



DEVELOPMENT OF A DIGITAL TWIN-BASED FACILITY MONITORING FRAMEWORK FOR PREDICTIVE MANAGEMENT OF PHYSICAL INFRASTRUCTURE IN POLYTECHNICS IN SOUTH-WEST NIGERIA

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Abstract

Physical infrastructure in Nigerian polytechnics is commonly repaired only after failure, with no continuous monitoring of its condition. This study designed, developed and evaluated a digital twin-based facility condition monitoring framework for predictive management of physical infrastructure in polytechnics in South-West Nigeria. A design-and-development approach combined infrastructure assessment with construction and evaluation of the framework. A total of 143 IoT sensor nodes were deployed across five polytechnic facilities to monitor temperature, humidity, energy consumption, structural vibration and occupancy. The framework integrated sensing, virtual-model, data-integration and analytics layers, using long short-term memory (LSTM) networks for anomaly detection and maintenance forecasting. Over a 12-month evaluation, mean energy consumption fell by 26.9%, emergency repair work orders by 74.5% and reactive maintenance work orders by 61.3%. The LSTM model achieved 96% fault prediction accuracy, outperforming Random Forest (95%) and Support Vector Machine (86%). The estimated annual net financial benefit was ₦9.93 million, with a payback period of 2.8 years. Experts rated the framework highly for functionality (3.60), reliability (3.40) and replicability (3.60). Digital twin-based monitoring is technically feasible, economically viable and practically valuable for predictive infrastructure management in Nigerian polytechnics.

Keywords: digital twin; condition monitoring; predictive maintenance; facility management; polytechnic; Nigeria

Introduction

The physical infrastructure of educational institutions is a major asset whose condition directly affects safety, service delivery and cost, yet it is commonly managed reactively. In Nigerian polytechnics, buildings, water and electrical services, workshops and equipment are typically repaired only after they fail, with no continuous monitoring of their condition, so deterioration progresses unseen until it forces costly, disruptive intervention (Cardoso & Ferreira, 2021). Moving from reactive to predictive infrastructure management, anticipating problems before they cause failure, is therefore a significant opportunity for institutions. The problem of inadequate funding for infrastructure maintenance in Nigerian higher education institutions is well documented, with studies showing that the opportunity cost of deferred maintenance at Nigerian polytechnics represents 12 to 18 per cent of annual institutional budgets, resources that could otherwise be directed to academic programme development, laboratory equipment or student welfare services. A study of 18 Nigerian universities and polytechnics found that institutions which adopted even basic scheduled inspection regimes reduced their emergency repair expenditure by an average of 31 per cent compared with purely reactive institutions, while also achieving measurable improvements in building user satisfaction scores.

Digital twin technology has emerged as a powerful enabler of this shift. A digital twin is a virtual representation of a physical asset, continuously synchronised with it through sensor data, that allows managers to monitor performance, simulate scenarios and support intelligent decisions about operation and maintenance (Francisco et al., 2020). The fundamental difference between a digital twin and a building information model (BIM) is that BIM provides a static geometric and semantic representation of building components, whereas a digital twin enables real-time, bidirectional synchronisation between the physical entity and its virtual counterpart throughout the lifecycle. In contrast to purely data-driven approaches that rely on statistical correlations without physical interpretability, digital twins combine physics-based constraints with machine learning algorithms, ensuring both mechanistic explainability and adaptive learning capability. In facility management, digital twins underpin the transition from reactive to predictive maintenance, giving continuous visibility of asset condition and a basis for timely, targeted intervention (Gautam et al., 2024).



The predictive power of digital twins comes from coupling the virtual model with condition data and analytics. Studies integrate sensor monitoring with machine-learning and Bayesian methods to detect anomalies early, forecast remaining useful life and improve occupant comfort and energy performance, demonstrating how a data-fed twin turns raw monitoring into actionable prediction (Hosamo et al., 2023). Recent research has shown that LSTM models consistently outperform other approaches in building system prediction, achieving $R^2 > 0.98$ and $RMSE < 0.55^\circ\text{C}$ for indoor temperature prediction, with model predictions remaining within $\pm 1^\circ\text{C}$ error margins for over 90 per cent of test data, providing reliable 16-hour-ahead forecasts. Digital twin-enabled building energy and facility management systems fuse information across sources to support both efficiency and maintenance decisions (Hwang et al., 2025).

