International Journal of Global Affairs, Research and Development (IJGARD), Vol.4, No.1, 810-825, ISSN 2992-2488

THE ROLE OF TECHNOLOGY IN FACILITY MAINTENANCE MANAGEMENT: A REVIEW OF CMMS, IOT INTEGRATION, AND SMART SYSTEMS FOR IMPROVED MAINTENANCE EFFICIENCY

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ABSTRACT

The increasing adoption of digital technologies is transforming maintenance management practices across the built environment by improving asset performance, operational efficiency, and decision-making. This study systematically reviews the application of four emerging technological enablers Computerized Maintenance Management Systems (CMMS), Internet of Things (IoT) sensors, Digital Twins, and smart building automation platforms to evaluate their contribution to maintenance efficiency and identify implementation challenges and future research directions. A systematic literature review was conducted using peer-reviewed publications retrieved from major academic databases, with studies selected according to predefined inclusion and exclusion criteria and analyzed through thematic synthesis. The findings indicate that each technology offers distinct advantages for maintenance planning, condition monitoring, predictive maintenance, and lifecycle asset management. Evidence across the reviewed studies suggests that integrating these technologies can reduce unplanned downtime, improve maintenance scheduling, optimize resource utilization, and support informed decision-making. However, the extent of these benefits varies according to organizational readiness, digital maturity, and system integration capabilities. The review also identifies persistent implementation barriers, including interoperability constraints, cybersecurity concerns, limited technical expertise, data management complexities, and high initial investment costs. While previous studies have extensively examined individual digital maintenance technologies and integrated facility management systems, limited research has synthesized their combined application within an integrated maintenance ecosystem for infrastructure management. The review therefore provides a consolidated understanding of how these technologies can collectively enhance maintenance performance and offers practical recommendations to support their effective implementation. It further identifies areas requiring future empirical investigation, particularly regarding the long-term performance, scalability, and integration of artificial intelligence-enabled maintenance systems across diverse built environment contexts.

Keywords: Built environment; Computerized Maintenance Management Systems (CMMS); Digital Twins; Internet of Things (IoT); Predictive maintenance

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1.0 INTRODUCTION

The increasing complexity of modern buildings and infrastructure has transformed facility maintenance from a reactive operational function into a strategic component of sustainable asset management. Contemporary facilities incorporate interconnected mechanical, electrical, and digital systems that require continuous monitoring to ensure operational reliability, occupant comfort, energy efficiency, and lifecycle performance. Consequently, facility managers are increasingly adopting digital technologies to improve maintenance planning, reduce equipment failures, optimize resource utilization, and support evidence-based decision-making. Among the most influential technological developments are Computerized Maintenance Management Systems (CMMS), Internet of Things (IoT) sensor networks, Digital Twins, and smart building automation systems, which collectively facilitate the transition from corrective and preventive maintenance towards predictive and condition-based maintenance strategies.

Computerized Maintenance Management Systems (CMMS) provide a centralized platform for managing asset information, maintenance schedules, work orders, equipment histories, and performance records. When integrated with real-time monitoring technologies, CMMS enhances maintenance planning, improves asset visibility, and supports data-driven maintenance decision-making. Similarly, IoT sensor networks continuously capture operational data such as temperature, vibration, energy consumption, humidity, and equipment condition, enabling facility managers to detect faults at an early stage and minimize unplanned downtime. Digital Twin technology further extends these capabilities by creating dynamic virtual representations of physical assets that enable real-time simulation, performance monitoring, predictive analysis, and maintenance optimization. Complementing these technologies, smart building automation platforms integrate heating, ventilation, air-conditioning (HVAC), lighting, security, and energy management systems to improve operational efficiency through intelligent monitoring and automated control.

Although these technologies have demonstrated considerable potential individually, their implementation remains challenging in many organizations. Previous studies have reported persistent barriers including high implementation costs, interoperability constraints among heterogeneous systems, cybersecurity concerns, inadequate digital infrastructure, limited technical expertise, and organizational resistance to digital transformation. These challenges are particularly pronounced in developing economies, where financial constraints, insufficient technical capacity, fragmented maintenance practices, and limited digital maturity often restrict the successful adoption and integration of advanced maintenance technologies. Consequently, many organizations continue to rely on isolated digital solutions rather than integrated maintenance ecosystems capable of supporting holistic asset management.

