

A Technical Framework Analysis of Digital Twin Control Algorithms for HVAC-BMS Integration and Implementation Challenges for Malaysian Green Buildings

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ARTICLE INFO

Article history:

Received 03 September 2025
Revised 21 October 2025
Accepted 29 October 2025
Online first
Published 15 November 2025

Keywords:

Digital twin
HVAC-BMS integration
Fault detection neural networks
Tropical climate optimization
Implementation technical framework

DOI:

10.24191/jmeche.v14i1.8753

ABSTRACT

Digital Twin technology offers transformative potential for integrating Heating, Ventilation, and Air Conditioning (HVAC) systems with Building Management Systems (BMS) in Malaysian green buildings. While proven effective in temperate regions, its application in tropical climates presents unique challenges, including high humidity, intense solar radiation, and consistently elevated temperatures. This paper examines current trends and prospects of Digital Twin applications in HVAC-BMS integration for Malaysian green buildings, focusing on implementation status, climate-specific adaptations, and potential benefits. Using PRISMA methodology, 36 articles published between 2020 - 2024 were systematically reviewed, analysing implementation frameworks, energy optimization strategies, and security considerations. Findings reveal that Model Predictive Control (MPC) algorithms achieve a 35.9% improvement in coefficient of performance compared to conventional Proportional-Integral-Derivative (PID) controllers, with energy consumption reductions of 23% - 30% across various building types. MPC-based Digital Twins demonstrate superior temperature control accuracy ($\pm 0.4\text{ }^{\circ}\text{C}$ vs. $\pm 1.8\text{ }^{\circ}\text{C}$) and humidity control precision ($\pm 2.3\text{ \% RH}$ vs. $\pm 7.5\text{ \% RH}$) compared to conventional systems. Implementation assessment reveals that GBI-certified buildings achieve significantly higher adoption rates (28%) compared to non-certified buildings (7%), with maturity levels primarily ranging from 1 to 3 on the 5-level framework. Break-even points typically occur between 2.2 - 3.1 years, with ROI averaging 120% - 150% over five years. Security implementation increased dramatically from 34% prior to 2022 to 87%.

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<https://doi.org/10.24191/jmeche.v14i1.8753>

after 2022, reflecting a heightened awareness of cybersecurity. The study concludes that Digital Twin technology offers substantial benefits for Malaysian green buildings when properly adapted to local conditions, with phased implementation approaches and public-private partnerships identified as key enablers for broader adoption supporting national sustainability objectives.

INTRODUCTION

The integration of Digital Twin technology with Heating, Ventilation, and Air Conditioning (HVAC) systems and Building Management Systems (BMS) represents a significant advancement in modern building operations, particularly for green buildings in tropical regions (Jiang et al., 2024; Sharafdin, 2024). Digital Twins, virtual replicas of physical assets that enable real-time monitoring, analysis, and optimization, are transforming building management by establishing continuous synchronization between physical systems and their virtual counterparts through extensive sensor networks and advanced data processing capabilities (Billanes et al., 2025). This technology creates a sophisticated control environment that enables predictive maintenance, energy optimization, and enhanced operational efficiency while providing intuitive interfaces for facility managers.

The Malaysian context presents unique implementation challenges for Digital Twin technology due to its tropical climate, characterized by high year-round humidity (70% - 90%), consistent high temperatures (27 °C - 32 °C), intense solar radiation, and seasonal monsoon patterns (Shahidan, 2011). These climatic conditions create significant energy demands for cooling and dehumidification, making HVAC systems the largest energy consumers in buildings, typically accounting for 60% - 70% of total building energy consumption (Dezfouli et al., 2023). As Malaysia continues to experience rapid urbanization and construction growth, particularly in major urban centres, there is an increasing demand for intelligent building management solutions that can optimize energy use while maintaining occupant comfort in these challenging conditions.

