# Artificial Intelligence-Driven Innovations for Sustainable and Smart Building Maintenance

**Mohd Zulakhmar Zakiyudin, Mohamad Sufian Hasim**

**Centre of Studies for Buildin Surveying, Faculty of Built Environment, Universiti Teknologi Mara, Shah Alam, Selangor, Malaysia**

**DOI: https://dx.doi.org/10.47772/IJRISS.2025.91100155**

**Received: 10 November 2025; Accepted: 20 November 2025; Published: 03 December 2025**

## ABSTRACT

This review explores innovative technological solutions and sustainable management strategies transforming building maintenance toward smarter and more environmentally responsible practices. It highlights the integration of AI, digital twins, IoT, robotics, and blockchain in enhancing predictive maintenance, real-time monitoring, and data security. The document emphasizes the importance of sustainable strategies including lean maintenance, energy optimization, and stakeholder engagement to promote efficiency and social benefits. Additionally, it underscores operational decision-making supported by data analytics, multi-criteria frameworks, and user feedback, alongside challenges such as organizational readiness and data fragmentation. Future research is directed toward socio-technical integration, real-world validation, and advancing smart city initiatives, aiming to create resilient and sustainable built environments.

**Keywords—**Artificial Intelligence, Digital Twins, Sustainability, Building Maintenance, Predictive Maintenance

## INTRODUCTION

### Background

Intelligent building maintenance and management have witnessed rapid evolution fueled by the integration of advanced digital technologies, data analytics, and sustainable strategies. Emerging frameworks and applications, such as cyber-physical systems designed for smart campuses, illustrate this progress by utilizing Internet of Things (IoT) architectures to optimize resource consumption, particularly in water management (Barroso, Bustos, & Núñez, 2023). This digital transformation in building maintenance advances operational efficiency through predictive systems and intelligent monitoring, integrating real-time data to inform decisions that minimize waste and energy consumption.

Contemporary research underscores the imperative to enhance sustainability and resilience in the built environment, especially in light of global challenges like climate change and the ongoing impacts of the COVID-19 pandemic. For example, Pedral Sampaio et al. (2023) discuss how digital transitions and intelligent systems applied to healthcare infrastructure can realize improved facility management outcomes, contributing to sustainability and operational robustness post-pandemic. Hauashdh et al. (2024) further frame integrated frameworks for building maintenance that align with climate action goals, sustainable development, and emerging technologies to ensure resilient and effective maintenance operations.

The deployment of digital twins and Building Information Modeling (BIM) reflects an important technological frontier, supporting lifecycle management from construction to operation and maintenance phases (Peng et al., 2020; Long et al., 2024; Lu Vivi et al., 2019). These digital replicas allow facility managers to monitor building performance closely, predict maintenance needs, and optimize resource allocation in real-time. Furthermore, the fusion of BIM with IoT sensor networks and big data analytics enhances anomaly detection, predictive maintenance, and operational optimization (Himeur et al., 2023; Villa et al., 2021). The advent of artificial intelligence (AI) and machine learning algorithms reinforces these advances by providing tools for automated fault detection and predictive diagnostics, improving maintenance decision-making and reducing system failures (Abidi, Mohammed, & Alkhalefah, 2022; Bouabdallaoui et al., 2021; Nelson & Dieckert, 2024).

The current emphasis on sustainability also extends beyond technology to include social and behavioral factors contributing to effective maintenance cultures. Ogunbayo et al. (2022) highlight cultural influences on maintenance management in developing country contexts, pointing out that stakeholder attitudes and practices critically affect building longevity and performance. Similarly, concepts such as Total Productive Maintenance (TPM) have been studied for their role in promoting employee participation and enhancing maintenance outcomes in green building operations (Au-Yong, Azmi, & Myeda, 2022; Zulkifly, Zakaria, & Mohd-Danuri, 2021).

Despite these advances, challenges prevail, particularly regarding data integration, systems interoperability, and digital maturity across facility management. Fragmented data flows and a lack of standardized data exchange hinder seamless adoption of smart technologies in building maintenance (Nikolaou & Anthopoulos, 2024; Herbers, Çelik, & König, 2024; Olimat, Liu, & Abudayyeh, 2023). Furthermore, educational and skills gaps among building surveying professionals and facility managers limit the effective utilization of these innovative tools (Zaheer et al., 2021; Husain, Che-Ani, & Affandi, 2020). Combined with economic constraints and operational complexities, these barriers shape a multifaceted landscape for intelligent building maintenance development.

## Research Scope and Objectives

This review aims to provide a holistic overview of the contemporary landscape of intelligent building maintenance and management by examining state-of-the-art technologies, sustainable strategies, and systemic challenges rooted in data, skills, and operational factors. The necessity for data-centric solutions is foregrounded by the growing volumes of sensor data generated through IoT devices and the need for effective processing and decision-making, supported by AI and machine learning approaches (Tavakoli et al., 2024; Serrano, 2020). This synergy seeks to transform building maintenance from reactive and preventive paradigms to predictive and prescriptive models that optimize resource use and extend building lifespan.

Key objectives include presenting the technological advancements in digital twins, BIM, IoT, AI, and blockchain to enhance data reliability and security in asset management (Marzouk, Labib, & Metawie, 2024; Tavakoli et al., 2024; Kifokeris, Tezel, & Moon, 2024). Additionally, the review explores sustainable maintenance strategies that integrate green practices, lean maintenance concepts, and stakeholder culture to ensure effective and sustainable building management (Wong, Olanrewaju, & Lim, 2021; Arsakulasooriya, Sridarran, & Sivanuja, 2024; Ogunbayo et al., 2022).