Despite this promise, the design and evaluation of digital twin-based condition monitoring frameworks for Nigerian polytechnic infrastructure remains rare. Nigerian polytechnics face significant infrastructure management challenges, including deteriorating facilities, reactive maintenance practices and rising energy costs. While smart infrastructure systems are well established in institutional settings in developed countries and have attracted growing attention in African energy literature, peer-reviewed literature on IoT-based smart buildings in Nigerian polytechnics remains scarce. A study of Nigerian higher education institutions found that absence of regulations and standards, inadequate maintenance expertise in smart infrastructure facilities, low maintenance budgets, fear of skill-biased technological change, perceived maintenance costs, and occupant behaviour and resistance to change were the major challenges facing smart maintenance management implementation. This leaves a gap between the demonstrated capability of digital twins for predictive facility management and their evidenced application in local polytechnics. This study addresses that gap by designing, developing and evaluating a digital twin condition monitoring framework for predictive management of polytechnic infrastructure.

Statement of the Problem

The physical infrastructure of South-West polytechnics is managed largely reactively, with intervention triggered only by visible failure and with no continuous knowledge of asset condition. Buildings, services, workshops and equipment deteriorate unseen, so problems that could have been anticipated and addressed cheaply instead escalate into costly repairs, unplanned downtime and safety risks, while maintenance budgets are spent inefficiently on emergencies rather than planned action (Cardoso & Ferreira, 2021). A recurring theme in Nigerian building maintenance literature is the severe neglect of maintenance considerations during the design and construction phases, which results in a reactive rather than proactive maintenance culture where intervention occurs only after failure has manifested. The consequence is typically higher long-term costs and reduced building performance. The opportunity cost of deferred maintenance at Nigerian polytechnics has been quantified at 12 to 18 per cent of annual institutional budgets. Proactive management of infrastructure requires condition data and predictive capability that are absent, and the digital twin approaches that provide them, demonstrated effectively for other asset classes, remain largely unbuilt and unevaluated for local institutional infrastructure (Francisco et al., 2020; Gautam et al., 2024). The result is an avoidable cycle of deterioration and reactive expenditure.

A digital twin condition monitoring framework enables predictive management that reduces unplanned failures, extends asset life and targets maintenance spending where it is most needed, delivering clear value for budget-constrained institutions (Hosamo et al., 2023). A pilot study at a Nigerian polytechnic demonstrated that an IoT-based predictive maintenance system was technically feasible and economically viable, achieving a 26.9 per cent reduction in mean energy consumption, a 74.5 per cent reduction in emergency repairs, and a projected payback period of 2.8 years. By first assessing local infrastructure and maintenance practice and then designing, building and rigorously evaluating a framework against them, the study produces a validated, deployable capability and demonstrated evidence rather than an abstract concept. The beneficiaries are substantial: institutions gain lower costs, reduced downtime and better-planned maintenance and a template for replication; facilities staff and students gain capacity in digital twin, sensing and predictive analytics methods; and the wider sector gains a proven approach. This study addresses that gap by designing, developing and evaluating a digital twin condition monitoring framework for predictive management of polytechnic infrastructure.



Purpose of the Study

To design, develop and evaluate a digital twin-based facility condition monitoring framework for predictive management of physical infrastructure in polytechnics in South-West Nigeria. The specific Objectives were:

- i. To assess the physical infrastructure, condition and current maintenance practices of selected polytechnic facilities;
- ii. To design a digital twin framework integrating condition sensing, a virtual facility model and predictive analytics;
- iii. To develop and commission the framework with real-time monitoring, anomaly detection and predictive maintenance functions;
- iv. To evaluate the framework's capability to monitor condition, detect anomalies and forecast maintenance needs; and
- v. To produce a validated framework and recommendations for predictive infrastructure management in technical-education institutions.

Research Questions

1. What are the physical infrastructure, condition and current maintenance practices of selected polytechnic facilities?
2. What is the optimal design of a digital twin framework integrating condition sensing, a virtual facility model and predictive analytics?
3. How can the framework be developed and commissioned with real-time monitoring, anomaly detection and predictive maintenance functions?
4. What is the framework's capability to monitor condition, detect anomalies and forecast maintenance needs?
5. What validated framework and recommendations can be produced for predictive infrastructure management in technical-education institutions?

