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PRIORITISING DIGITAL TWIN APPLICATIONS ACROSS CONSTRUCTION PROJECT LIFECYCLE PHASES: EVIDENCE FROM NIGERIA

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ABSTRACT

The adoption of emerging technologies such as Digital Twin (DT) in the Nigerian construction industry has been constrained by limited technical capacity and inadequate contextual understanding. Although prior studies have examined DT applications and benefits in developing economies, a systematic classification and prioritisation of its applications across a construction project lifecycle remains insufficiently explored within the Nigerian context. The study aims to identify, prioritise, and categorise DT applications throughout the project lifecycle. A quantitative research design was adopted, employing a purposive sampling technique to draw on data from 109 construction professionals, including project managers, architects, civil engineers, and consultants, collected through a web-based survey. Descriptive statistics and principal component analysis (PCA) were employed to examine the underlying structure of DT applications. The analysis identified two principal components: Virtual Prototyping and Operations Management, which together explain 68.99% of the total variance and underpin enhanced decision-making and improved project performance. These components enabled the study to determine which DT applications hold the strongest practical relevance across the pre-construction, construction, and post-construction phases of the Nigerian construction industry. Future research should consider to implement and test DT in a longitudinal way based on several case studies from different countries to get more in-depth insights in the applicability of DT in developing economies.

Keywords: Building information modelling (BIM), Construction project lifecycle, Digital twin, Nigeria, Principal component analysis, Virtual prototyping

1 INTRODUCTION

The construction industry accounts for approximately 13% of global gross domestic product (GDP), equivalent to expenditure on construction-related goods and services valued at over US\$70 trillion (Su et al., 2023). Despite its economic relevance, the industry continues to face persistent productivity challenges, project delays, cost overruns, and coordination inefficiencies. In response, organisations have increasingly adopted cutting-edge technologies, including the Internet of Things (IoT), Building Information Modelling (BIM), Machine Learning (ML), Artificial Intelligence (AI), and augmented and virtual reality, to enhance project delivery performance (Opoku et al., 2022). Notwithstanding these technological advancements, construction projects remain susceptible to design inconsistencies, constructability errors, coordination failures, and late design modifications (Lucchi, 2023). These challenges are intensified by fragmented communication structures, limited real-time data integration, and inadequate monitoring systems. As industry pressures intensify due to labour shortages and increasing performance expectations, construction organisations require comprehensive, real-time, and data-driven decision-support mechanisms (Ammar et al., 2022).

In the Nigerian construction context, project delays, cost overruns, and quality deficiencies remain prevalent, often attributable to material wastage, limited monitoring capacity, and reliance on traditional inspection methods (Mahamid, 2024). Conventional monitoring approaches, characterised by manual supervision and periodic reporting, frequently result in delayed identification of defects and inefficiencies. Although BIM has been increasingly positioned as a transformative solution, its functionality is primarily model-based and dependent on manual data updates, thereby limiting its real-time responsiveness (Deng et al., 2021).

Digital Twin (DT) technology has emerged as a more dynamic alternative, enabling the integration of physical assets with real-time digital representations to support monitoring, simulation, and lifecycle management. By facilitating continuous data exchange between physical and virtual environments, DT enhances predictive analysis, operational optimisation, and integrated project delivery processes. However, within the Nigerian construction industry, the scope, significance, and prioritisation of DT applications remain insufficiently examined. Existing studies suggest that limited technical familiarity and low adoption maturity constrain effective implementation (Oke et al., 2024). While developed economies such as the United Kingdom, Australia, Italy, and the United States have advanced DT utilisation to improve project performance (Arowoia et al., 2024), empirical evidence concerning structured application patterns in Nigeria remains limited. Although certain enabling technologies, such as 3D modelling tools, sensor networks, GPS, ultra-wideband systems, and IoT infrastructures, are present within the industry (Oke et al., 2024), their integration into comprehensive DT strategies appears fragmented.

