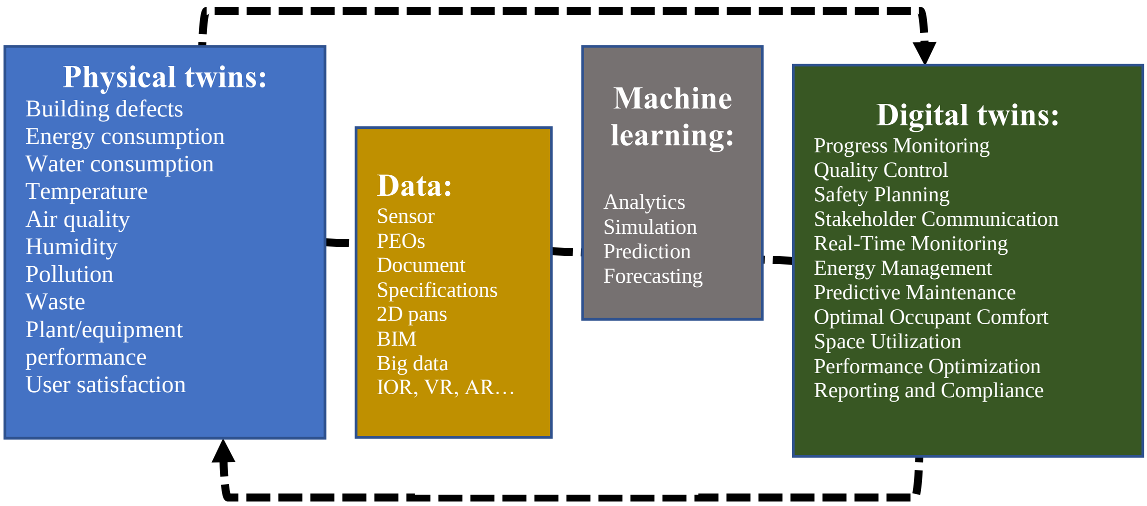

Figure 1: Mechanism for the operation of digital twins for a building

2.1 CONCEPTUAL FRAMEWORK OF DIGITAL TWINS

The conceptual framework of digital twins includes data collection, modelling and simulation, real-time monitoring, analysis, and decision support. Digital twins allow stakeholders to visualise and simulate building designs, evaluate alternative scenarios, and optimise energy efficiency, resource utilisation, and environmental performance beginning with the early stages of project development. During the construction phase, digital twins provide real-time monitoring of construction progress, quality control, and safety compliance, resulting in improved project efficiency, decreased rework, and increased worker safety. The digital twin technologies also enable stakeholders to identify inefficiencies, predict maintenance needs, and optimise building operations to maximise energy efficiency, occupant comfort, and overall sustainability by continuously monitoring and analysing building performance data. Digital twins provide a single platform for stakeholders to interact, share information, and make data-driven decisions on construction projects. By incorporating sustainability requirements into decision-making processes, digital twins enable stakeholders to assess the environmental and social impacts of design and operational choices, identify trade-offs, and make informed decisions that align with sustainability goals.

Despite the growing popularity of digital construction twins, there remains a lack of understanding about the challenges and opportunities associated with this emerging technology. Existing research reveals that a lack of awareness and integration among various construction stakeholders, as well as technological constraints and a skilled workforce shortage, may impede the widespread implementation of digital twins in the construction industry. With specific relevance to the aim of this research, while digital twins have the potential to increase project efficiency, cost savings, safety, and sustainability, there has been little research on the specific benefits and drawbacks of using digital twins in sustainable construction projects. As a result, this study seeks to fill this gap by investigating the benefits of digital twin adoption in sustainable construction projects. Specifically, the impact of the technologies on project efficiency, resource optimisation, and sustainability outcomes across diverse geographical contexts will be explained. By identifying and analysing the global benefits associated with digital twin implementation in sustainable construction, this research seeks to provide valuable insights and recommendations for stakeholders in the construction sector to improve sustainability practices and achieve sustainable development goals.