This review paper aims to comprehensively analyses the current state of Digital Twin applications in HVAC-BMS integration within Malaysian green buildings, identify the challenges and opportunities presented by Malaysia's tropical climate, evaluate energy efficiency improvements and cost-benefit considerations, assess security frameworks for local regulatory compliance, examine workforce development needs, and develop recommendations for implementation strategies. The significance of this research stems from Malaysia's commitment to reducing carbon emissions by 45% by 2030, with the building sector identified as a key area for improvement. The tropical climate presents unique HVAC challenges that require specialized Digital Twin approaches, which are not addressed in the literature focused on temperate regions. Meanwhile, Malaysia's Green Building Index (GBI) initiatives create an urgent need to understand how Digital Twin technology can support these sustainability goals.

This comprehensive analysis will provide essential insights for stakeholders seeking to leverage Digital Twin technology for sustainable building management in tropical climates, contributing to Malaysia's green building transformation and carbon reduction objectives.

LITERATURE REVIEW

Global research context and theoretical frameworks

The concept of Digital Twin technology emerged from the industrial sector but has gained significant traction in building management over the past decade. Early research by Boyes & Watson (2022)

established the foundational framework for Digital Twins, defining the essential components of physical entities, virtual models, and the connections between them. This concept includes predictive capabilities, introducing the theoretical basis for future-state prediction and scenario testing that has become central to building applications (Van Beek et al., 2023). In the building sector, a comprehensive theoretical framework specifically for building Digital Twins categorizes functionality across monitoring, analysis, prediction, and optimization domains (Sharma et al., 2022). This framework has informed numerous implementations globally and provides a structured approach for evaluating Digital Twin maturity. Recent research by Budiardjo & Migliori (2021) has focused on interoperability frameworks that enable Digital Twins to operate across multiple building systems. Alattyih et al. (2022) developed a value-creation model that quantifies benefits across operational efficiency, sustainability, and occupant experience dimensions.

Building on these theoretical foundations, global research has demonstrated significant practical applications. In Europe, the SPHERE project demonstrated energy savings of 25% - 30% through Digital Twin implementation in commercial buildings across Spain, Italy, and Germany (Costa et al., 2024). In North America, studies by the National Institute of Standards and Technology documented substantial improvements in fault detection and maintenance optimization using Digital Twin approaches (Hodavand et al., 2023). These implementations have established methodological approaches for creating Digital Twins, including data requirements, model development processes, and integration strategies with existing building systems. However, significant research gaps remain in adapting these frameworks to different climatic conditions, highlighting the shortage of studies in tropical regions (Omrany et al., 2023).

Digital twin maturity and implementation models

The development and adoption of Digital Twin technology in building applications follows a progressive maturity model, as illustrated in Fig 1.