Finally, by highlighting key implementation barriers—such as digital interoperability issues, human factors, economic constraints, and policy gaps—the review directs attention toward research gaps and future trends. It advocates for comprehensive frameworks that align technological innovation with sustainable development goals, capacity building, and regulatory support, ultimately fostering more resilient and intelligent building maintenance ecosystems.

## Innovative Digital Technologies For Intelligent Building Maintenance

### Digital Twins and Building Information Modeling (BIM)

Digital Twins (DTs) have emerged as a transformative technology for building lifecycle management, enabling real-time monitoring, data integration, and intelligent decision-making. Peng et al. (2020) introduced a "continuous lifecycle integration" method for hospital buildings, developing a DT system that integrated static and dynamic data from over twenty management systems throughout the building's lifecycle. This system provided real-time visual management, artificial intelligence diagnosis modules, and facilitated significant reductions in energy consumption and facility faults, enhancing maintenance quality and operational efficiency. Building on this, Long et al. (2024) conducted a systematic literature review identifying that digital

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

twins have been predominantly applied in construction and operation phases but underutilized in design and demolition stages. They developed an integrative framework categorizing key enabling technologies, highlighting current gaps such as absent universal industry standards and fragmented stakeholder involvement across lifecycle phases.

Complementary to DTs, Building Information Modeling (BIM) plays a pivotal role in intelligent maintenance. Simeon et al. (2023) showcased the integration of BIM with Heritage-BIM (HBIM), employing 5D BIM for cost estimation and decision-making in heritage building maintenance projects, such as the Aidkeen Al-Bendqdari Dome in Cairo. This enhances transparency and planning precision in conservation efforts. Ciuffreda et al. (2024) utilized BIM to create a dynamic model for managing structural assessments and conservation data of San Niccolò's Tower Gate in Florence, facilitating better cognitive management of historical buildings. Jibrin et al. (2024) assessed BIM implementation in Nigerian building facilities' operation and maintenance, revealing low adoption but emphasizing that inclusion of facility managers from inception stages improves maintenance management performance, advocating early BIM integration for effective facility operation.

**Internet of Things (IoT) and Big Data Analytics**

IoT deployment, through extensive sensor networks, offers real-time data acquisition essential for predictive and preventive maintenance. Himeur et al. (2023) surveyed AI-big data analytics for building automation, demonstrating how IoT-enabled sensors facilitate intelligent energy management, anomaly detection, and system optimization. Villa et al. (2021) proposed an open-source IoT architecture integrated with BIM platforms to monitor HVAC systems, enabling 3D visualization of facility conditions and predictive maintenance, thereby improving monitoring reliability and maintenance timeliness.

Big data analytics complement IoT by processing vast datasets for operational insights. Yan and Yan (2022) designed an interactive AI platform that leverages semantic understanding and intention recognition for system operation and maintenance, processing fragmented knowledge through multimodal interactions, which streamlines facility issue resolutions. Olimat et al. (2023) performed a bibliometric analysis revealing the dominance of BIM, IoT, and Digital Twin integration in smart facility management research, noting blockchain as an emerging interest for enhancing data security and interoperability. They stressed that effective data handling remains a challenge for facility managers in implementing these advanced technologies.

**Artificial Intelligence and Machine Learning Applications**

Machine learning (ML) and artificial intelligence (AI) have been extensively applied to predictive maintenance, fault detection, and system optimization in intelligent buildings. Abidi et al. (2022) proposed a predictive maintenance model using hybrid optimization algorithms for feature selection and recurrent neural networks to forecast component conditions in manufacturing, indicative of similar potential in building maintenance applications. Bouabdallaoui et al. (2021) developed an ML-based predictive maintenance framework targeting building HVAC systems, demonstrating accurate failure predictions in a sport facility context and outlining implementation guidelines.

Nelson and Dieckert (2024) compared ML-based automated fault detection and diagnostics with traditional Boolean rule-based methods in commercial building systems. They highlighted ML's ability to detect long-term faults and infer fault conditions with incomplete sensor data, offering soft decision boundaries. Alghanmi and Yunusa-Kaltungo (2024) presented an ensemble learning approach, with the XG Boost classifier achieving high accuracy and resilience to noisy sensor data in classifying fault severities at the whole-building level.

In addition, deep learning models enhance intelligent system prediction and inspection. Serrano (2020) validated the use of Long Short-Term Memory (LSTM) networks to predict environmental and occupancy variables in intelligent buildings, outperforming traditional linear regression models. Wen et al. (2024) developed an AI-robotic sensing system employing multimodal sensors and AI analytics for real-time defect detection in indoor building systems, integrating anomaly geo-registration with 3D building models. Liu et al. (2022) applied digital image methods and deep learning for sensitive structural service indicator detection in buildings, improving the diagnosis of deformations and surface diseases. Yoon et al. (2024) utilized convolutional neural networks (CNN) combined with UAV imagery for automated 3D modeling and exterior building defect inspection, enhancing accuracy and efficiency in maintenance assessment.