3. RESEARCH DESIGN

The question that this research aims to address is: what are the advantages of digital twin technology in the procurement of sustainable construction? It is critical to understand the benefits of adopting and applying digital twin technologies to boost construction productivity and profit margins while reducing claims, disputes, and penalties. The original data were collected using convenience sampling. Convenience sampling is a data collection method in which surveys are administered to respondents who are available, accessible, and willing to participate in the survey. The method is appropriate when adequate information on population size and sample frame is unavailable (Sekaran & Bougie, 2016). While its findings may not be generalisable, they can be representative if enough respondents are included. Thus, the key idea is that if enough data are collected while keeping objective, the results will be representative of the population. The survey was conducted online. The survey was conducted from July 2023 to September 2023. Respondents were asked to rate their agreement with each of the benefits of digital twins in the procurement of sustainable construction based on evidence. The levels of agreement were measured on a five-point scale, with 5 denoting extreme benefit and 1 denoting the least benefit. 3 represents a moderate benefit. Two and four were positioned in between. The questionnaire went through two pilot stages of surveys consisting of key stakeholders. An Average Benefit Index (ABI) (Eq. 1) was used to measure the extent to which the technologies provided the listed benefits. The average benefit index was based on the cumulative weighting of the initial frequency scores of each construct.

$$ABI = \frac{\sum_{i=0}^{5} a_i x_i}{5\sum_{i=0}^{5} x_i} \times 100 \qquad \text{(Eq. 1)}$$

Where a_i was the index of a group; constant expressing the weight given to the group; x_i was the frequency of the responses, i = 1, 2, 3, 4, and 5 and described as below: x_1, x_2, x_3, x_4, x_5 were the frequencies of the responses corresponding to $a_1 = 1, a_2 = 2, a_3 = 3, a_4 = 4, a_5 = 5$, respectively. An ABI score of 1.00 - 20.00 denotes the least benefit; 21.00-40.00 defines less benefit; 41.00-60 denotes moderate benefit; 61.00-80 denotes significant benefits; and 81.00-100.00 denotes highly beneficial. There is a 1.0% difference between the scales. The construct associated with the highest ABI score will be the most beneficial. Other statistical tests performed were the one-way t-test, Crunbach alpha reliability tests, convergent validity tests, factor analysis tests, mode tests, and standard deviation tests. IBM SPSS Statistics was used to analyse the data.

4. RESULTS AND DISCUSSION

The survey forms were administered to over 500 stakeholders who filled out the online survey form. However, 36 online responses were received by the deadline, following multiple reminders. However, because the snowballing technique was used, the exact number of forms that were administered is unknown.

4.1 ANALYSING THE RESPONDENTS' PROFILE

According to the findings, almost 90% of respondents have more than five years of work experience, while around 40% have more than ten years (Table 1). Table 2 contains the respondents' locations. Investment in construction technology is modest (see Table 3). The respondents held strategic positions are shown in Figure 2.

Table 1: Your work experience

Year	Less than 5 years	5 years to 10 years	11years - 15 years	16years - 20 years	More than 20 years
Frequency	4	10	8	22.2	8
Percentage	11.1	27.8	22.2	16.7	22.2

Table 2: Respondent's location

Year	Malaysia	Singapore	Nigeria	Pakistan	Other
Frequency	9	6	12	3	6
Percentage	25.0	16.7	33.3	8.3	16.7

Table 3: How much has your company invested in construction digital twins?