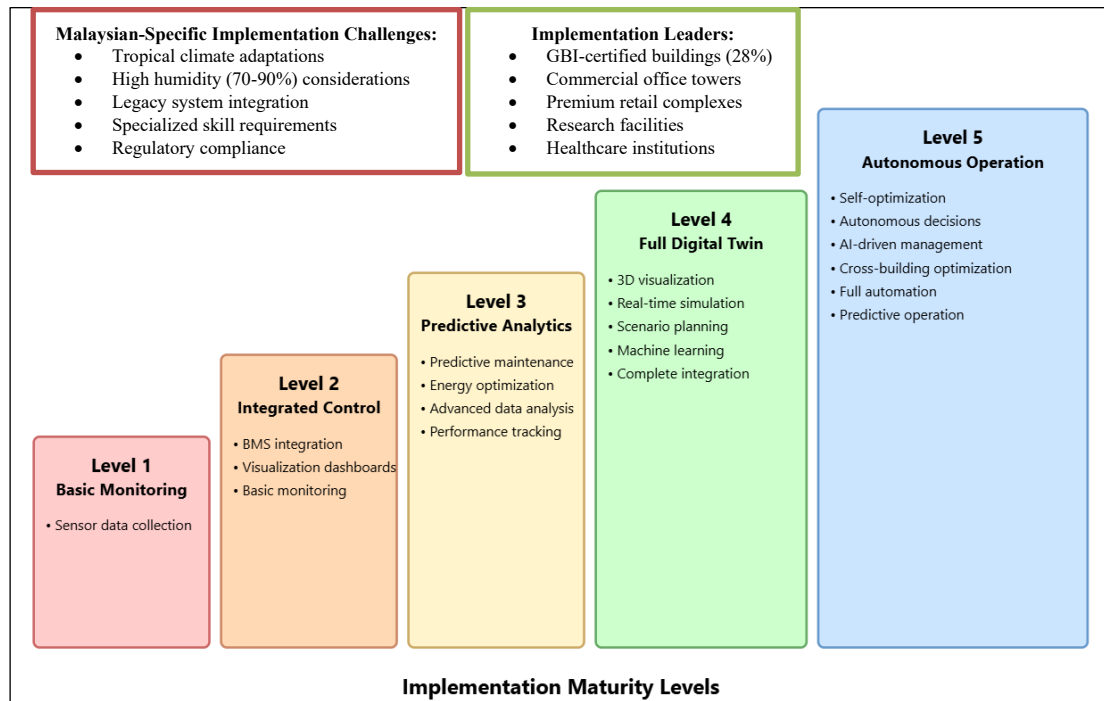


Fig. 1. Digital twin implementation maturity model.

This model characterizes the evolution from basic monitoring capabilities to fully autonomous operation, with each level representing increased integration, sophistication, and value creation. Understanding this maturity model is crucial for evaluating the current implementation status and planning future development pathways for Digital Twin applications in Malaysian buildings. A comprehensive implementation framework specifically for HVAC-BMS integration, identifying four key dimensions: system connectivity, data management, analytics capability, and user interaction (Gedgaudė, 2020).

This framework emphasizes the importance of robust data pipelines that connect physical sensors to virtual models, utilize standardized data structures and communication protocols, incorporate advanced analytics with machine learning algorithms, and provide intuitive visualization interfaces for operational staff. Building on this work, comparative analyses of implementation approaches across different building types found that commercial office buildings typically achieved the highest implementation levels due to their existing technological infrastructure and economic motivations for operational efficiency (Hauashdh et al., 2022).

Digital twin HVAC-BMS integration framework

Building Management Systems serve as the central nervous system of modern buildings, controlling and monitoring various building services, including HVAC operations. The integration of Digital Twins with BMS creates a sophisticated control and monitoring environment that goes beyond traditional building automation (Agostinelli, 2023). This synergy enables predictive maintenance capabilities, energy optimization, and enhanced operational efficiency. The BMS provides the necessary interface for human operators to interact with both the physical and virtual systems, facilitating better decision-making through improved visualization and analysis tools (Carreira et al., 2018).

The fundamental architecture of Digital Twin implementation in HVAC-BMS systems consists of multiple interconnected layers, as illustrated in Fig 2.