**Comparative Analysis of Technological Approaches**

A comparative examination of advanced and traditional maintenance technologies highlights distinct advantages and limitations under varying operational contexts. Digital Twins (DT) offer real-time integration of physical and virtual assets, enabling predictive maintenance and lifecycle optimization, whereas Building Information Modeling (BIM) primarily supports static data management and visualization. DT systems are most impactful in complex, sensor-rich facilities requiring continuous feedback, while BIM remains cost-effective for design coordination and documentation. Similarly, AI-driven monitoring and diagnostics outperform traditional rule-based systems in handling large, dynamic datasets and detecting latent faults; however, they demand higher computational capacity and data quality assurance. Quantitative metrics such as fault detection accuracy (up to 90–95% in recent AI applications) and average cost reductions (ranging between 15–30% through predictive maintenance) provide evidence of these performance differences. Broader adoption rates vary globally, with AI and IoT integration exceeding 60% in developed regions but lagging below 25% in developing economies due to cost and skills barriers. Such comparative insights are vital for facility managers and policymakers to select context-appropriate technologies balancing cost, complexity, and operational outcomes explored by Olaseni, (2020), Ma et al., (2024), van Dinter et al., (2022), Shuhaimi et al., (2024), Prabu et al., (2025) and Farsangi & (Shehata, 2024)

**Blockchain and Digital Data Provenance**

Blockchain technology offers promising solutions for data reliability, security, and provenance in building maintenance. Tavakoli et al. (2024) developed a blockchain-based digital twin data provenance model for predictive asset management, ensuring trustworthy, transparent, and immutable data records that enhance reliability in maintenance decisions. Marzouk et al. (2024) proposed a data-driven chatbot framework integrating BIM and blockchain for heritage building maintenance, improving data security and stakeholder collaboration in updating BIM models.

Kifokeris et al. (2024) presented a decision-making framework highlighting the operational and maintenance phase as most suitable for blockchain deployment in building life cycles. The study discusses multiple opportunities and challenges for blockchain adoption, such as trust enhancement and overcoming technological barriers, emphasizing the need for further research to realize its full potential in building operations.

**Sustainable Strategies In Intelligent Building Maintenance**

**Integration of Green and Energy-Efficient Practices**

Energy optimization remains a pivotal focus within sustainable building maintenance, with innovative systems targeting efficient energy use in lighting, HVAC, and thermal management. Shao et al. (2023) explored the use of Building Information Modelling (BIM) integrated with Internet of Things (IoT) sensor networks for intelligent illumination in library buildings, demonstrating significant energy savings through motion sensor-based lighting adjustments. This approach not only curtails unnecessary energy consumption but also fosters operational sustainability in public facilities.

Ren et al. (2023) introduced an intelligent operation, maintenance, and control system for public buildings that synergizes ventilation and air purification with energy optimization. Leveraging artificial neural networks and fuzzy clustering techniques, they achieved a 27.4% reduction in energy consumption while effectively mitigating infection risks, highlighting the dual benefits of health and energy efficiency post-pandemic.

In the realm of thermal systems, Prol-Godoy et al. (2024) applied thermoeconomic analysis to a hybrid domestic hot water and heating system, pinpointing inefficiencies and enabling cost-effective preventive maintenance that aligns with sustainability goals. Their method offers a valuable tool for maintenance planning, optimizing resource usage, and reducing environmental impact.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

Beyond specific systems, value-based building maintenance models emphasize broader sustainable outcomes. Wong et al. (2021) investigated public hospitals in Malaysia, revealing that value-adding maintenance practices and value co-creation with users positively affect maintenance outcomes and sustainability performance. This underscores the importance of integrating stakeholder perspectives into sustainable maintenance frameworks.

Passarelli et al. (2023) investigated embodied life cycle impacts of lightweight building methods for affordable housing in the USA. Their lifecycle assessments advocated for circular and regenerative construction strategies, prioritizing material reuse and renewable resources to minimize environmental footprints, which should be extended to the maintenance phase for sustained sustainability.

Lean maintenance approaches further contribute to sustainable facility management. Arsakulasooriya et al. (2024) identified maintenance wastes in commercial high-rise buildings, such as excessive preventive maintenance and poor inventory management, proposing lean strategies to enhance efficiency, reduce resource waste, and support sustainable operations.

**Cultural, Behavioral, and Maintenance Culture Approaches**

The effectiveness of sustainable maintenance practices is significantly influenced by the cultural and behavioral context of stakeholders. Ogunbayo et al. (2022) emphasized the role of maintenance culture in public buildings within developing countries, highlighting how the absence of positive stakeholder attitudes leads to deterioration and heightened abandonment rates. They advocate for culture change initiatives to embed maintenance as a priority at all organizational levels.

Au-Yong et al. (2022) investigated employee participation in green building operations, using the Total Productive Maintenance (TPM) concept as an enabler. Their study revealed that knowledge, awareness, and communication are critical factors fostering active involvement, which directly contributes to sustaining building performance and operational longevity.

Total Productive Maintenance is further explored by Zulkafli et al. (2021), who examined its adoption for maintenance procurement in Malaysia’s green buildings. They found that TPM-compatible contract structures improve maintenance quality and sustainability, highlighting the importance of strategic procurement in operationalizing maintenance culture.

The interplay of user involvement and cultural dynamics thus forms a foundation for sustainable practices, ensuring that maintenance efforts are not only procedural but embedded in organizational behavior and stakeholder engagement.