Size of investment	Percentage	Cumulative Percentage
Less than 5%	13	40.625
5% to 10%	3	9.375
10% to 15%	5	15.625
15% to 20%	3	9.375
20% to 25%	2	6.25
25% to 30%	2	6.25
35% to 40%	1	3.125
40% to 45%	2	6.25
50 and above	1	3.125

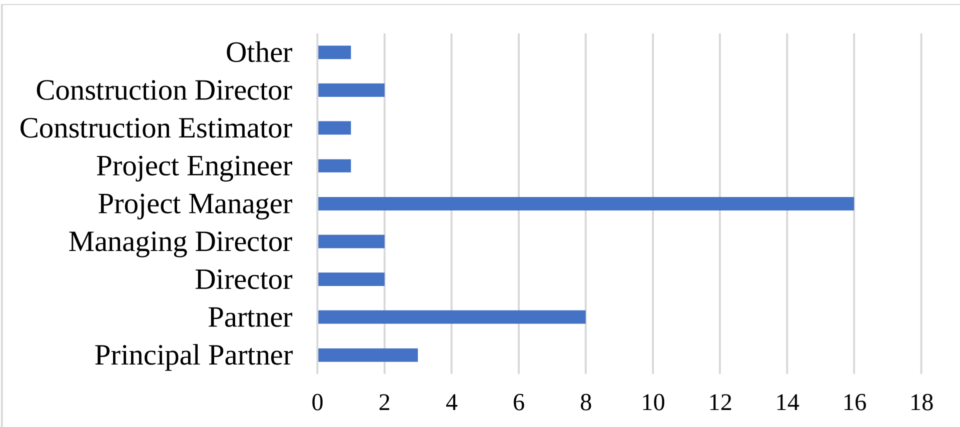

Figure 2: Respondent position in their organisation

4.2 RESULTS OF THE BENEFITS OF DIGITAL TWIN IN SUSTAINABLE CONSTRUCTION

The goodness of fit of the benefits was performed through reliability and validity analyses. Both the Spearman-Brown Coefficient and the Guttman Split-Half Coefficient have high values (0.987 for both), indicating very high reliability for the overall survey instrument (Table 4). This suggests that the survey instrument consistently measures the constructs of interest and produces reliable results, both when the instrument is split into halves and when it is treated as a single entity. The construct validity of the data ranges from 0.72 to 0.93. These results provide strong evidence for the reliability and validity of the survey instrument, indicating that it effectively measures the constructs of interest and produces consistent and dependable results. The data revealed that about 20% of the respondents measured that digital twins have the least or less benefits to sustainable projects (Table 5). While 27% of respondents agreed that digital twins have moderate benefits, evidently more than 50% of the respondents measured that the technologies have high or extreme benefits in the procurement of sustainable construction and for the performance of sustainable construction projects.

Table 4: Guttman split-half coefficient

Cronbach's Alpha	Part 1	Value	0.978
		N of Items	9a
	Part 2	Value	0.982
		N of Items	8b
	Total N of Items		17
Correlation Between Forms			0.975
Spearman-Brown Coefficient	Equal Length		0.987
	Unequal Length		0.987
Guttman Split-Half Coefficient			0.985

a. The items are reduced cost, Increased innovation/better ideas, Able to launch products/services more quickly, Able to scale the business more easily/faster, Reduced paper-based process, Improved efficiency, more satisfied customers, Easier to plan and make better business decisions, more engaged and motivated staff.

b. The items are: More engaged and motivated staff, better reputation, reduces project risk, Higher valuation, Collaboration among partners, gaining an edge on the teams, making faster internal decisions, Improved communication, Improves trust among project team.