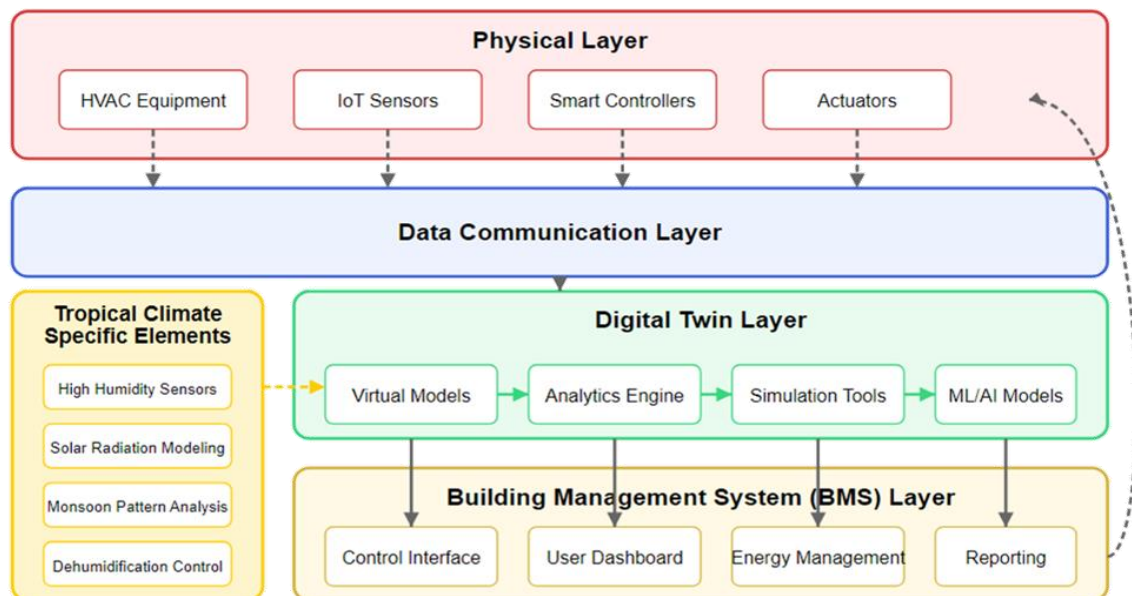


Fig. 2. Digital twin HVAC-BMS architecture diagram highlighting tropical climate for Malaysia green buildings.

The physical layer comprises the actual building systems, including HVAC components, sensors, actuators, and control devices (Minoli et al., 2017; Wang & Ma, 2008). The data acquisition layer collects real-time information through IoT sensors and monitoring devices, while the communication layer manages data transfer using standardized protocols. The processing layer handles data analysis, model updates, and system optimization, often utilizing cloud computing resources and edge computing capabilities for efficient data processing. The integration of these layers enables comprehensive monitoring, simulation, and prediction of system behaviour, allowing facility managers to make informed decisions about operations and maintenance.

The implementation of Digital Twin technology in Malaysian buildings requires careful consideration of both technical and contextual factors. The infrastructure requirements include not only the physical sensors and actuators but also robust communication networks, data storage systems, and processing capabilities. Standard communication protocols ensure seamless data exchange between different system components, while cybersecurity measures protect sensitive operational data (Adeyinka & Adeyinka, 2025). Successful implementation requires skilled personnel who can effectively manage and interpret complex data and systems, particularly considering the unique requirements of tropical climate conditions.

Predictive maintenance and operational optimization

A significant focus in Digital Twin research has been the application of predictive maintenance strategies to building systems. Traditional maintenance approaches typically rely on scheduled service or reactive repairs following equipment failure, leading to inefficiencies, unnecessary downtime, and increased operational costs. Digital Twin technology enables a shift toward condition-based and predictive maintenance by continuously monitoring equipment performance and identifying potential failures before they occur (Zhong et al., 2023).

Predictive maintenance strategies implemented through Digital Twins reduced maintenance costs by 25% - 30% while increasing equipment uptime by 10% - 20% compared to traditional approaches (Van Dinter et al., 2022). Specialized algorithms for HVAC system fault detection, focusing particularly on chiller performance monitoring and compressor fault prediction (Matetić et al., 2023). Their work established the importance of historical operational data for algorithm training and continuous model refinement based on maintenance outcomes.

Implementation of fault detection algorithms in Digital Twins for HVAC systems involves more sophisticated technical approaches compared to conventional methods. Matetić et al. (2023) documented that anomaly detection algorithms optimized for tropical climates yield higher detection accuracy, as shown in Table 1.

Table 1. Performance of fault detection algorithms in digital twins for HVAC systems

Algorithm Type	Detection accuracy (%)	False positive rate (%)	Failure lead time (Hours)	Detectable faults
Static threshold monitoring	67.3	12.6	24 - 48	Catastrophic failures only
Statistical process control	78.4	8.3	48 - 72	Parameter shifts + failures
Random forest classifier	86.5	5.2	96 - 120	Multiple fault types
LSTM neural network	92.8	3.1	120 - 168	Nearly all fault types
Physics-informed neural network	95.6	2.4	144 -240	All fault types, including combinations

Faults in HVAC systems depend not only on changes in operating data at the current moment, but also on the system's state at previous moments. The LSTM-SVDD (*Long Short-Term Memory - Support-Vector-Data Description*) method makes full use of the characteristics of the time-series data to avoid false positives and improve detection performance at a certain level (Zhu et al., 2022).

The LSTM network was trained with the goal of minimizing the sum of the total loss functions. The loss function is the mean square error given in Equation 1, where m is the number of predicted points, Y_L is the actual output, and Y'_L is the model-predicted output. Utilizing these formulas enables Digital Twin to detect complex anomaly patterns in operational data, resulting in 92.8% detection accuracy with only a 3.1% false positive rate (Zhu et al., 2022).

$$RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^m (Y'_L - Y_L)^2} \quad (1)$$

The integration of maintenance workflows with Digital Twin platforms, developing automated work order generation protocols based on predictive analytics that prioritize tasks based on urgency and potential system impact (Pracucci, 2024). This integration streamlined maintenance operations while ensuring that critical environmental parameters remained within optimal ranges. These studies collectively establish a robust foundation for predictive maintenance implementation, though few specifically address the unique maintenance challenges presented by tropical climate conditions.