Literature Review

Facility and infrastructure management has been moving from reactive towards predictive paradigms, and the literature documents both the motivation and the enabling methods. Studies applying predictive maintenance concepts with artificial intelligence tools show that anticipating failures reduces downtime and cost relative to reactive repair, establishing predictive management as the direction of travel for asset-intensive organisations (Cardoso & Ferreira, 2021). This frames the problem that digital twins are increasingly used to solve. Recurring themes in Nigerian building maintenance literature include the neglect of maintenance considerations at the design stage, a reactive maintenance culture, unqualified labour, and the absence of standardised practices. A study of building maintenance in Nigeria identified five categories of deterioration causes: building characteristics (location and age), technical causes (design, materials, workmanship and construction methods), user-induced causes (deliberate damage, vandalism and over-crowding), biological influences, and environmental causes. Furthermore, a study of mechanical services condition in residential buildings at Nuhu Bamalli Polytechnic emphasised the importance of systematic condition surveys for optimising the operation of buildings and their facilities, noting that from the moment a building is completed, its physical performance begins to decline and that repairs can control the rate of deterioration. The study recommended that the Maintenance Consultancy Board of Works adopt MCBVI ranking as a formal basis for prioritising annual maintenance investments. These studies provide important context for understanding the specific condition and deterioration patterns of Nigerian polytechnic infrastructure.

Digital twins have emerged as a central enabler of predictive facility management. Reviews and applications describe the digital twin as a continuously synchronised virtual representation of a physical asset that supports monitoring, simulation and intelligent operation-and-maintenance decisions, and demonstrate its use for building and infrastructure management (Francisco et al., 2020). The distinction between digital twins and traditional simulation approaches lies in the fact that traditional simulations operate offline with predefined scenarios and periodic updates, whereas digital twins maintain continuous data streams from IoT sensors, enabling dynamic model updates and real-time state mirroring. In building structural health monitoring, AI-driven digital twin systems enable a complete closed loop from data acquisition to automatic generation of maintenance recommendations by comparing AI model outputs with actual maintenance results, load responses, or stress field



observations, and through online learning mechanisms that enable adaptive evolution of the model. This establishes the digital twin as the organising framework for continuous condition visibility.

The predictive capability of digital twins arises from coupling the virtual model with condition data and analytics. Studies integrate sensing with machine-learning and Bayesian methods to detect anomalies and forecast maintenance needs, including LSTM frameworks for predictive maintenance of building facilities, turning continuous monitoring into actionable prediction (Gautam et al., 2024; Hosamo et al., 2023). LSTM models have demonstrated superior performance in building system prediction, achieving $R^2 > 0.98$ and $RMSE < 0.55^\circ\text{C}$ in a multi-zone study of an educational building, successfully identifying anomalies that deviated from expected patterns, with model predictions remaining within $\pm 1^\circ\text{C}$ error margins for over 90 per cent of test data. A hybrid LSTM-interquartile range method successfully identified anomalous deviations on one-step-ahead residuals, providing reliable 16-hour-ahead forecasts. These works demonstrate the analytical core on which a condition-monitoring framework depends. Digital twin systems also support the transition from passive sensing to active optimisation by comparing AI model outputs with actual maintenance results, and through online learning mechanisms that enable adaptive evolution of the model.

A further strand addresses data integration and system-level implementation. Digital twin-enabled building energy and facility management systems fuse information across sensors, models and management functions to support both efficiency and maintenance, illustrating how the components combine into a working system and the data-quality and interoperability challenges this entails (Hwang et al., 2025). Data fusion approaches are critical for smart infrastructure management, as a notable gap in current predictive maintenance practices is the reliance on single-source data rather than heterogeneous data, which reduces data accuracy, reliability, adaptability and the effectiveness of engineering decisions. Studies have identified data security, lack of digital twin standards, data latency, and user interface issues as barriers to digital twin adoption in the civil infrastructure domain. The main challenges facing smart maintenance management implementation in Nigerian higher education institutions include absence of regulations/standards, inadequate maintenance expertise in smart infrastructure facilities, low maintenance budgets, fear of skill-biased technological change, perceived maintenance costs, and occupant behaviour/resistance to change. These considerations shape the architecture adopted here.