Table 5: Descriptive statistics of benefits of digital twin technologies

Benefit	Least beneficial	Less beneficial	Moderate beneficial	Strong beneficial	Extreme beneficial	Std. Deviation	ABI
Making faster internal decisions	3	4	6	18	5	22.69	70.00
Easier to plan and make better business decisions	4	3	6	17	5	23.67	69.14
Improved communication	4	3	6	19	4	23.16	68.89
Improved efficiency	4	3	7	16	5	23.62	68.57
More engaged and motivated staff	3	4	10	13	5	22.41	67.43
Increased innovation /better ideas	5	2	10	13	6	24.97	67.22
Reduced paper-based process	4	4	8	15	5	23.98	67.22
Better reputation	2	6	9	15	4	21.95	67.22
Improved trust among project team	5	2	11	11	7	25.45	67.22
Able to launch products/services more quickly	3	4	11	13	4	22.41	66.29
Reduce project risk	3	5	11	12	5	23.47	66.11
Higher valuation	3	5	11	13	4	22.85	65.56
Collaboration among partners	4	4	12	10	6	24.77	65.56
More satisfied customers	3	5	13	10	5	22.44	65.00
Able to scale the business more easily /faster	5	2	12	14	3	23.50	64.44
Reduced project cost	3	7	11	10	5	23.85	63.89
Gaining an edge on the teams	5	3	12	12	4	24.36	63.89

5. DISCUSSION OF THE BENEFITS OF DIGITAL TWIN

These results highlight the multifaceted benefits of digital twin technologies in sustainable construction projects, ranging from improved decision-making and communication to enhanced efficiency, innovation, and staff engagement. The consistent recognition of these benefits underscores the transformative potential of digital twins in driving positive outcomes and advancing sustainability goals within the construction sector. It is interesting that making faster internal decisions is the highest benefit of the digital twin technologies in sustainable construction. It is understandable that stakeholders' value faster internal choices enabled by digital twin technologies. The ability to expedite decision-making processes can significantly impact project success and overall organisational performance. Faster decision-making directly improves operational efficiency by decreasing delays and bottlenecks in project execution. Digital twin technologies offer real-time data and insights, allowing project stakeholders to make data-driven decisions quickly. Organisations that can make quick judgements are better positioned to seize new opportunities and respond quickly to market developments.

Timely decisions help to optimise resource allocation, ensuring that personnel, materials, and equipment are used properly. This optimisation can result in cost savings and better project outcomes.

Similarly, the data revealed that implementing digital twins in sustainable construction will make it easier to plan and make better business decisions. Digital twin technologies provide a significant advantage in sustainable construction projects by allowing for more effective planning and better commercial decisions. Digital twins enable real-time access to detailed and accurate data on numerous areas of a construction project, such as design, construction progress, resource utilisation, and environmental conditions. It also enables stakeholders to see the complete project lifecycle in a virtual environment. This visualisation capacity allows them to model multiple situations, assess the possible impact of different actions, and identify the best solutions prior to implementation. By viewing the effects of their actions in a simulated environment, stakeholders can make more informed decisions that correspond with project objectives and stakeholders' value systems for the projects.

It is not surprising that improved communication emerges as a critical advantage facilitated by digital twin technologies for sustainable construction. Improved communication enabled by digital twin technology will boost collaboration, transparency, and efficiency in sustainable construction projects. Digital twins act as central repositories for project data, documentation, and communication channels (Madubuike et al., 2022). This centralisation guarantees that all project stakeholders have access to current information, promoting transparency and alignment within the project team. Digital twins enable project stakeholders to share data and insights in real time, regardless of location or time zone. This real-time communication lowers delays, which are common for sustainable construction, and allows for fast decision-making, therefore improving overall project efficiency and responsiveness (Olanrewaju, 2022). Improved communication plays a pivotal role in enhancing project efficiency and productivity by facilitating timely decision-making, reducing rework, fostering collaboration, optimising resource allocation, mitigating risks, engaging stakeholders, and supporting continuous improvement efforts. As a fundamental aspect of sustainable construction project management, effective communication ensures that projects are delivered on time, within budget, and to the satisfaction of all stakeholders involved.