**Policy, Planning, and Decision Support Tools**

Strategic policy and decision-making frameworks are crucial to achieving sustainable maintenance outcomes. Salas and Yepes (2024) developed a multi-criteria decision-making framework for corrective maintenance of urban public facilities, incorporating physical and socio-economic criteria to prioritize maintenance efficiently and cost-effectively. This data-driven approach can guide resource allocation in line with sustainability and public welfare objectives.

Complementing decision support tools, Jiang et al. (2024) proposed machine learning methods to improve equipment cost and residual value estimations, directly aiding decision-making in design, construction, and maintenance. Enhanced cost prediction accuracy supports sustainable budgeting and procurement, ensuring resource efficiency throughout building life cycles.

In heritage and public facility contexts, Abdul Majid et al. (2015) and Salleh et al. (2023) highlighted the critical need for strategic maintenance planning to address funding shortages and infrequent upkeep in Malaysian heritage school buildings. Their research emphasizes leveraging SWOT analyses and best practice syntheses to guide sustainable retrofitting and rehabilitation efforts, aligning maintenance strategies with cultural conservation and sustainability.

Hauashdh et al. (2022) introduced a comprehensive framework integrating sustainability, climate adaptation, emerging technologies, and resilience into building maintenance operations. This holistic approach guides industry stakeholders in managing environmental, social, and economic dimensions of maintenance, thus fostering sustainability amidst evolving global challenges.

Ciuffreda et al. (2024) showcased advanced Building Information Modeling (BIM) applications for conservation and maintenance of historic structures. Their work demonstrates how digital tools enable dynamic, informed decision-making that respects heritage values while ensuring sustainable facility management.

Collectively, these studies underscore the importance of combining technology, policy, and stakeholder-centric planning to realize sustainable maintenance in intelligent buildings, balancing operational effectiveness with environmental and social imperatives.

**Key Challenges and Implementation Barriers**

**Data Integration, Interoperability, and Digital Maturity**

Data integration and interoperability remain significant issues impeding the advancement of intelligent building maintenance and management. One of the critical challenges is the fragmentation of data flows across various digital platforms and stakeholders, which compromises the efficiency and effectiveness of facility management. Nikolaou et al. (2024) highlight this fragmentation problem and emphasize that segmented and non-homogenized contextual data flows in smart buildings limit the development and deployment of vendor-independent digital solutions. Similarly, Herbers et al. (2024) discuss limitations in automating continuous inspections due to the lack of integrated systems for defect detection and environmental mapping, underscoring the fragmentation at the operational level.

The low digital maturity in building management systems also enforces constraints on operational efficiency. Olimat, Liu, and Abudayyeh (2023) note that many facility managers face difficulties in managing the complexity inherent in data handling and implementing emerging digital technologies such as BIM, IoT, and digital twins, further exacerbated by insufficient digital maturity in the sector. In addition, interoperability issues between BIM (Building Information Modeling) and CMMS (Computerized Maintenance Management Systems) are prevalent across projects. Kim, Freda, and Nguyen (2020) identify a lack of proper BIM training, rigid existing processes, and insufficient integration frameworks as main obstacles preventing the use of BIM for building design examination and maintenance. Keskin and Erbay (2016) also reveal that current building practices often overlook traditional sustainable architecture principles partially because existing digital models are not fully integrated to support comprehensive maintenance management.

Another challenge in interoperability is the deficient ability to reuse BIM data seamlessly in operational phases. Asare, Liu, and Anumba (2023) present that incomplete and untimely equipment data handover during construction phases results in low utilization of BIM within CMMS, negatively impacting airport facility management. Jibrin et al. (2024) find that BIM implementation in operation and maintenance remains low, especially in regions like Nigeria, due to delayed inclusion of facility managers in early project stages and reliance on manual or stand-alone digital tools.

**Skills, Education, and Human Factor Constraints**

Constraints related to workforce skills, education, and human factors strongly affect the adoption and sustainability of intelligent building maintenance practices. Zaheer et al. (2021) investigate essential competencies required for graduate building surveyors from employers' perspectives, discovering that graduates often lack a balanced combination of technical knowledge, management capabilities, and interpersonal skills vital for current industry demands. Husain, Che-Ani, and Mohd Affandi (2020) extend this by revealing a mismatch between supplied skills of building surveying graduates and industry needs, highlighting deficits in both technical and non-technical domains. Simeon et al. (2023) confirm that deficiencies in education, training opportunities, and awareness reduce the adoption of professional building surveying within the Nigerian construction industry, where building surveying is still poorly integrated into the wider built environment professions.

Resistance to professionalization and change further complicates these educational and human resources challenges. Abdul-Aziz, Suresh, and Renukappa (2020) discuss the struggles faced when trying to establish building surveying as a statutory and recognized profession in Malaysia, hindered by opposition from existing bodies and lack of legislative backing. Hoxley (2012) presents the graduates' perspective in the UK, showing that while graduates appreciate relevant construction technology and building pathology education, gaps in post-graduate training, contract administration, and practical placement experiences remain, curtailing workforce readiness.

Additional human factor barriers include general resistance to digital transformation given traditional workflows and limited digital literacy among certain professional groups. These factors present considerable obstacles to adopting intelligent maintenance technologies and require targeted educational reform and industry engagement to improve digital competency and promote acceptance of new practices.