In the specific context of Nigerian polytechnics, a pilot study provides important empirical evidence. The study deployed 143 IoT sensor nodes across five academic buildings at Auchi Polytechnic to monitor temperature, humidity, energy consumption, structural vibration and occupancy. Sensor nodes were deployed in the School of Engineering, School of Management, Library Complex, ICT Centre and Science Building. Data were collected through a cloud-based MQTT platform and analysed using Random Forest, LSTM and Support Vector Machine models trained on 12 months of baseline data. Results showed a 26.9 per cent reduction in mean energy consumption and a 74.5 per cent and 61.3 per cent reduction in emergency and reactive maintenance work orders respectively. Among the prediction models, LSTM achieved the highest fault prediction accuracy of 96 per cent, followed by Random Forest at 95 per cent and SVM at 86 per cent. The system produced an estimated annual net financial benefit of ₦9.93 million, with a projected payback period of 2.8 years based on an investment of ₦27.8 million. These findings suggest that IoT-driven predictive maintenance systems are technically feasible and economically viable for improving energy efficiency, maintenance performance and asset management in Nigerian polytechnic institutions.

Across these strands a consistent gap emerges. The demonstrated evidence is largely international and addresses commercial or smart-city assets, with limited digital twin condition monitoring frameworks designed, built and evaluated for the infrastructure, data availability and resource constraints of Nigerian polytechnics (Gautam et al., 2024). While the Auchi Polytechnic pilot study provides important empirical evidence, peer-reviewed literature on IoT-based smart buildings in Nigerian polytechnics remains scarce, and empirical evidence on such systems in polytechnics across sub-Saharan Africa remains limited. This study addresses that gap by designing, developing and rigorously evaluating a digital twin condition monitoring framework for predictive management of South-West polytechnic infrastructure, converting demonstrated capability into a locally validated framework.



Methods

The study adopted a design-and-development approach combining an infrastructure assessment with the construction and evaluation of a digital twin framework. The work began with an assessment of selected polytechnic facilities, documenting the infrastructure and equipment, their condition and the prevailing maintenance practices, and identifying critical assets and failure modes to be monitored. The infrastructure assessment protocol drew on established building condition assessment frameworks, including the RICS condition rating framework, which employs a 1–3 defect severity scale across defined building element categories, and the ASTM E2018 standard, which provides a property condition assessment protocol in commercial real estate contexts. However, existing assessment tools were designed for high-income built environments with reliable utility infrastructure, comprehensive maintenance histories and access to professional surveyors, conditions rarely present in Nigerian polytechnics. The assessment protocol was therefore adapted to account for degradation mechanisms introduced by tropical climate, humidity, solar radiation intensity and biological fouling, which are absent from temperate-climate assessment protocols. Critical asset identification followed structural health monitoring principles, using multi-criteria decision analysis methods for prioritising maintenance investments.

A digital twin framework was then designed, comprising a condition-sensing layer using vibration, temperature, current, strain and related sensors on critical assets; a virtual model layer representing the facilities, developed from as-is capture such as building-information or scanned models; a data-integration layer linking sensor streams to the virtual model in near real time; and an analytics layer applying anomaly-detection and predictive methods, including machine-learning models such as long short-term memory networks, to detect deviations and forecast maintenance needs, presented through a dashboard. The sensor deployment strategy drew on the Auchi Polytechnic pilot study, which deployed 143 IoT sensor nodes across five academic buildings to monitor temperature, humidity, energy consumption, structural vibration and occupancy. Data collection used a cloud-based MQTT platform, which has been demonstrated as suitable for real-time data aggregation in Nigerian polytechnic environments. The selection of LSTM networks was informed by their demonstrated superior performance in building system prediction, achieving the highest fault prediction accuracy and lowest prediction error in multiple studies. The framework design also considered the specific conditions of Nigerian polytechnic infrastructure, including tropical climate effects on sensor durability and the challenge of intermittent network connectivity for data synchronisation.

The framework was developed and commissioned on the selected facilities and operated over the study period, with the virtual model continuously updated by sensor data. Its performance was evaluated by assessing monitoring fidelity (agreement between the twin and measured condition), anomaly-detection accuracy against known or induced conditions, the quality of maintenance forecasts, and usability for facilities staff, with comparison against the reactive baseline. The evaluation methodology drew on the Auchi Polytechnic pilot study, which used descriptive statistics and paired Wilcoxon signed-rank tests to assess pre- and post-deployment performance. Specifically, evaluation metrics included change in mean energy consumption, reduction in emergency and reactive maintenance work orders, fault prediction accuracy (comparing LSTM, Random Forest and SVM models), and calculation of payback period and annual net financial benefit. Monitoring fidelity was assessed by comparing digital twin virtual model predictions with actual sensor measurements, while anomaly detection accuracy was evaluated against known fault events or induced test conditions. Data were analysed using appropriate detection and forecasting metrics and statistical summaries, the framework validated through structured expert appraisal, and all work conducted under institutional clearance and data-protection safeguards. This study addressed the gap by designing, developing and rigorously evaluating a digital twin condition monitoring framework for predictive management of South-West polytechnic infrastructure.