The data also revealed that improved efficiency has a strong rating. This is intuitive because a digital twin can help improve efficiency. Digital twins contribute to the project's overall sustainability by finding inefficiencies and optimising resource allocation, thereby reducing waste and environmental effects. It improves construction workflows and processes by providing a single platform for project management and coordination. The increased efficiency enabled by digital twins in construction projects is critical to ensuring sustainability because it optimises resource management, streamlines workflows, improves decision-making, reduces downtime and rework, promotes collaborative project management, and allows continuous performance tracking and optimisation. In addition, the data revealed that digital twins can help engage and motivate staff. For instance, the use of digital twin technologies in sustainable construction projects can significantly increase employee engagement and motivation by improving communication, facilitating collaboration and input, providing recognition and feedback mechanisms, supporting professional development, and aligning with sustainability goals. By exploiting these benefits, project teams may foster a good and motivating work environment that inspires employees to give their all and achieve project success. The technologies offer a platform for better collaboration and transparency in construction projects and provide team members with real-time information by centralising project data, status updates, and communication channels. This transparency helps to build trust and engagement among employees, who feel more informed and involved in project decisions. Also, because the staff members can access full project information using digital twins, the accessibility empowers employees by providing them with the necessary knowledge and resources to contribute effectively to the project. Employees who feel empowered and equipped with the necessary information are more likely to be engaged and driven to work at their best.

The data also revealed that digital twins also help to increase innovation and generate better ideas, suggesting that digital twins are catalysts for fostering innovation and generating better ideas within construction projects. To explain the visualisation tool that the digital twin enables, it fosters creativity and innovation by allowing users to experiment with new ideas and approaches to design and construction by comparing multiple scenarios on a project. In addition, the digital twins allow stakeholders to make educated decisions and identify opportunities for innovation and improvement within the project by providing them with access to extensive data and analytics.

Digital twins also help to promote environmental sustainability by reducing paper consumption and the associated environmental implications such as deforestation, energy consumption, and greenhouse gas emissions. This is consistent with the overall goals of sustainable construction, which are to reduce resource use and prevent environmental degradation. Digitalising paper-based operations lowers the expenses of printing, storing, and managing physical records. Unlike traditional construction, a lot of information and documents are involved in sustainable construction. However, digital twins can help because they save money and time by streamlining document management and automating operations. The use of digital twins in sustainable construction projects reduces paper-based processes, which not only improves environmental sustainability but also saves money, increases accessibility and transparency, improves data integrity and security, streamlines workflows and compliance, and allows for future growth.

6. CONCLUSIONS

This research presents the preliminary results of research on the implementations, constraints, benefits, and shortcomings of construction technologies in Malaysia. The findings underscore the transformative potential of digital twins in advancing sustainability, efficiency, and innovation in construction projects. By leveraging digital twin technologies strategically and collaboratively, stakeholders can drive positive outcomes, improve project performance, and contribute to the advancement of sustainable construction practices. The results demonstrate that digital twin technologies offer a wide range of benefits for sustainable construction project. These benefits span various aspects of project management and operations, indicating the significant potential of digital twins to drive efficiency, innovation, and success in construction projects. The benefits identified in the study address the needs and priorities of diverse stakeholders involved in sustainable construction projects. Digital twins add value across the project lifecycle, catering to the needs of owners, contractors, designers, and other stakeholders. Certain benefits, such as better productivity, less project risk, and faster decision-making, emerge as particularly strategic advantages of digital twin adoption. These benefits not only contribute to project success but also align with broader organisational goals, such as achieving sustainability targets, maintaining competitive advantage, and maximising return on investment. While the study identifies several benefits of digital twins, there is also room for further exploration and optimisation. As technology continues to evolve and construction practices evolve, there may be opportunities to enhance the performance and capabilities of digital twin systems, unlocking additional value and benefits for sustainable construction projects. To fully advance the benefits of digital twins, stakeholders must carefully consider various factors, such as data quality, interoperability, cybersecurity, and organisational readiness. Effective implementation strategies, robust governance frameworks, and stakeholder engagement are essential for maximising the value of digital twins while mitigating potential challenges and risks. Furthermore, while the respondents held strategic positions and had cognisance work experience, the sample size was small. Therefore, future research should be conducted with a larger sample size.

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