Three key gaps exist within the current body of knowledge that this research aims to address. First, whilst a global catalogue of individual DT applications exist, there is a lack of empirical research that have attempted to prioritize DT applications throughout the three phases of a construction project within a single study conducted within the Nigerian context utilizing a multitude of statistical analysis. Secondly, existing empirical studies on the adoption of DT within Nigeria (Oke et al., 2024; Arowoia et al., 2024) investigated into the driving forces and barriers to its adoption rather than structurally categorizing DT applications and prioritising them where necessary. Finally, the key contribution of this study lies in its context, as it provides empirical evidence of the application and prioritization of DT within Nigeria, a region and subject that is currently under-represented within the global literature serving the developing economies, in addition to the methodological contribution of applying PCA to uncover the latent structural dimensions of clusters of DT applications, a statistical method that has not been utilized previously for prioritising DT applications within the given context.

Given this context, systematic identification and prioritisation of DT applications across the construction project lifecycle is required to inform strategic implementation. Accordingly, this study seeks to identify, prioritise, and categorise Digital Twin applications within the Nigerian construction industry using empirical evidence derived from industry professionals. The leading variables in each component indicate the key determinants of DT applications in practice and were used to suggest practical implementation guidance for industry stakeholders in the Nigerian construction industry.

2 LITERATURE REVIEW

A systematic literature review was conducted on Digital Twin applications in preconstruction, construction, and post-construction phases (see Figure 1) (Visartsakul and Damrianant, 2023). However, despite its recognised potential, a structured classification of DT applications across construction project phases remains limited.

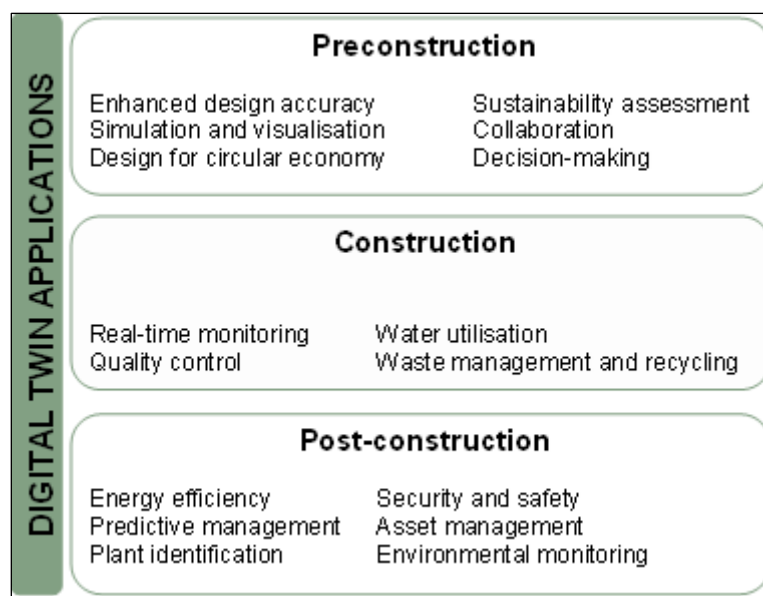


Figure 1: Digital Twin applications across construction project phases (Adu-Amankwa et al., 2023)

This lifecycle perspective provides a structured lens for analysing its functional deployment across project delivery stages.

2.1 Preconstruction phase

Studies on integrating DT for preconstruction activities focused on planning and design, decision-making, tendering evaluation, sustainability assessment, and environmental monitoring (Abou-Ibrahim et al., 2022). DT has the potential to help collect data, make efficient designs and allocate resources as part of the preconstruction process. Digital Twin can simulate different scenarios, such as traffic flow and building performance; allowing designers to optimise the design and ensure the desired performance standards are met (Yan et al., 2025). By creating a virtual model, designers can test and refine the design before it is built. This allows for more efficient and effective design iterations, reducing the risk of errors and rework. Urban-scale DT implementations demonstrate the value of simulation during early planning stages. For example, the urban digital twin developed for the city of Herrenberg enables the simulation of traffic flows and environmental performance to improve collaboration among planners and other smart city stakeholders (Dembski et al., 2020). Such prototypes provide a shared digital environment where planning alternatives can be assessed before physical implementation.