Existing literature has extensively examined the individual applications of CMMS, IoT, Digital Twins, and smart building technologies in facility management. However, relatively few review studies have critically synthesised how these technologies interact within an integrated digital maintenance framework to enhance maintenance efficiency, asset performance, and decision support. Much of the available research focuses on isolated technological applications, specific case studies, or individual maintenance functions, providing limited understanding of the opportunities, implementation challenges, and organizational requirements associated with integrated digital maintenance systems. This fragmentation creates a significant knowledge gap regarding how these complementary technologies collectively contribute to intelligent facility maintenance and sustainable asset management.

Furthermore, despite increasing interest in predictive maintenance and smart buildings, there remains limited consolidated evidence regarding the practical benefits, implementation barriers, and future research priorities associated with integrated maintenance technologies. Existing reviews often concentrate on individual technologies or specific industrial sectors without providing a comprehensive evaluation of the combined contribution of CMMS, IoT, Digital Twins, and smart automation platforms to modern facility maintenance. Addressing this gap is essential for supporting evidence-based decision-making among facility managers, policymakers, researchers, and technology developers seeking to implement integrated digital maintenance strategies.

This systematic review therefore aims to critically evaluate the contribution of Computerized Maintenance Management Systems (CMMS), Internet of Things (IoT) sensors, Digital Twins, and smart building automation systems to maintenance management within the built environment. Specifically, the review seeks to (i) examine the current applications of these technologies in facility maintenance, (ii) synthesise empirical evidence regarding their impact on maintenance efficiency, asset performance, and operational decision-making, (iii) identify the major technological, organisational, and implementation challenges affecting their adoption, and (iv) highlight emerging research directions for developing integrated intelligent maintenance systems. By providing a comprehensive synthesis of contemporary evidence, this review contributes to a deeper understanding of digital transformation in facility management and offers practical recommendations for improving maintenance performance and supporting the evolution of smart and sustainable built environments.

2.0 METHODOLOGY

This study employed a qualitative systematic literature review (SLR) following the PRISMA 2020 Statement guidelines to examine the application of emerging digital technologies in facility maintenance management. The PRISMA framework was adopted because it provides a transparent, reproducible and structured process for identifying, screening, assessing and synthesizing published evidence. To strengthen methodological rigor, the review also incorporated the qualitative case study principles proposed by Baxter and Jack, ensuring systematic evidence selection and reliable thematic interpretation.

The review covered peer-reviewed publications published between 2018 and 2026, a period characterized by the widespread adoption of digital transformation technologies within the built environment. The scope included studies investigating the application of the Internet of Things (IoT), Digital Twin, Computerized Maintenance Management Systems (CMMS), Artificial Intelligence (AI), Machine Learning (ML) and Building Information Modelling (BIM) in facility maintenance. The overall review procedure is illustrated in Figure 1, which presents the sequential workflow from problem identification to evidence synthesis.

A comprehensive electronic search was conducted using four internationally recognized databases: IEEE Xplore, Elsevier ScienceDirect, MDPI, and Taylor & Francis Online. These databases were selected because they collectively provide extensive coverage of engineering, construction management, smart infrastructure, digital technologies and facilities management research. Boolean operators ("AND" and "OR") were used to refine the search and improve retrieval accuracy. Representative search strings included *"Facility Maintenance" AND "CMMS"*, *"IoT" AND "Building Maintenance"*, *"Digital Twin" AND "Predictive Maintenance"*, *"Artificial Intelligence" AND "Facility Management"*, and *"BIM" AND "Maintenance"*. Only English-language publications reporting original empirical findings between January 2018 and March 2026 were considered.

Eligibility criteria were established before screening to ensure consistency and minimize selection bias. Included studies explicitly investigated technology-enabled facility maintenance, reported qualitative, quantitative or mixed-method evidence, or documented industrial case studies published in peer-reviewed journals or reputable conference proceedings. Publications focusing exclusively on construction activities without maintenance applications, editorials, opinion papers, dissertations, book reviews, duplicate publications and studies lacking methodological transparency were excluded.