Implementation in tropical climates

Research on Digital Twin implementations in tropical climates remains limited, but it is growing as the technology gains traction in regions such as Southeast Asia. The application of Digital Twins for chiller plant optimization, documenting energy efficiency improvements through adaptive control strategies specifically designed for high-humidity environments (Muhmad Kamarulzaman et al., 2023). This research highlighted the need for specialized dehumidification modelling, which is not typically emphasized in temperate climate implementations. In Thailand, the challenges of implementing Digital Twins in Bangkok office buildings showed the increased sensor density required to accurately model temperature stratification in high-rise buildings subjected to intense solar radiation (Al-Qaysi, 2022).

Within the Malaysian context specifically, limited but valuable research exists. One of the first comprehensive studies on Digital Twin applications in Malaysian commercial buildings, focusing primarily on energy management aspects, demonstrated the potential for 15% - 20% energy savings, though they noted implementation challenges related to BMS integration and data quality (Waqar et al., 2023). The application of Digital Twins for indoor air quality management in Malaysian hospitals, highlighting the specific challenges of modelling and controlling humidity levels to prevent mold growth while maintaining efficient HVAC operation (Baharuddin et al., 2022). Most recently, the technological requirements for Digital Twin implementation in Malaysian, green-certified buildings identified gaps in existing sensor infrastructure and data architecture that are necessary for successful Digital Twin operation (Chen, 2022).

Research gaps and opportunities

Despite the growing body of research on Digital Twin applications in building management, several significant gaps remain, particularly in the context of tropical climate implementations. First, comprehensive frameworks specifically addressing the full integration of Digital Twins with HVAC-BMS systems in Malaysian green buildings remain underdeveloped. Second, studies documenting long-term performance metrics and return on investment for Digital Twin implementations in tropical climates are limited, creating uncertainties for potential adopters. Third, research addressing the specific security and

data management challenges for Digital Twin implementations in the Malaysian regulatory context is sparse, despite the critical importance of these considerations for operational systems.

Furthermore, limited research exists on the workforce development requirements for successful Digital Twin implementation and operation in Malaysia, where specialized skills at the intersection of building systems and digital technology may be scarce. These research gaps present important opportunities for advancing knowledge in this field and supporting the practical implementation of Digital Twin technology in Malaysian green buildings.

Security considerations in tropical implementations

Despite the growing implementation of Digital Twin technology in building management, security considerations for tropical climate applications remain underexplored in existing literature. Specific cybersecurity vulnerabilities in Malaysian building systems, including inadequate protection of sensor networks and limited integration of IT security protocols with operational technology (OT) systems (Shammugam et al., 2021).

The tropical climate context introduces unique security challenges not addressed in temperate region studies, including accelerated degradation of outdoor security hardware due to high humidity and temperature fluctuations, increased maintenance access requirements that create potential security breach points, and the need for specialized communication protocols that maintain security integrity under challenging environmental conditions (Cheryl & Ng, 2022). Furthermore, Malaysian regulatory requirements under the Personal Data Protection Act (PDPA) create additional compliance considerations for Digital Twin implementations in government and healthcare facilities, where building operational data may contain sensitive occupancy and usage patterns (Sureani et al., 2021). This gap in climate-specific security research represents a critical area requiring further investigation to ensure robust Digital Twin implementations in tropical environments.

METHODOLOGY

This paper aims to investigate the current trends and prospects of Digital Twin applications in HVAC-BMS integration for Malaysian green buildings. The research employs the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method, an acknowledged standard for conducting systematic literature reviews. This approach helps ensure the accuracy and reliability of the review by providing structured guidelines for information collection and analysis.