Digital Twin supports the decision-making process by providing new opportunities for value co-creation in both manufacturing and non-manufacturing sectors (West et al., 2021). DT also enhances collaborative design environments by enabling shared digital platforms accessible to architects, engineers, contractors, and operators (Omrany et al., 2023; Nnadi, 2025). This improved collaboration reduces the risk of miscommunication and ensures all stakeholders are aligned on the design. Real-time data integration and visualisation capabilities of Digital Twin enable stakeholders to make informed decisions and coordinate efforts across construction project lifecycle phases. Sustainability-oriented applications are increasingly prominent. DT supports lifecycle material tracking, carbon footprint analysis, and circular economy strategies (Mohandes et al., 2024). Empirical evidence demonstrates measurable environmental benefits; for instance, energy performance modelling in the Malaysian city of Bertam achieved an estimated 8.6% carbon reduction benchmark through DT-enabled simulation (Tahmasebinia et al., 2023).

At broader geographic scales, national digital twin initiatives further illustrate the planning and governance potential of this technology. Estonia's national 3D digital modelling programme (Invest in Estonia, 2019) and Luxembourg's geoportal platform (The National Geoportal of the Grand Duchy of Luxembourg) provide large-scale digital representations of national infrastructure and geographic information systems, enabling improved planning coordination and asset governance. Collectively, preconstruction applications emphasise predictive modelling, collaborative planning, and sustainability optimisation.

2.2 Construction phase

The construction phase is the most resource-intensive stage of the project lifecycle (Mohandes et al., 2024), making DT applications particularly valuable for monitoring, safety, scheduling, and quality control. Reality-capture and sensor-based systems enable real-time progress tracking and comparisons between planned and actual performance, improving transparency and supporting timely corrective actions (Talmaki and Kamat, 2022; Alizadehsalehi and

Yitmen, 2023). DT enhances quality assurance through geometric verification and completeness checks, reducing defects and rework (Piras et al., 2024). DT-supported scheduling further strengthens cost and time forecasting.

Safety-related applications incorporate environmental and behavioural sensors to detect hazards, predict risks, and issue real-time alerts, shifting site safety practices toward proactive prevention (Bevilacqua et al., 2020; Khajavi et al., 2023). DT-based safety platforms also extract actionable data to support safety protocols (Khajavi et al., 2023), while continuous sensory feeds improve hazard identification and worker notification (Bevilacqua et al., 2020). Additional applications include DT-supported inspection frameworks (Adu-Amankwa et al., 2023) and environmental sensing models that provide managers with real-time insights into work performance and building conditions (Wang et al., 2024). DT further assists in monitoring water consumption during construction and operation (Ammar et al., 2022). Overall, DT enhances the construction phase through real-time visibility, predictive control, and improved operational efficiency.

2.3 Post-construction phase

The post-construction phase encompasses real-time interactions, predictability, and enhanced decision-making during operations and maintenance activities, as well as, facility and asset management (Visartsakul and Damrianant, 2023). Unlike earlier lifecycle stages that emphasise design and execution, post-construction applications focus on sustaining operational efficiency and extending asset lifespan. Safety management also becomes a key priority in this phase. By integrating data from sensors, security cameras, and other security devices, DT provides a platform for continuous monitoring and enables the simulation of emergency scenarios, thereby improving the safety of building occupants in the vicinity (Khajavi et al., 2023).

In building asset management, DT integrates continuous sensor data to monitor structural performance, energy consumption, environmental conditions, and system efficiency throughout the asset lifecycle (Ammar et al., 2022). Applications include fault detection and the prediction of building component conditions. The DT model continuously processes information collected from HVAC systems, lighting fixtures, indoor sensors, pumps, and other devices to provide an accurate and up-to-date representation of its physical counterpart, thereby supporting energy efficiency and sustainability (Khan, 2020). For example, vibration frequencies in pumping systems can be monitored for early error detection (Mohandes et al., 2024).