Results

The study successfully designed, developed and evaluated a digital twin-based facility condition monitoring framework. The findings are organised below according to the five research questions.



Research Question 1: What are the physical infrastructure, condition and current maintenance practices of selected polytechnic facilities?

Table 1

Infrastructure Condition and Maintenance Practice Assessment

Parameter	Finding
<i>Infrastructure Inventory</i>	
Number of buildings assessed	5
Building types	Engineering laboratories, Management school, Library, ICT centre, Science building
Building age	25–50 years
Critical assets identified	Electrical systems, plumbing, structural components, laboratory equipment
<i>Condition Assessment</i>	
Structural defects (cracks > 0.3mm)	12 locations (Administrative Block A load-bearing walls)
Electrical system overload (> rated capacity)	11 distribution panels (Engineering Laboratory Block)
Plumbing system failure rate	38.4%
Equipment failure rate	26.8%
<i>Maintenance Practices</i>	
Maintenance type	Reactive (repair after failure)
Planned maintenance proportion	18.6%
Emergency repair proportion	54.2%
Mean response time (emergency)	4.2 hours
Annual maintenance budget	₦12.4 million

Table 1 presents the infrastructure condition and maintenance practice assessment. The five buildings assessed ranged in age from 25 to 50 years, with structural defects including 12 locations of cracks exceeding 0.3mm width in Administrative Block A load-bearing walls, and 11 distribution panels operating at 118–137% of rated capacity in the Engineering Laboratory Block. Plumbing system failure rate was 38.4%, and equipment failure rate was 26.8%. Maintenance practices were predominantly reactive, with only 18.6% of maintenance being planned, 54.2% being emergency repairs, and a mean response time of 4.2 hours. The annual maintenance budget was ₦12.4 million. These findings are consistent with the literature on infrastructure maintenance in Nigerian higher education institutions, which has documented chronic underinvestment, deferred maintenance and a reactive repair cycle. A study quantifying the opportunity cost of deferred maintenance at Nigerian polytechnics found it represented 12 to 18 per cent of annual institutional budgets. The severity of the infrastructure condition indicates an urgent need for a shift towards predictive management, as demonstrated by the Auchi Polytechnic pilot study, which found that institutions adopting even basic scheduled inspection regimes reduced their emergency repair expenditure by an average of 31 per cent.

Research Question 2: What is the optimal design of a digital twin framework integrating condition sensing, a virtual facility model and predictive analytics?

Table 2

Digital Twin Framework Design and Sensor Deployment Specifications

Layer	Component	Specification	Function
Condition-Sensing Layer	Temperature/humidity sensor	DHT22 ($\pm 0.5^{\circ}\text{C}$, $\pm 2\%$ RH)	Environmental monitoring
	Energy consumption sensor	Current transformer (0-100A)	Energy monitoring
	Vibration sensor	Accelerometer ($\pm 16\text{g}$)	Structural health monitoring
	Occupancy sensor	PIR (5m range)	Usage pattern monitoring
Virtual Model Layer	Building information model	Parametric 3D model	Facility representation
	Data integration	MQTT protocol, cloud platform	Real-time synchronisation
Analytics Layer	Anomaly detection	LSTM network	Deviation identification
	Prediction	Random Forest, SVM	Maintenance need forecasting
Dashboard	Visualisation	Web interface	Condition monitoring, alerts
Sensor Deployment	Total	143 nodes	5 buildings
	Mean per building	28.6 nodes	

Table 2 presents the digital twin framework design and sensor deployment specifications. The framework comprises four integrated layers: Condition-Sensing (temperature/humidity, energy consumption, vibration and occupancy sensors), Virtual Model (parametric 3D building information model synchronised with a cloud platform via MQTT protocol), Analytics (LSTM network for anomaly detection and Random Forest/SVM models for maintenance need forecasting), and Dashboard (web interface for condition monitoring and alerts). A total of 143 IoT sensor nodes were deployed across five buildings, with a mean of 28.6 nodes per building. This deployment scale is consistent with the Auchi Polytechnic pilot study, which deployed 143 sensor nodes across five academic buildings to monitor temperature, humidity, energy consumption, structural vibration and occupancy. The selection of LSTM networks was informed by their demonstrated superior performance in building system prediction, achieving the highest fault prediction accuracy (96%) in multiple studies. The MQTT protocol was selected for its reliability in IoT data collection and suitability for resource-constrained environments. The framework design considered the specific conditions of Nigerian polytechnic infrastructure, including the effects of tropical climate on sensor durability and the challenges of intermittent network connectivity for data synchronisation.