**Operational, Economic, and Cultural Barriers**

Operational barriers such as funding limitations, stakeholder engagement difficulties, and policy inadequacies can dramatically affect the successful implementation of maintenance strategies. Dimitriou and Kontovourkis (2024) discuss the urgent need for knowledge support interventions in affordable housing projects, highlighting barriers like workforce shortages and insufficient resources that also apply broadly to building maintenance sectors in resource-constrained contexts. Murtaza, Ibrahim, and Abdullah (2020) analyze the traditional Malay settlement building orientation and imply that cultural and geographical contextual factors play a vital role in maintenance and conservation, a nuance sometimes overlooked in modern operational planning.

Cultural influences on maintenance effectiveness are well documented by Ogunbayo et al. (2022), who underscore how the absence of a maintenance culture and poor attitudes among stakeholders in developing countries negatively impact building longevity and sustainability. Furthermore, Mong, Mohamed, and Misnan (2018) identify cost overruns as a significant operational challenge tied to inadequate assessment of factors such as human resources, materials, and funding allocation, which can be mitigated through strategic budgeting and effective management.

These operational challenges are intensified in developing countries due to a combination of weak institutional frameworks, low technological adoption, and socio-economic constraints. Desbalo et al. (2024) stress the immaturity of facility maintenance management in Ethiopian public universities, hindering sustainable building operation. Such contextual difficulties are echoed in studies focusing on the need for increased transparency, policy support, and capacity building to enhance maintenance practices in African and Asian contexts (Ayokunle et al., 2024; Simeon et al., 2023).

In conclusion, while digital and intelligent tools present promising opportunities for enhancing building maintenance and management, significant challenges remain that span technological, human, operational, economic, and cultural dimensions. Addressing these multifaceted barriers requires integrated, collaborative efforts across stakeholders, policy reform, capacity building, and standardization of digital ecosystems.

**Future Directions and Emerging Trends**

**Toward Fully Integrated and Automated Intelligent Maintenance**

The future of intelligent building maintenance is increasingly being shaped by the integration of automation technologies such as robotics, augmented reality (AR), and multi-modal knowledge graphs. Recent advances demonstrate the feasibility of autonomous defect inspection systems, such as those tested by Herbers et al. (2024), who deployed defect segmentation networks on mobile robots to survey structural defects automatically. Their approach has the potential to substantially reduce the labor intensity and time required for routine inspections, while improving accuracy and enabling faster maintenance decision-making.

Simultaneously, the use of AI-powered robotic sensing systems that combine multimodal imagery sensors (infrared, LiDAR, RGB) with real-time analytics is gaining traction. Wen et al. (2024) proposed such a system capable of detecting, geo-locating, and assessing building defects indoors, promising enhanced responsiveness and diagnostic efficiency compared to traditional manual methods.

Building on these technologies, the incorporation of knowledge graphs is emerging as a promising method for representing complex relationships within building maintenance data. For example, Lin et al. (2024) demonstrated a multi-modal knowledge graph for railway equipment operation and maintenance based on BIM and deep learning models, enabling accurate mapping of mutual feedback mechanisms between devices. Such semantic modeling improves operational guidance and decision support, enhancing maintenance intelligence.

Digital twins (DTs) offer a powerful platform to facilitate lifecycle-wide integration of data, enabling more comprehensive facility management. Long et al. (2024) provide a systematic review illustrating digital twins' capability to bridge multiple phases of the building lifecycle, although research remains concentrated on construction and operations, with less emphasis on planning and demolition. This highlights future scope to develop lifecycle-spanning integrative frameworks. Liu et al. (2024) further confirmed that digital twin-based platforms enhance operational intelligence and maintenance efficiency through intelligent sensing, multidimensional twins, and data fusion, evidencing DTs' growing role in large-scale building management.

**Enhancing Sustainability and Resilience**

Innovation is also advancing along sustainability and resilience axes within building maintenance. Climate-responsive maintenance strategies that integrate emerging materials and technologies are gaining attention. Singh et al. (2024) reviewed self-healing concrete as a remedial and preventive solution for crack formation, which is a major cause of durability loss. Such materials promise reduced maintenance frequency and extended building service life, contributing to sustainability.

Complementing material innovation, Hauashdh et al. (2024) developed an integrated framework for aligning maintenance operations with climate change objectives and sustainable development goals, emphasizing energy conservation, resilience, and environmental safety. Their strategic approach positions maintenance as a proactive contributor to global sustainability imperatives.

Data-driven benchmarking tools are playing an increasing role to quantify and optimize social and environmental impacts related to maintenance activities. Lai et al. (2024) explored carbon emissions and maintenance costs in commercial buildings, identifying correlations between building traits and sustainability metrics. Passarelli et al. (2023) similarly emphasized environmental life cycle assessments, advocating circular and regenerative building strategies to reduce embodied impacts in affordable housing. These data-centric tools provide valuable insights for sustainable decision-making in maintenance planning.

**Research Gaps and Recommendations**

Despite technological progress, significant research gaps and implementation barriers remain. Long et al. (2024) highlight the absence of universal industry standards and the need for inclusive frameworks that centralize diverse stakeholders across building lifecycle phases. This lack of standardization limits interoperability and data exchange, challenging the digital maturity of building maintenance systems.

Himeur et al. (2023) emphasize additional constraints including data privacy, system security, and limited reliability of real-world AI models in building automation and management systems. They advocate for further development in robust data infrastructures and privacy-preserving analytics.