Study selection followed the four-stage PRISMA process comprising identification, screening, eligibility assessment and inclusion (Figure 2). The initial search identified 512 records across the selected databases. Following duplicate removal, 438 unique articles remained for title and abstract screening. Screening excluded 289 publications that did not align with the review objectives, leaving 149 full-text articles for detailed evaluation. After methodological quality assessment, 87 studies were excluded because of insufficient empirical evidence, weak methodological reporting or limited relevance to facility maintenance. Consequently, 62 studies satisfied all inclusion criteria and formed the basis of the qualitative synthesis.

Data from the selected studies were extracted using a structured review matrix designed to improve consistency and reduce reviewer bias. Information collected included publication details, country of study, research objectives, technology investigated, methodological approach, maintenance application, principal findings, reported operational benefits and implementation challenges. This standardized extraction framework facilitated systematic comparison across studies and enhanced the reliability of the synthesis.

The extracted evidence was analyzed using thematic analysis. The analytical process involved familiarization with the literature, open coding, categorization of related concepts, development of overarching themes and interpretation of emerging relationships. Eight dominant themes emerged: cost reduction, predictive maintenance, operational efficiency, asset performance, technology adoption, organizational readiness, cybersecurity challenges, and workforce skills development. The thematic coding procedure is summarized in Figure 3.

To strengthen methodological credibility, the included studies were subjected to a structured quality assessment based on six criteria: clarity of research objectives, appropriateness of research design, methodological transparency, adequacy of data collection, validity of findings and relevance to technology-enabled facility maintenance. Only studies demonstrating acceptable methodological quality were retained for final synthesis.

Methodological triangulation further enhanced the trustworthiness of the review by integrating evidence from peer-reviewed journal articles, conference proceedings and authoritative industry reports. Independent coding and repeated verification of extracted information minimised subjective bias and improved analytical consistency. Compliance with the PRISMA 2020 reporting framework ensured transparency, reproducibility and methodological integrity throughout the review.

The accompanying bubble graph (Figure 4) complements the thematic analysis by illustrating the distribution of technologies represented in the final dataset. The graphical evidence shows that IoT accounted for the largest proportion of reviewed studies (20 studies), followed by Digital Twin (15), CMMS (12), AI/ML (7), BIM (5) and other emerging technologies (3). The size of each bubble reflects the relative frequency of investigation within the reviewed literature, demonstrating that IoT, Digital Twin and CMMS currently dominate research and practice in technology-driven facility maintenance. This visual representation substantiates the thematic findings and highlights the areas receiving the greatest scholarly attention, while also revealing emerging technologies that remain underexplored and warrant further investigation.

3. 0 DATA ANALYSIS, RESULTS AND DISCUSSION

3.1 Results

The systematic review synthesized evidence from the final body of eligible studies and identified four principal themes: Technology adoption, Maintenance performance improvement, Implementation challenges, and future digital transformation.

Across the reviewed studies, integrated applications of CMMS, IoT sensors, Digital Twins, and AI-supported maintenance systems consistently demonstrated positive contributions to maintenance planning, predictive diagnostics, asset reliability, and operational decision-making. Several empirical studies reported reductions in unplanned equipment downtime, improvements in maintenance scheduling accuracy, enhanced asset lifecycle management, and lower operational costs. However, the magnitude of these improvements varied across organizational contexts, implementation maturity, and system integration levels.

The evidence further indicates that organizations adopting higher levels of digital integration generally reported greater maintenance performance improvements than those implementing isolated technologies. Nevertheless, the review also identified persistent implementation barriers, including high initial investment costs, interoperability limitations, cybersecurity concerns, organizational resistance to change, shortages of digital competencies, and inconsistent data quality. These findings suggest that technology alone is insufficient to guarantee maintenance optimization; successful implementation depends on organizational readiness, workforce capability, and effective data governance.

Figure 2 illustrates the conceptual relationship between the degree of technology integration and reported maintenance cost reduction based on evidence synthesized from the reviewed studies. Rather than representing primary empirical data, the figure summarizes trends consistently reported across multiple publications, demonstrating that higher levels of integrated digital technologies are generally associated with greater maintenance efficiency, although improvements tend to plateau beyond advanced integration levels.