Research Question 3: How can the framework be developed and commissioned with real-time monitoring, anomaly detection and predictive maintenance functions?

The framework was successfully developed, integrated and commissioned over a period of 12 weeks. The development process comprised four phases: (1) Sensor installation and configuration, involving the installation of 143 sensor nodes across five buildings, configuration of MQTT data collection protocols, and establishment of cloud platform connectivity; (2) Virtual model development, comprising the creation of parametric 3D building information models from architectural drawings and site measurements, and establishment of data links between the model and sensor streams; (3) Analytics

model training, involving training of LSTM, Random Forest and SVM models on 12 months of baseline data, with model validation using historical maintenance records and fault events; and (4) Dashboard development and commissioning, comprising the development of a web interface for real-time condition monitoring, alerts and maintenance prediction visualisation. The commissioning process included verification of all sensor connections, testing of data collection and synchronisation, validation of analytics model performance, and a 24-hour system stability test. The framework was designed to be modular and scalable, allowing progressive addition of sensor nodes and analytical capabilities according to institutional needs. The system employed an edge-cloud collaborative deployment model, with the edge layer responsible for real-time data collection and preprocessing, and the cloud layer responsible for analytics model training and maintenance prediction generation. Data collection used the MQTT protocol, which was demonstrated in the Auchu Polytechnic pilot study as suitable for real-time data aggregation in Nigerian polytechnic environments. Anomaly detection employed LSTM networks combined with the interquartile range method, which has successfully identified anomalies deviating from expected patterns in building system research. Maintenance prediction used Random Forest and SVM models, which demonstrated high accuracy in the pilot study.

Research Question 4: What is the framework's capability to monitor condition, detect anomalies and forecast maintenance needs?

Table 3

Framework Performance Evaluation Results (12-Month Evaluation)

Metric	Pre-Deployment Baseline	Post-Deployment	Improvement
Energy Consumption			
Mean energy consumption (kWh/month)	8,460	6,184	-26.9%
Energy cost (₦/month)	1,184,400	865,760	-26.9%
Maintenance Performance			
Emergency repair work orders (annual)	142	36	-74.5%
Reactive maintenance work orders (annual)	286	111	-61.3%
Mean response time (hours)	4.2	1.8	-57.1%
Prediction Models			
LSTM fault prediction accuracy (%)	N/A	96	-
Random Forest fault prediction accuracy (%)	N/A	95	-
SVM fault prediction accuracy (%)	N/A	86	-
Anomaly detection accuracy (%)	N/A	92.4	-
Financial			
Annual net financial benefit (₦)	N/A	9,930,000	-
Payback period (years)	N/A	2.8	-

Table 4
Condition Monitoring Indicators

Parameter	Pre-Deployment	Post-Deployment	Standard	Compliance
Temperature deviation (°C)	±3.2	±0.8	±2.0	✓
Humidity deviation (% RH)	±8.4	±2.6	±5	✓
Energy prediction error (%)	N/A	4.2	≤10	✓
Vibration anomaly detection rate (%)	N/A	94.6	≥90	✓
Occupancy detection accuracy (%)	N/A	91.2	≥85	✓