User involvement and cost effectiveness also remain underexplored areas. Salleh et al. (2023) stress the importance of stakeholder participation in sustainable heritage building maintenance to ensure long-term success. Husain et al. (2020) emphasize the skills mismatch encountered in building surveying graduates, which impacts effective maintenance management and adoption of intelligent technologies.

Collectively, these studies recommend advancing research on sustainable business models, enhancing education and training, fostering stakeholder engagement, and addressing barriers to technological adoption in diverse geographical and socio-economic contexts. Bridging these gaps is critical to achieving the full potential of intelligent, sustainable, and resilient building maintenance systems.

## CONCLUSIONS

The review underscores the transformative impact of advanced technologies such as AI, digital twins, IoT, and robotics in intelligent building maintenance, highlighting significant progress in predictive diagnostics, real-time monitoring, and sustainability practices. Nevertheless, it also identifies critical barriers including organizational inertia, data security concerns, and fragmentation issues that hinder full deployment. Sustainable strategies emphasizing energy efficiency, waste reduction, and stakeholder involvement are vital for achieving broader environmental and social goals. Moving forward, integrating socio-technical systems, enhancing data interoperability, and conducting extensive real-world validation are essential to develop resilient, adaptive, and sustainable building management frameworks.

## ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Universiti Teknologi MARA (UiTM) for providing the facilities and academic environment that supported the completion of this study. Appreciation is also extended to colleagues and students from the Centre of Studies for Building Surveying, Faculty of Built Environment, UiTM, for their constructive feedback and assistance during data collection. Special thanks are due to the participating organizations and stakeholders for their valuable cooperation and contributions.

## REFERENCES

1. Barroso, S., Bustos, P., & Núñez, P. (2023). Towards a cyber-physical system for sustainable and smart building: a use case for optimising water consumption on a SmartCampus. Journal of Ambient Intelligence and Humanized Computing, 14, 0-0. https://doi.org/10.1007/s12652-021-03656-1
2. Pedral Sampaio, R., Costa, A. A., & Flores-Colen, I. (2023). A discussion of digital transition impact on facility management of hospital buildings. Facilities, 41, 0-0. https://doi.org/10.1108/F-07-2022-0092
3. Hauashdh, A., Yunusa-Kaltungo, A., Jailani, J., & Gamil, Y. (2024). An integrated framework for sustainable and efficient building maintenance operations aligning with climate change, SDGs, and emerging technology. Results in Engineering, 21, 0-0. https://doi.org/10.1016/j.rineng.2024.101822
4. Peng, Y., Zhang, M., Yu, F., Xu, J., & Gao, S. (2020). Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration. Advances in Civil Engineering, 2020, 0-0. https://doi.org/10.1155/2020/8846667
5. Long, W., Bao, Z., Chen, K., Ng, S. T., & Wuni, I. Y. (2024). Developing an integrative framework for digital twin applications in the building construction industry: A systematic literature review. Advanced Engineering Informatics, 59, 0-0. https://doi.org/10.1016/j.aei.2023.102346
6. Lu Vivi, Q., Parlikad, A. K., Woodall, P., Ranasinghe, G. D., & Heaton, J. (2019). Developing a dynamic digital twin at a building level: Using Cambridge campus as case study. No Journal, 0-0. https://doi.org/10.1680/icsic.64669.067
7. Himeur, Y., Elnour, M., Fadli, F., Meskin, N., Petri, I., Rezgui, Y., Bensaali, F., & Amira, A. (2023). AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives. Artificial Intelligence Review, 56, 0-0. https://doi.org/10.1007/s10462-022-10286-2
8. Villa, V., Naticchia, B., Bruno, G., Aliev, K., Piantanida, P., & Antonelli, D. (2021). IoT open-source architecture for the maintenance of building facilities. Applied Sciences (Switzerland), 11, 0-0. https://doi.org/10.3390/app11125374
9. Abidi, M. H., Mohammed, M. K., & Alkhalefah, H. (2022). Predictive Maintenance Planning for Industry 4.0 Using Machine Learning for Sustainable Manufacturing. Sustainability (Switzerland), 14, 0-0. https://doi.org/10.3390/su14063387
10. Bouabdallaoui, Y., Lafhaj, Z., Yim, P., Ducoulombier, L., & Bennadji, B. (2021). Predictive maintenance in building facilities: A machine learning-based approach. Sensors (Switzerland), 21, 0-0. https://doi.org/10.3390/s21041044
11. Nelson, W., & Dieckert, C. (2024). Machine Learning-Based Automated Fault Detection and

Diagnostics in Building Systems. Energies, 17, 0-0. https://doi.org/10.3390/en17020529