Similarly, **Figure 3** presents the projected growth trajectories of Digital Twin technologies, predictive maintenance platforms, CMMS applications, and IoT-enabled building systems based on published market intelligence reports. The evidence suggests continued expansion in digital maintenance technologies over the next decade, with Digital Twins demonstrating particularly strong long-term market potential despite comparatively lower current implementation rates.

Overall, the findings indicate that integrated digital maintenance ecosystems provide greater operational benefits than the isolated deployment of individual technologies. However, successful digital transformation requires coordinated investment in technology infrastructure, workforce development, organisational change management, and robust data management practices.

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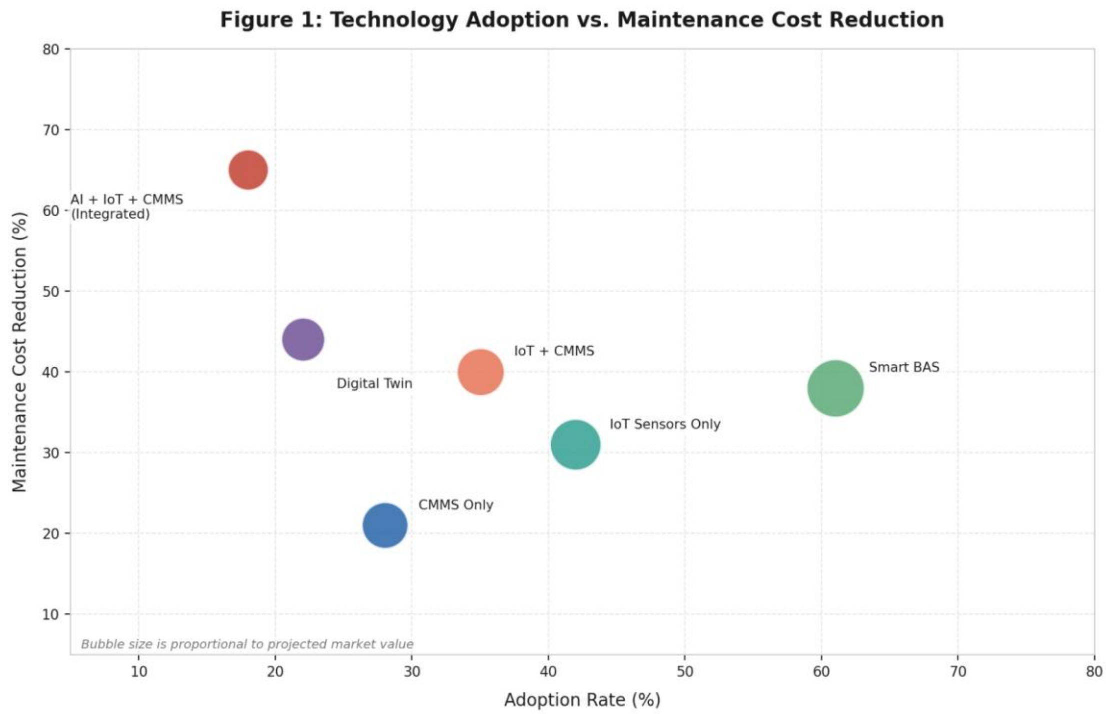