Real-world infrastructure demonstrates the practical value of DT-enabled monitoring during operational phases. For instance, the San Francisco–Oakland Bay Bridge integrates sensor-enabled monitoring systems that continuously track structural performance and support resilience management, helping authorities maintain safety and operational reliability (Wang et al., 2024). At the infrastructure scale, DT applications extend to transport systems and utilities management. Digital representations of traffic systems supported by the Internet of Vehicles (IoV) enable simulation-based maintenance planning and congestion analysis (Najafi et al., 2024). In water distribution networks and smart-city systems, DT supports resource regulation, usage optimisation, and environmental monitoring (Botín-Sanabria et al., 2022).

3 METHODOLOGY

3.1 Research design

This study adopted a quantitative research design to identify, prioritise, and categorise Digital Twin (DT) applications across the construction project lifecycle in Nigeria. A structured questionnaire survey comprises 19 Likert-scale items representing DT applications were employed as the primary data collection instrument, consistent with established quantitative research protocols. The questionnaire was developed following an extensive review of relevant literature and validated through supervisory review to ensure content adequacy and alignment with the study objectives. Descriptive analysis was applied to obtain primary data, explore variables, and rank responses to determine which DT applications deliver the highest value at each project phase (Farrow et al., 2020), while Principal Component Analysis (PCA) was employed to reduce the identified variables into dual-factor components demonstrating the structural dimensions of DT applications in practice. The leading variables (factor loadings ≥ 0.7) in each component indicate the key determinants of DT success. These results were used to recommend which DT applications hold the strongest practical relevance across pre-construction, construction, and post-construction phases in the Nigerian construction industry.

3.2 Selection criteria

3.2.1 Inclusion Criteria

- Research conducted in Abuja, the capital city of Nigeria.

- Studies focused on the region with a high concentration of construction activities.
- Papers addressing Digital Twin application in construction.
- Research papers published in English.
- Peer-reviewed journal articles published between **2017** till date.
- Empirical research, case studies, and theoretical frameworks.

3.2.2 Exclusion Criteria

- Regions with limited or no construction technology sophistication.
- Non-peer reviewed publications.
- Papers focusing on manual method of construction monitoring.
- Studies produced before 2017.
- Duplicate publications.

3.3 Selection Process

The target population consisted of 500 organisations, comprising 215 contracting firms registered with the Federation of Construction Industry (FOCI), 192 consulting firms registered with the Council for the Regulation of Engineering in Nigeria (COREN), and 93 architectural firms registered with the Architect Registration Council of Nigeria (ARCON). A purposive sampling technique was employed to select 200 firms for participation (Kothari, 2019). In total, 109 valid responses were obtained, resulting in a 54.5% response rate, which is considered acceptable for survey-based research.

3.4 Data collection

The results obtained were used to make necessary amendments and to check for clarity and proper wording of the items before the questionnaires were administered to all the participants of this research. It consists of two sections: the first section gathers demographic information of the respondents, such as gender, age group, experience, professional affiliation, educational status, organisational position, company size, and the nature of the projects undertaken. The second section focused on evaluating the importance of Digital Twin applications (19 variables) throughout the construction project lifecycle. Respondents were requested to indicate their level of agreement with the statements on a five-point Likert scale, where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

The applications were scrutinously extracted from the synthesis of previous studies on DT applications (Mohandes et al., 2024). The collected data shows the perceived importance of DT applications throughout the construction project lifecycle, providing an empirical basis for diagnosing prevailing underutilisation within the industry. The data were screened for completeness and consistency prior to statistical analysis.

3.5 Data analysis method

The statistical analysis was performed in SPSS version 22. Cronbach alpha measured the internal consistency of the collected data, and it is numerically treated between 0 and 1 (Ahmad et al., 2024). Descriptive statistics, including frequency, percentage, standard deviation (SD), and mean item score were used to rank data, with lesser SD values indicating a greater consensus among respondents relative to the particular variable. To substantiate the results, factor analysis (PCA) was conducted to categorise the Digital Twin applications across the construction project lifecycle. In this study, the PCA effectively revealed the latent factor structure and reduced the original set of 19 application variables into a smaller number of meaningful components (Shrestha, 2021).