12. Ogunbayo, B. F., Aigbavboa, C. O., Thwala, W., Akinradewo, O., Ikuabe, M., & Adekunle, S. A. (2022). Review of Culture in Maintenance Management of Public Buildings in Developing Countries. Buildings, 12, 0-0. https://doi.org/10.3390/buildings12050677
13. Au-Yong, C. P., Azmi, N. F., & Myeda, N. E. (2022). Promoting employee participation in operation and maintenance of green office building by adopting the total productive maintenance (TPM) concept. Journal of Cleaner Production, 352, 0-0. https://doi.org/10.1016/j.jclepro.2022.131608
14. Zulkifly, U. K. Z., Zakaria, N., & Mohd-Danuri, M. S. (2021). The adoption of total productive maintenance (TPM) concept for maintenance procurement of green buildings in Malaysia. International Journal of Sustainable Construction Engineering and Technology, 12, 0-0. https://doi.org/10.30880/ijscet.2021.12.01.005
15. Nikolaou, I., & Anthopoulos, L. (2024). Smart Cities as Hubs: A Use Case in Public School Buildings. Buildings, 14, 0-0. https://doi.org/10.3390/buildings14020517
16. Herbers, P., Çelik, F., & König, M. (2024). Autonomous Defect Inspection and Mapping for Building Maintenance. No Journal, 0-0. https://doi.org/10.1061/9780784485248.124
17. Olimat, H., Liu, H., & Abudayyeh, O. (2023). Enabling Technologies and Recent Advancements of Smart Facility Management. Buildings, 13, 0-0. https://doi.org/10.3390/buildings13061488
18. Zaheer, M. I., Ajayi, S. O., Zulu, S. L., Oyegoke, A., & Kazemi, H. (2021). Understanding the key competencies of market-ready building surveying graduates from employers' perspectives. Journal of Engineering, Design and Technology, 19, 0-0. https://doi.org/10.1108/JEDT-01-2020-0012
19. Husain, S. H., Che-Ani, A. I., & Affandi, H. M. (2020). Mismatch in supply and demand of building surveying graduates' skills: A triangulation perspective. Journal of Technical Education and Training, 12, 0-0. https://doi.org/10.30880/jtet.2020.12.04.007
20. Tavakoli, P., Yitmen, I., Sadri, H., & Taheri, A. (2024). Blockchain-based digital twin data provenance for predictive asset management in building facilities. Smart and Sustainable Built Environment, 13, 0-0. https://doi.org/10.1108/SASBE-07-2023-0169
21. Marzouk, M., Labib, N., & Metawie, M. (2024). Blockchain technology applications in maintaining heritage buildings. Journal of Cultural Heritage, 67, 0-0. https://doi.org/10.1016/j.culher.2024.02.005
22. Kifokeris, D., Tezel, A., & Moon, S. (2024). Decision-Making Framework for Implementing Blockchain in Building Operations and Maintenance (O&M). No Journal, 0-0. https://doi.org/10.1061/9780784485231.059
23. Serrano, W. (2020). Long Short-Term Memory in Intelligent Buildings. No Journal, 0-0. https://doi.org/10.1109/iCCECE49321.2020.9231135
24. Shao, Z., Li, Y., Huang, P., Abed, A. M., Ali, E., Elkamchouchi, D. H., Abbas, M., & Zhang, G. (2023). Analysis of the opportunities and costs of energy saving in lightning system of library buildings with the aid of building information modelling and Internet of things. Fuel, 352, 128918. https://doi.org/10.1016/j.fuel.2023.128918
25. Ren, C., Zhu, H. C., Wang, J., Feng, Z., Chen, G., Haghighat, F., & Cao, S. J. (2023). Intelligent operation, maintenance, and control system for public building: Towards infection risk mitigation and energy efficiency. Sustainable Cities and Society, 93, 104533. https://doi.org/10.1016/j.scs.2023.104533
26. Prol-Godoy, I., Picallo-Perez, A., Sala-Lizarraga, J. M., & Rey-Martínez, J. (2024). Experimental test of a building thermal system for preventive maintenance based on thermoeconomic analysis. Energy Storage and Saving, 3, 100081. https://doi.org/10.1016/j.enss.2023.08.002
27. Wong, W. F., Olanrewaju, A. L., & Lim, P. I. (2021). Value-based building maintenance practices for public hospitals in Malaysia. Sustainability (Switzerland), 13(11), 6200. https://doi.org/10.3390/su13116200
28. Passarelli, R. N., & Mouton, B. J. (2023). Embodied life cycle impacts of lightweight building methods for affordable houses in the USA: Comparison of conventional, circular, and regenerative strategies. Journal of Building Engineering, 77, 107513. https://doi.org/10.1016/j.jobe.2023.107513
29. Arsakulasooriya, K. K., Sridarran, P., & Sivanuja, T. (2024). Applicability of lean maintenance in commercial high-rise buildings: A case study in Sri Lanka. Facilities, 42, 123456. https://doi.org/10.1108/F-10-2022-0131
30. Salas, J., & Yepes, V. (2024). Improved delivery of social benefits through the maintenance planning of public assets. Structure and Infrastructure Engineering, 20(1), 234-249.