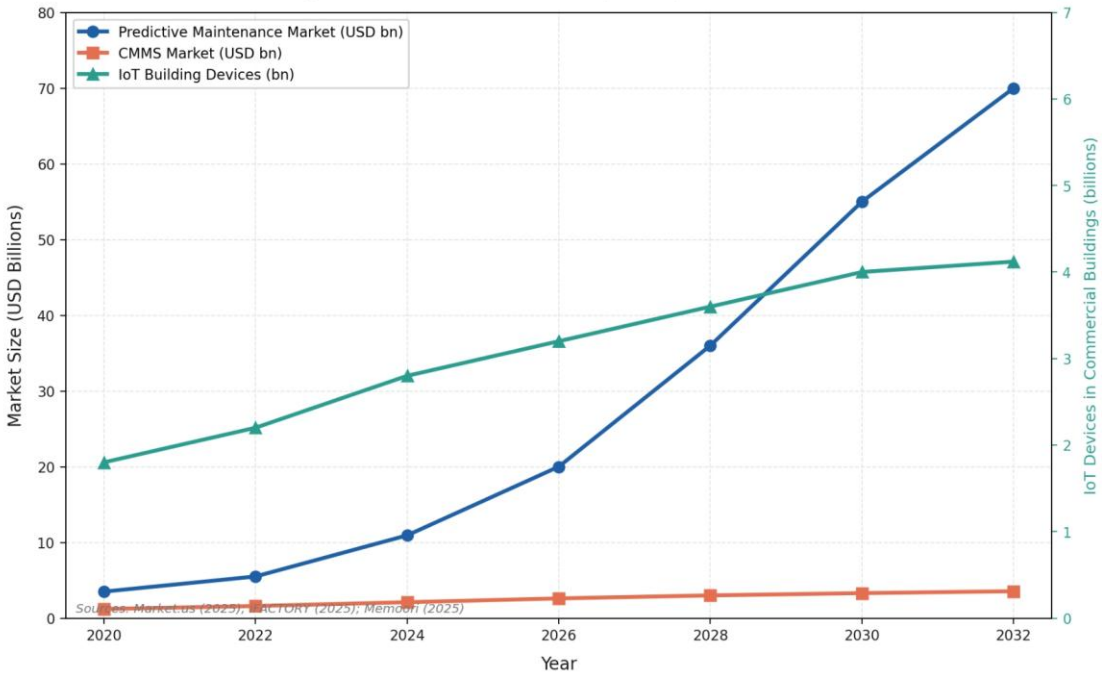
Figure 1

Technology Adoption Rate Versus Maintenance Cost Reduction

Note. Bubble size is proportional to projected market value. Technologies plotted represent varying levels of system integration.

The analysis of growth patterns of markets shows that the contribution of strategic investments in data-driven technologies is highly substantial. The digital twin technology reflects an interesting situation, when there is relatively low penetration at the moment, while the market value itself is enormous, suggesting that there is a stage of development during which investment has not yet transformed into active implementation. Figure 2 demonstrates the growth patterns of predictive maintenance, CMMS, and IoT building devices from 2020 to 2032.

Figure 2: Market Growth Trajectory (2020–2032)