4 RESULTS AND DISCUSSION

4.1 Demographic of respondents

A total of 109 respondents participated in the study, representing a professionally relevant sample for evaluating Digital Twin applications across the construction project lifecycle. The majority of participants were civil engineers (67.7%), followed by project managers (14.7%) and architects (11.9%), indicating strong representation from core professions directly involved in planning, design, and project execution. The respondents also possessed substantial industry exposure, with most reporting more than two years of work experience, including 38.5% with 2–5 years and 22.9% with 5–10 years of experience, ensuring informed and practice-based insights. Educational attainment was generally high, as 66.1% held a Bachelor's degree, while a further 22.1% had postgraduate qualifications (Master's or Doctorate). The sample reflected involvement in a range of project types, predominantly residential (49.5%) and commercial buildings (22.0%), with additional representation from industrial, highway, and hydraulic infrastructure projects. In terms of exposure to Digital Twin concepts, 48.6% of respondents reported being somewhat familiar and 19.3% very familiar with the technology, indicating that the majority possessed at least a functional understanding necessary to contribute meaningfully to the study's validation process.

Table 1: Respondents' profile

Demographic	Characteristics	Frequency (n=109)	%
Position	Architect	13	11.9
	Civil engineer	74	67.7
	Consultant	3	2.8
	Project manager	16	14.7
	Intern	3	2.8
Work experience (years)	<1	7	6.4
	1-2	20	18.3
	2-5	42	38.5
	5-10	25	22.9
	10-20	10	9.2
	20-30	4	3.7
	>30	1	0.9
Education (NQF level in brackets)	Undergraduate	9	8.3
	Diploma	4	3.7
	Bachelor's Degree	72	66.1
	Master's	21	19.3
	Doctorate	3	2.8
Nature of projects	Residential Building	54	49.5
	Commercial Building	24	22.0
	Industrial Building	10	9.2
	Recreational Building	2	1.8
	Highway	15	13.8
	Hydraulic Structures	3	2.8
Level of acquaintance with Digital Twin	Not Familiar	35	32.1
	Somewhat Familiar	53	48.6
	Very Familiar	21	19.3

4.2 Descriptive analysis

Table 2 summarises respondents' ratings of 19 Digital Twin (DT) applications across the construction project lifecycle. An overall composite mean score of 3.72 indicates that these applications are generally considered important by the respondents. The highest-rated item, rendering of real site into a digital model (MS = 4.01), was the only application to exceed the 'very important' threshold, highlighting the foundational role of accurate digital-physical integration (interaction between the physical site and the virtual model) in DT technology.

Two additional applications were also rated highly: provision of advanced project models (MS = 3.93) and data collection on existing building performance (MS = 3.92). These reinforce the importance of sophisticated modelling and data-centric capabilities within DT systems. Several other applications also achieved strong mean scores, including real-time construction site monitoring (MS = 3.88), resource management (MS = 3.85), and fault detection in building components (MS = 3.82). Functions such as improved measurement outcomes, HVAC energy simulations, cost reduction, and weather-condition simulations (MS = 3.75–3.80) similarly fall within the "important" category.

Table 2: Ranking of Digital Twin applications

Code	DT Application Cronbach Alpha = 0.968	SD	MS	Rank
AP1	Rendering of real site into a digital model	1.014	4.01	1
AP2	Provision of advanced project models	0.930	3.93	2
AP3	Data collection on the performance of existing building	0.954	3.92	3
AP4	Real-time monitoring of construction site	1.034	3.88	4
AP5	Resource management throughout project's life cycle	0.941	3.85	5
AP6	Detection of faults in building components	1.038	3.82	6
AP7	Improved measurement outcomes	0.998	3.80	7
AP8	Energy simulations for HVAC systems	1.031	3.78	8
AP9	Reduction of construction costs	0.959	3.77	9
AP10	Simulation of effect of weather condition	0.925	3.75	10
AP11	Performance prediction of building materials	1.091	3.71	11
AP12	Effective communication among project stakeholders	0.982	3.67	12
AP13	Monitoring of power consumption	1.057	3.65	13
AP14	Enhanced workforce safety on site	0.979	3.62	14
AP15	Monitoring of building settlement	1.009	3.61	15
AP16	Diagnosis of error in pump system	1.092	3.56	16
AP17	Reduction in carbon footprint	1.015	3.52	17
AP18	Waste management during construction	1.068	3.50	18
AP19	Regulation of household water consumption	0.990	3.24	19
	Composite score		3.72	