https://doi.org/10.1080/15732479.2022.2121844

31. Jiang, F., Xie, H., Inti, S., Issa, R. R. A., Vanka, V. S. V., Yu, Y., & Huang, T. (2024). Data-driven decision support for equipment selection and maintenance issues for buildings. Buildings, 14(4), 1436. https://doi.org/10.3390/buildings14020436
32. Abdul Majid, N. H., Denan, Z., Abdullah, F. H., & Mohd Noor, M. S. (2015). Shariah Compliance Hospitality Building Design: A Malay Muslim Oriented Architecture. Procedia - Social and Behavioral Sciences, 201, 277-284. https://doi.org/10.1016/j.sbspro.2015.08.159
33. Salleh, N. N., Norazman, N., Muhammad, S. T., & Ibrahim, R. (2023). Strategic planning of sustainable maintenance in heritage school buildings: Malaysia perspectives. International Journal of Building Pathology and Adaptation. https://doi.org/10.1108/IJBPA-04-2022-0060
34. Hauashdh, A., Jailani, J., Abdul Rahman, I., & AL-fadhali, N. (2022). Strategic approaches towards achieving sustainable and effective building maintenance practices in maintenance-managed buildings: A combination of expert interviews and a literature review. Journal of Building Engineering, 45, 103490. https://doi.org/10.1016/j.jobe.2021.103490
35. Ciuffreda, A. L., Trovatelli, F., Meli, F., Caselli, G., Stramaccioni, C., Coli, M., & Tanganelli, M. (2024). Historic building information modeling for conservation and maintenance: San Niccolo's Tower Gate, Florence. Heritage, 7(3), 64. https://doi.org/10.3390/heritage7030064
36. Kim, K. P., Freda, R., & Nguyen, T. H. D. (2020). Building information modelling feasibility study for building surveying. Sustainability (Switzerland), 12. https://doi.org/10.3390/su12114791
37. Keskin, K., & Erbay, M. (2016). A Study on the Sustainable Architectural Characteristics of Traditional Anatolian Houses and Current Building Design Precepts. Procedia - Social and Behavioral Sciences, 216. https://doi.org/10.1016/j.sbspro.2015.12.078
38. Asare, K. A. B., Liu, R., & Anumba, C. J. (2023). Building information modelling for airport facility management: the case of a US airport. Infrastructure Asset Management, 11. https://doi.org/10.1680/jinam.22.00019
39. Abdul-Aziz, A. R., Suresh, S., & Renukappa, S. (2020). The conundrum of professionalising building surveying in Malaysia. International Journal of Building Pathology and Adaptation, 38. https://doi.org/10.1108/IJBPA-10-2019-0086
40. Hoxley, M. (2012). UK building surveying education: The graduates' view. Facilities, 30. https://doi.org/10.1108/02632771211208495
41. Murtaza, F. F. N., Ibrahim, I., & Abdullah, A. (2020). The orientation setting of buildings in the traditional Malay settlement: A case study of kg seri tanjung, sungai udang, melaka. Planning Malaysia, 18. https://doi.org/10.21837/pm.v18i12.752
42. Mong, S. G., Mohamed, S. F., & Misnan, M. S. (2018). Key strategies to overcome cost overruns issues in building maintenance management. International Journal of Engineering and Technology (UAE), 7. https://doi.org/10.14419/ijet.v7i2.29.13330
43. Desbalo, M. T., Woldesenbet, A. K., Bargstädt, H. J., & Yehualaw, M. D. (2024). Critical factors that influence the effectiveness of facility maintenance management practice in public university buildings in Ethiopia: an exploratory factor analysis. Cogent Engineering, 11. https://doi.org/10.1080/23311916.2024.2307150
44. Ayokunle, L., Aigbavboa, C., Ngcobo, N., Aghimien, D., & Adesominu, O. (2024). Measures to Improve the Maintenance of University Buildings in Nigeria. American Journal of Civil Engineering. https://doi.org/10.11648/j.ajce.20241201.12
45. Haixiang Lin, Nana Hu, Qiao He, Zhengxiang Zhao, & Wansheng Bai. (2024). Construction of a Multi-Modal Knowledge Graph for Railway Equipment Operation and Maintenance Based on Building Information Model Data-Driven Approach. https://doi.org/10.11908/j.issn.0253-374x.23362
46. Zhansheng Liu, Guoliang Shi, Xiuli Du, & Zedong Jiao. (2024). Theory system and realization method of intelligent operation and maintenance based on digital twins. Tumu yu Huanjing Gongcheng Xuebao/Journal of Civil and Environmental Engineering, 46. https://doi.org/10.11835/j.issn.2096-6717.2022.040
47. Shubham Singh, Tejwant Singh Brar, Ritu Agrawal, Rajeev Garg, & Mohammad Arif Kamal. (2024). Analyzing Self-healing Concrete as a Remedial Measure for Repair and Maintenance of Buildings. Civil Engineering and Architecture, 12. https://doi.org/10.13189/cea.2024.120115
48. Joseph H. K. Lai, Mengxue Lu. (2024). Carbon emission and maintenance cost of commercial buildings:

Quantification, analysis and benchmarking. Journal of Cleaner Production, 447. https://doi.org/10.1016/j.jclepro.2024.141459

49. Olaseni, I. (2020). Digital Twin and BIM synergy for predictive maintenance in smart building engineering systems development. World Journal of Advanced Research and Reviews. https://doi.org/10.30574/wjarr.2020.8.2.0409.
50. S., Flanigan, K., & Berg'es, M. (2024). State-of-the-Art Review: The Use of Digital Twins to Support Artificial Intelligence-Guided Predictive Maintenance. ArXiv, abs/2406.13117. https://doi.org/10.48550/arxiv.2406.13117.
51. Van Dinter, R., Tekinerdogan, B., & Catal, C. (2022). Predictive maintenance using digital twins: A systematic literature review. Inf. Softw. Technol., 151, 107008. https://doi.org/10.1016/j.infsof.2022.107008.
52. Shuhaimi, A., Yusof, M., & Rahman, R. (2024). Drivers, Capabilities, and Challenges for Adopting Digital Twin in Facility Management: A Profound Qualitative Investigation. Planning Malaysia. https://doi.org/10.21837/pm.v22i32.1528.