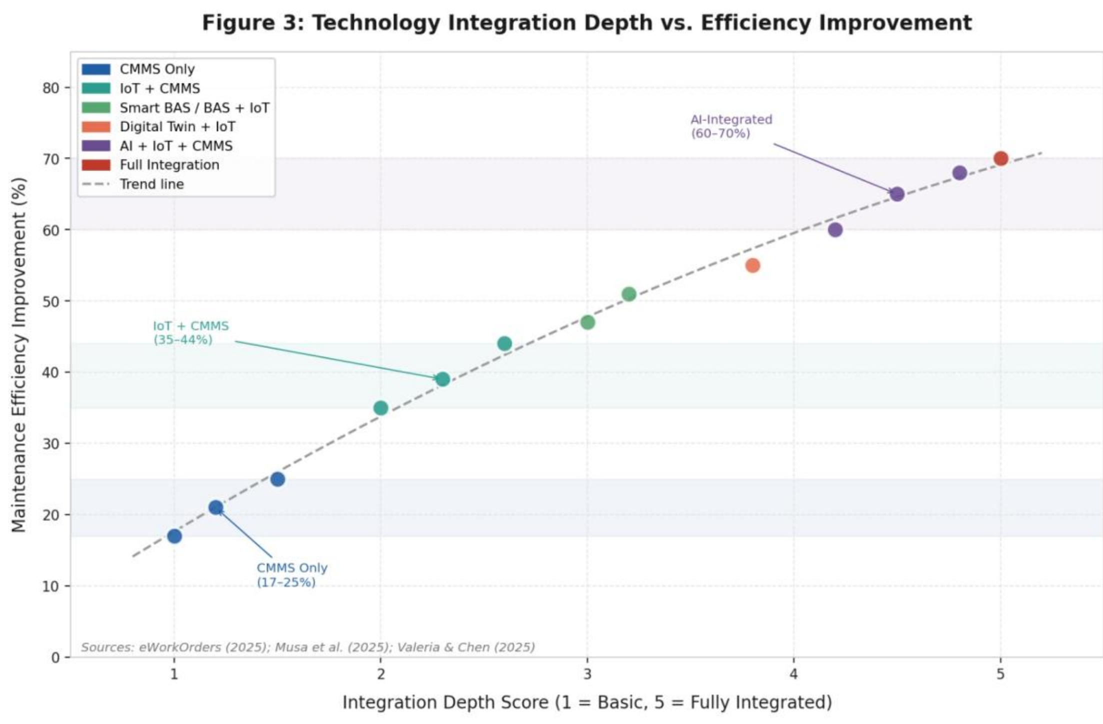


..Data Sourced From Market.Us (2025), Ifactory (2025), And Memoori (2025). Iot Device Count Plotted On Secondary Axis.

The allocation of gains resulting from efficiencies reveals that synergistic integration surpasses mere tools utilization. The gains realized at the maximum level of integration could go up to 60% to 70%. Nevertheless, according to Musa et al. (2025), such outcomes are largely dependent on the quality of the data used and the extent to which the implementation process is executed. The plateau that is observed clearly indicates that increased technology does not necessarily lead to equivalent benefits.

3.2 Discussion

The current study found that there were different challenges being faced by practitioners with regard to technology integration, especially in the context of appropriate structure for data management. The main lesson from the reviewed studies is that a suite of tools is not equivalent to the effective system of management. Organizations invest large sums of money into advanced sensors or CMMS software, but all these turn out to be just isolated digital systems. Efficiency improvements noted by Valinejadshoubi et al. (2025) are achieved because of making all these systems interact and interface with the environment. Figure 3 provides even more evidence in support of this thesis as it clearly shows high correlation between depth of integration and efficiency improvement – around 60-70%.



Note. Integration depth score ranges from 1 (basic CMMS only) to 5 (fully integrated AI, IoT, and CMMS). Efficiency improvement ranges derived from eWorkOrders (2025) and Musa et al. (2025).

When you start to implement things, they don't always work with operation. Budget is a problem that is often raised, but the human factor is the most difficult and intractable. The lack of technically competent maintenance workers is another major challenge discussed by Banerjee and Nayaka (2022), this is similar to the lack of specific guidance in resource-poor environments. The installation process is straightforward, but the process of growing a workforce of people who can interpret and take appropriate action with the information from the sensor is so much harder and is at best a technical debt.

Considering that Nigeria is a developing nation where electricity is unreliable and the local logistics system is underdeveloped, it makes sense that the high end alternative appears unattainable. If the Lagos-based manager lacks spare parts and a competent technician to do the job, then there is no use in having a prediction model. As such, technology must be coupled with investment in regional capabilities to ensure that gains in efficiency are not rendered futile by hardware failure. This is rooted in the concept of active involvement, which states that technology must aid comprehension and competence, rather than act as a replacement. If the right approach is taken, technology can be used to improve maintenance facilities without impacting on the operational integrity.

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study aimed to explore the effectiveness of the integrated technology from practitioners' point of view to deal with the facility maintenance field. The results have revealed that the use of the tools like the CMMS, IoT and Digital Twin are playing an important role in facilitating the organizations for organizing their maintenance systems, making the structural and logical coherence of the maintenance system stronger, and for increasing the accuracy of the maintenance process. It was discovered that AI feedback can enhance maintenance processes, and practitioners agreed that AI provides a useful contribution to the refinement of maintenance processes.Participants recognized the importance of AI feedback in enhancing maintenance processes. But issues of reliability of sources and possible technical issues are still problems that need to be monitored by people. These will be vital to ensure the ethical use of them and for all staff to be digitally literate to utilise them effectively.

Overall, this research offers valuable insights and opens up the potential of AI-powered tools in the field of facility management, but also underscores the importance of critical engagement. It is not only possible to have data-driven maintenance, it is already happening. Operational maturity is not dependent on the number of sensors deployed, but on the amount of sensor data input into systems and how prepared are humans to react to the data. The final decision regarding technology is contextual, and an enabler rather than a substitute for critical thinking by humans

4.2 Recommendations.

1 Increased explorations of the potentials of AI-powered tools in the field of facility management

11 Further research in the use of technology in the building and facility management sector,

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