4.3 Principal Component Analysis

Principal Component Analysis (PCA) was employed in this study to reduce the dimensionality of the dataset by transforming the original 19 observed variables into two latent components that account for a substantial proportion of the variance. As shown in Table 3, the Kaiser–Meyer–Olkin (KMO) Measure of Sampling Adequacy yielded a value of 0.936, which is well above the recommended minimum threshold of 0.50, indicating that the data were suitable for factor analysis. The Bartlett's Test of Sphericity was highly significant ($\chi^2 = 1825.397$, $df = 171$, $p < 0.001$), confirming that sufficient correlations existed among the variables to justify the use of PCA.

Table 3: KMO and Bartlett's test of DT applications.

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		.936
Bartlett's Test of Sphericity	Approx. Chi-Square	1825.397
	df	171
	Sig.	0.000

Table 4 indicates that, after rotation, two components with eigenvalues greater than 1.0 were retained, representing meaningful underlying dimensions of Digital Twin (DT) applications. Component 1 (Virtual Prototyping) accounts for 61.86% of the total variance, while Component 2 (Operations Management) explains an additional 7.14%. Collectively, these two components explain approximately 68.99% of the cumulative variance, demonstrating a strong and coherent

factor structure. The extracted components were analysed by examining the inherent relationships among variables within each factor.

Table 4: Summary of High-Loading DT Applications by Component

Code	DT applications	Components	
		1 Virtual prototyping	2 Operations management
AP1	Rendering of real site into a digital model	0.857	
AP2	Provision of advanced project models	0.827	
AP11	Performance prediction of building materials.	0.813	
AP7	Improved measurement outcomes	0.770	
AP9	Reduction of construction costs	0.763	
AP6	Detection of faults in building components	0.716	
AP3	Data collection on the performance of existing building	0.660	
AP5	Resource management throughout project's lifecycle	0.654	
AP17	Reduction in carbon footprint	0.583	
AP19	Regulation of household water consumption		0.788
AP14	Enhanced workforce safety on site		0.782
AP16	Diagnosis of error in pump system		0.774
AP15	Monitoring of building settlement		0.713
AP10	Simulation of effect of weather condition		0.685
AP18	Waste management during construction		0.669
AP8	Energy simulations for HVAC systems		0.666
AP4	Real-time monitoring of construction site		0.662
AP13	Monitoring of power consumption		0.623
AP12	Effective communication among project stakeholders		0.615
	Eigenvalue	11.753	1.356
	Proportion of variance (%)	61.857	7.136
	Cumulative variance (%)	61.857	68.993
	Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalisation. Rotation converged in 3 iterations.		

4.3.1 Component 1: Virtual prototyping

Component 1 consists of nine variables and accounts for 61.8% of the total variance, with an eigenvalue of 11.753. Variables in this component reflects the simulation-driven and modelling capabilities of DT, particularly during planning and design phases of construction projects. The strong loadings of 'rendering of real site into a digital model' and 'provision of advanced project models' highlight the importance of visualisation and digital representation in supporting project planning and analysis within the Nigerian construction context, as noted by Piras et al. (2024). The presence of variables related to cost reduction and improved measurement accuracy suggests that respondents perceive digital technologies primarily as decision-support and optimisation tools. Through virtual testing and scenario simulation, digital models can reduce reliance on physical prototyping and minimise rework, thereby improving cost efficiency and productivity (Adu-Amankwa et al., 2023). These findings are consistent with prior conceptualisations of Digital Twin as a dynamic digital replica capable of simulating system performance and predicting behaviour across the project lifecycle, as discussed by Michael Grieves (2022) and Piras et al. (2024).

The dominance of the first component (61.8% variance explained) suggests that a large proportion of the variables share a common underlying dimension related to virtual prototyping. This may also reflect the current stage of adoption of digital technology in the construction sector, where modelling and simulation applications are more widely recognised than operational lifecycle monitoring capabilities.