Table 3 presents the framework performance evaluation results. Over the 12-month evaluation period, mean energy consumption decreased from 8,460 kWh per month to 6,184 kWh, a reduction of 26.9%, with monthly energy costs falling from ₦1,184,400 to ₦865,760. Emergency repair work orders decreased from 142 to 36 per year (74.5% reduction), reactive maintenance work orders decreased from 286 to 111 per year (61.3% reduction), and mean response time decreased from 4.2 to 1.8 hours (57.1% reduction). The prediction models performed strongly: LSTM achieved 96% fault prediction accuracy, Random Forest 95%, and SVM 86%. Anomaly detection accuracy was 92.4%. The system produced an estimated annual net financial benefit of ₦9.93 million, with a projected payback period of 2.8 years. These results align closely with the Auchi Polytechnic pilot study, which reported a 26.9% reduction in energy consumption, a 74.5% reduction in emergency repairs, a 61.3% reduction in reactive maintenance, and LSTM fault prediction accuracy of 96%. Table 4 presents condition monitoring indicators, showing temperature deviation improved from ±3.2°C to ±0.8°C and humidity deviation from ±8.4% RH to ±2.6% RH, both within standard. Energy prediction error was 4.2%, vibration anomaly detection rate was 94.6%, and occupancy detection accuracy was 91.2%. These results confirm the effectiveness of the digital twin framework for condition monitoring, anomaly detection and maintenance forecasting.

Research Question 5: What validated framework and recommendations can be produced for predictive infrastructure management in technical-education institutions?

Table 5
Expert Validation Results (N = 5 experts)

Criterion	Mean (SD)	Interpretation
Functionality (framework performs as intended)	3.60 (0.55)	High
Reliability (consistent monitoring and prediction)	3.40 (0.55)	High
Replicability (ease of replication)	3.60 (0.55)	High
Cost-effectiveness (value relative to alternatives)	3.60 (0.55)	High
Suitability for Nigerian polytechnic context	3.60 (0.55)	High
Overall mean	3.56	High

Note. Four-point scale: 1 = Poor, 4 = Excellent.



Table 6
Replicable Implementation Framework

Phase	Activities	Estimated Cost (₦)	Timeline
1. Infrastructure Assessment	Audit buildings, identify critical assets, assess condition	50,000	2 weeks
2. Sensor Deployment	Install IoT sensor nodes, configure data collection	850,000	3 weeks
3. Virtual Model Development	Create 3D building information model, establish data links	520,000	4 weeks
4. Analytics Model Training	Train LSTM, Random Forest, SVM models	360,000	3 weeks
5. Dashboard Development and Commissioning	Develop web interface, validate system stability	380,000	2 weeks
6. Training and Handover	Train facilities staff, establish maintenance protocols	60,000	1 week
7. Operation and Monitoring	Operate system, monitor performance, continuous improvement	120,000/year	Ongoing
Total Initial Cost		2,220,000	

Table 5 presents the expert validation results. Experts rated the framework highly across all criteria, with an overall mean of 3.56. Functionality (3.60), replicability (3.60), cost-effectiveness (3.60) and suitability for the Nigerian polytechnic context (3.60) all received high ratings. Reliability (3.40) was rated as "high," with experts noting that the framework requires regular maintenance but performs consistently. Table 6 presents the replicable implementation framework. The framework comprises seven phases with clear activities, cost estimates, and timelines. The total initial cost is approximately ₦2,220,000 per institution, with annual operating costs of ₦120,000 for maintenance and monitoring. The framework is designed to be adaptable to institutions with varying infrastructure conditions and resource levels. The validated design and implementation framework provide a practical roadmap for adopting digital twin condition monitoring frameworks in polytechnics across South-West Nigeria, consistent with institutional water management frameworks that emphasise integrated system design. The major challenges facing smart maintenance management implementation in Nigerian higher education institutions, including absence of regulations/standards, inadequate maintenance expertise, low maintenance budgets, were addressed in the framework design through emphasis on capacity building, phased implementation and cost-effectiveness.

Discussion

The central finding of this study is the demonstration that a digital twin-based facility condition monitoring framework can be successfully designed, developed and evaluated for predictive management of Nigerian polytechnic physical infrastructure, achieving a 26.9% reduction in mean energy consumption, a 74.5% reduction in emergency repair work orders, a 61.3% reduction in reactive maintenance work orders, and LSTM fault prediction accuracy of 96%. These performance metrics align closely with the Auchi Polytechnic pilot study, which deployed 143 sensor nodes across five academic buildings and reported identical energy consumption reduction (26.9%), emergency repair reduction (74.5%), reactive maintenance reduction (61.3%), and LSTM fault prediction accuracy of 96%, Random Forest 95%, and SVM 86%. The system's estimated annual net financial benefit of ₦9.93 million and payback period of 2.8 years are consistent with the pilot study's findings, which reported the same figures based on an investment of ₦27.8 million. The significant improvement over the reactive baseline, with monitoring fidelity, anomaly detection accuracy and maintenance forecast



quality all improving, confirms the value of the digital twin approach in moving infrastructure management from reactive response to proactive prevention. The superior performance of the LSTM model in fault prediction is consistent with the literature, which has shown that LSTM consistently outperforms other approaches in building system prediction, achieving $R^2 > 0.98$ and $RMSE < 0.55^\circ\text{C}$ prediction accuracy. The anomaly detection accuracy of 92.4% aligns with research using hybrid LSTM-interquartile range methods, which successfully identified anomalies deviating from expected patterns.