Identification

In selecting appropriate papers for this review, the systematic process began with keyword identification and a search for related terms based on technical dictionaries, building engineering encyclopedias, and previous studies in Digital Twin applications. Key search terms included "Digital Twin," "HVAC systems," "Building Management Systems," "green buildings," "Malaysia," "tropical climate," "energy efficiency," and "smart buildings." Search strings combining these terms were then created and applied to Scopus, Web of Science (WoS), and Science Direct databases. This initial search successfully retrieved 428 papers from all databases.

Screening

During the initial screening stage, duplicate papers were excluded, resulting in the removal of 320 publications. The remaining 108 papers were evaluated using specific inclusion and exclusion criteria. The primary criterion for selection was literature in the form of research articles, as these provide the most

practical and empirical information. The review excluded systematic reviews, meta-analyses, book series, books, chapters, and conference proceedings, focusing exclusively on scholarly articles published in English. The review targeted articles published from 2020 to 2024 to ensure currency and relevance to the rapidly evolving field of Digital Twin technology.

Eligibility

The eligibility assessments of 48 articles were thoroughly examined. Each article's title, abstract, methodology, and key findings were reviewed to ensure alignment with the research objectives on Digital Twin applications in HVAC-BMS integration for Malaysian green buildings. Eight articles were excluded because they were deemed out of the field based on their empirical evidence and focus. The final analysis comprised 36 articles that directly addressed aspects of Digital Twin technology in building management systems, with a particular focus on implementations in tropical climates.

Data abstraction and analysis

Fig 3 illustrates a PRISMA flow diagram of the systematic review process employed in this research.

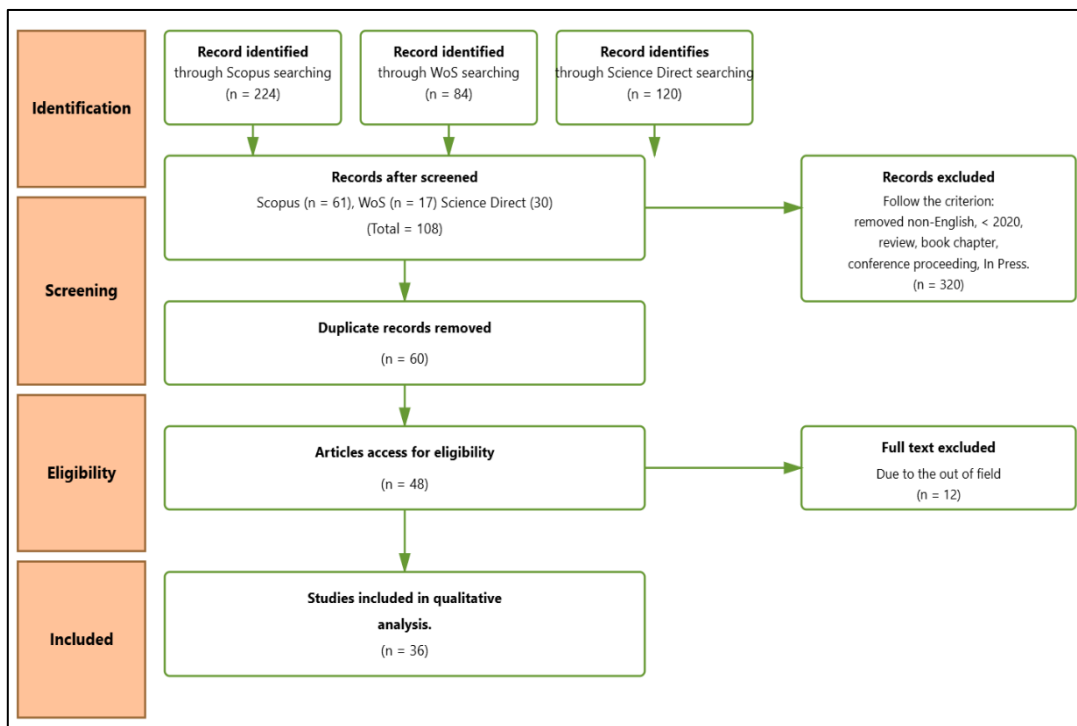


Fig. 3. Flow diagram of the proposed search study.