Component 1: Virtual Prototyping is aligned to the pre-construction lifecycle phase where the greatest value of Digital Twist (DT); linked design models, constructability checks and cost optimisation simulations are delivered. The existence of applications such as AP1 – Rendering of real site into digital model and AP6 – Detection of faults in building components indicates that the Component extends into the construction phase where progress monitoring and the comparison of the as-built situation with the digital plan can be facilitated. Thus, Component 1 is associated with design and construction, the early and mid-phases of the Nigerian construction project lifecycle, and constitutes the fundamental layer of implementation of DT.

4.3.2 Component 2: Operations management

Component 2 comprises ten variables, explaining 7.1% of the total variance, with an eigenvalue of 1.356. These variables reflect the operational, maintenance, and performance-monitoring applications of DT technology during both construction and post-construction phases. The presence of variables related to real-time monitoring, safety management, and energy simulation illustrates the role of integrated sensors, data collection, and analytics in supporting operational decision-making. Although this component explains a smaller proportion of the total variance, it nevertheless represents an important operational dimension of digital technology implementation within construction projects. Previous studies suggest that technologies such as Internet of Things and digital monitoring systems enable improved facility management, predictive maintenance, and sustainable operational practices (Ammar et al., 2022). The clustering of variables related to safety management, energy monitoring, water regulation, and fault detection further indicates that respondents recognise the potential of Digital Twin technologies to support sustainable building operations and facility management, as highlighted in previous research (Botín-Sanabria et al., 2022; Bevilacqua et al., 2020).

4.4 Limitations of the study

This study is subject to certain limitations. First, the sample size of 109 respondents may constrain the statistical power and generalisability of findings beyond the study area. However, the sample remains adequate for exploratory PCA in construction management research. Second, the study relied exclusively on quantitative survey data. The absence of qualitative interviews limits deeper contextual insights into experiential and organisational factors influencing DT adoption.

4.5 Further research direction

These results reinforce the understanding that DT adoption in Nigeria is currently concentrated at the planning and design stages rather than later operational phases. Other high-ranking applications, such as data collection on building performance and real-time site monitoring, suggest growing awareness of lifecycle data integration. However, future research should be directed towards the operational deployment which is still emerging. This pattern aligns with observations in developing construction economies where digital transformation typically begins with design-phase tools before evolving into comprehensive real-time operational systems.

Recommendations

The study indicates how the range of capabilities of DT are not confined to creating static digital models of objects, but in reality are utilized for supporting a dynamic, data driven management of the various lifecycle phases of a project. Building on these insights, future research should deepen operational evidence through longitudinal case studies, integrate sensor/IoT data streams with DT workflows, and assess the cost–benefit realisation of predictive maintenance and energy-efficiency use cases at scale. For practice, targeted capacity-building and collaborative programmes between firms and research institutions, especially in IoT, artificial intelligence, and cyber-physical systems can accelerate translation from virtual modelling strengths to robust operations-level deployment.

5 CONCLUSION

The main contributions of this paper are three-fold. Firstly, an empirically validated PCA-based classification for applications of Digital Technology (DT) is presented. This classification is specifically designed and validated within the construction context of a developing economy. A large body of existing research on the applications of DT within construction comes from a developed economy context, therefore this paper fills a significant gap in current knowledge. Secondly, this paper presents lifecycle prioritization patterns within the DT capabilities of Virtual Prototyping, covering pre-construction and the construction phase, and of Operations Management, covering the construction and post-

construction phases, as two separate adoption clusters with different technical prerequisite profiles. Thirdly, this paper presents methodological insights on how to apply PCA to uncover the hidden structural dimensions of clusters of applications of DT within a practitioners' survey.

Ultimately, wider implementation of DT technologies has the potential to enhance construction productivity, promote sustainable resource management, and improve infrastructure resilience. Aligning DT utilisation with lifecycle optimisation and sustainability objectives can strengthen the sector's contribution to the 2030 Agenda for Sustainable Development.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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