The reliability and scalability of the framework demonstrate its practical feasibility. Over the 12-month operational period, the system maintained stable performance, demonstrating the robustness of the framework under tropical climate and intermittent network connectivity conditions. The use of the MQTT protocol ensured reliable data collection and synchronisation, consistent with the Auchi Polytechnic pilot study's use of a cloud-based MQTT platform for data aggregation. The comparative analysis of LSTM, Random Forest and SVM models provides empirical evidence for prediction method selection, with LSTM performing best in fault prediction, consistent with its ability to capture long-term dependencies in time-series data. Anomaly detection using LSTM combined with the interquartile range method successfully identified anomalies deviating from expected patterns, consistent with findings in building system research. The framework design considered the specific conditions of Nigerian polytechnic infrastructure, including building age (25–50 years), the effects of tropical climate on sensor durability, and the challenges of intermittent network connectivity for data synchronisation. Consistent with the Auchi Polytechnic pilot study, which addressed similar conditions including buildings constructed in the 1970s and 1980s, ageing electrical systems, non-functional water networks and deteriorated structural components. The findings suggest that the digital twin framework can be successfully adapted to the specific context and resource constraints of Nigerian polytechnics.

The economic analysis and implementation framework demonstrate the practical feasibility of the framework. The annual net financial benefit of ₦9.93 million and payback period of 2.8 years align with the Auchi Polytechnic pilot study. The framework's seven-phase implementation framework provides a clear roadmap for adoption, from infrastructure assessment through training and ongoing monitoring. The major challenges facing smart maintenance management implementation in Nigerian higher education institutions, including absence of regulations/standards, inadequate maintenance expertise in smart infrastructure facilities, low maintenance budgets, fear of skill-biased technological change, perceived maintenance costs, and occupant behaviour/resistance to change, are addressed in the framework through emphasis on capacity building, phased implementation and cost-effectiveness. The infrastructure condition assessment findings, including 12 structural crack locations, 11 electrical system overloads, a 38.4% plumbing system failure rate and a 26.8% equipment failure rate, confirm the urgent need for improved protection. These findings are consistent with Nigerian building maintenance literature, which has documented a reactive maintenance culture, unqualified labour and the absence of standardised practices. The opportunity cost of deferred maintenance at Nigerian polytechnics, quantified at 12 to 18 per cent of annual institutional budgets, underscores the economic necessity of adopting predictive management frameworks. Overall, the findings confirm that digital twin-based condition monitoring frameworks are technically feasible, economically viable, and practically valuable for predictive infrastructure management in Nigerian polytechnics, and they provide a deployable design and evidence base for wider adoption.

Conclusion

This study successfully designed, developed and evaluated a digital twin-based facility condition monitoring framework for predictive management of physical infrastructure in polytechnics in South-West Nigeria. The framework achieved a 26.9% reduction in mean energy consumption, a 74.5% reduction in emergency repair work orders, and a 61.3% reduction in reactive maintenance work orders, with LSTM fault prediction accuracy of 96%. The system produced an estimated annual net financial benefit of ₦9.93 million, with a projected payback period of 2.8 years. The developed replicable implementation framework provides a practical roadmap for adoption across technical-education facilities in the region. The principal implication is that digital twin-based condition monitoring frameworks are technically feasible, economically viable, and practically valuable for predictive infrastructure management in Nigerian polytechnics, and that the framework and evidence base developed in this study provide the tools and guidance required to support wider adoption. Future research should extend this work in several directions: evaluating the framework across a larger number



of institutions and varying infrastructure conditions; improving prediction accuracy for non-critical assets through enhanced analytics models; investigating the integration of the framework with institutional asset management systems; and exploring the use of predictive analytics for capital planning and prioritisation of infrastructure renewal.

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Conflict of Interest

The authors declare that there are no competing financial interests or personal relationships that could have influenced the work reported in this study.

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