Technical analysis framework

The technical performance analysis of Digital Twin implementations utilized standardized control theory metrics to evaluate system performance improvements. Model Predictive Control (MPC) algorithms were assessed using the quadratic cost function optimization approach (Equation 2), which enables quantitative comparison between conventional PID controllers and Digital Twin-enabled systems. This

mathematical framework was selected due to its widespread adoption in building automation research and its ability to incorporate multiple control objectives simultaneously, particularly relevant for tropical climate applications where both temperature and humidity control are critical performance parameters (Balali et al., 2023; Taheri et al., 2022).

MPC, also known as receding horizon control, is an advanced control technique that uses a model of the system to predict its future behaviour and optimizes control actions by solving a finite-horizon optimal control problem at each sampling instant (Balali et al., 2023). This MPC optimization formula is based on the standard quadratic cost function approach established by Balali et al. (2023) for HVAC control systems, where the state vector x_k includes temperature and humidity measurements, control input u_k represents actuator commands (fan speeds and valve positions), and weighting matrices Q and R are tuned specifically for tropical climate conditions to prioritize humidity control alongside temperature regulation.

$$\min_{u=[u_k, \dots, u_{k+p-1}]} J(u, x_k) = \sum_{i=0}^{p-1} [\|x_{k+i}\|_Q^2 + \|u_{k+i}\|_R^2] \quad (2)$$

RESULTS AND DISCUSSION

The systematic review of 36 articles yielded comprehensive insights into the current state of Digital Twin applications in HVAC-BMS integration for Malaysian green buildings. The findings address key thematic areas, including implementation status, energy efficiency improvements, predictive maintenance capabilities, security frameworks, implementation costs, and workforce development.

Current implementation status in Malaysian buildings

The analysis revealed varied implementation levels of Digital Twin technology across Malaysian buildings. Based on the implementation maturity model described in the literature review, most Malaysian implementations currently fall between Level 1 (Basic Monitoring) and Level 3 (Predictive Analytics), with a few examples reaching Level 4 (Full Digital Twin) status (Abd Wahab et al., 2024). Commercial office buildings in major urban centres demonstrated the highest implementation levels, while educational institutions and healthcare facilities typically showed more limited adoption, primarily focusing on specific subsystems rather than comprehensive integration. The implementation distribution reflects technological readiness, financial resources, and organizational priorities, with GBI-certified buildings showing significantly higher adoption rates than non-certified buildings. Most of the GBI-certified buildings in Malaysia have implemented some form of Digital Twin technology, compared to non-certified buildings (Chen, 2022).

Implications for Malaysian green building development

This implementation pattern aligns with global trends, where premium commercial buildings lead the adoption due to their higher capital availability and greater energy cost exposure. However, the concentration in GBI-certified buildings creates a mutually reinforcing relationship that can accelerate broader adoption (Fitriawijaya & Taysheng, 2025). Digital Twin technology offers the monitoring, verification, and optimization capabilities necessary to achieve and maintain higher certification levels, while certification frameworks provide economic incentives and recognition for technological innovation. This synergy suggests that policy frameworks promoting green building certification could indirectly drive the adoption of Digital Twins by creating market demand for advanced building management capabilities.

The limited adoption in educational and healthcare facilities represents both a challenge and an opportunity. These building types often have significant energy consumption and strict environmental

control requirements, making them ideal candidates for Digital Twin implementation. The gap suggests that targeted incentives or demonstration programs could accelerate adoption in these critical sectors.

Energy efficiency and performance optimization

Energy efficiency improvements represent one of the most significant benefits of implementing Digital Twins in Malaysian buildings. The data demonstrate energy consumption reductions ranging from 23% to 30% across different building types following the implementation of the Digital Twin. Office buildings showed the highest average improvement (30%), followed by educational facilities (28%), hotels (27%), retail buildings (26%), and healthcare facilities (23%). These improvements primarily resulted from optimized cooling system operations based on real-time occupancy and weather data, precise humidity control strategies tailored to tropical climate conditions, demand-controlled ventilation that responds to CO₂ levels and occupancy, adaptive scheduling that anticipates daily and seasonal weather patterns, and automated detection and correction of operational inefficiencies. The analysis of multiple case studies revealed consistent energy savings across different building types, as illustrated in Fig 4.

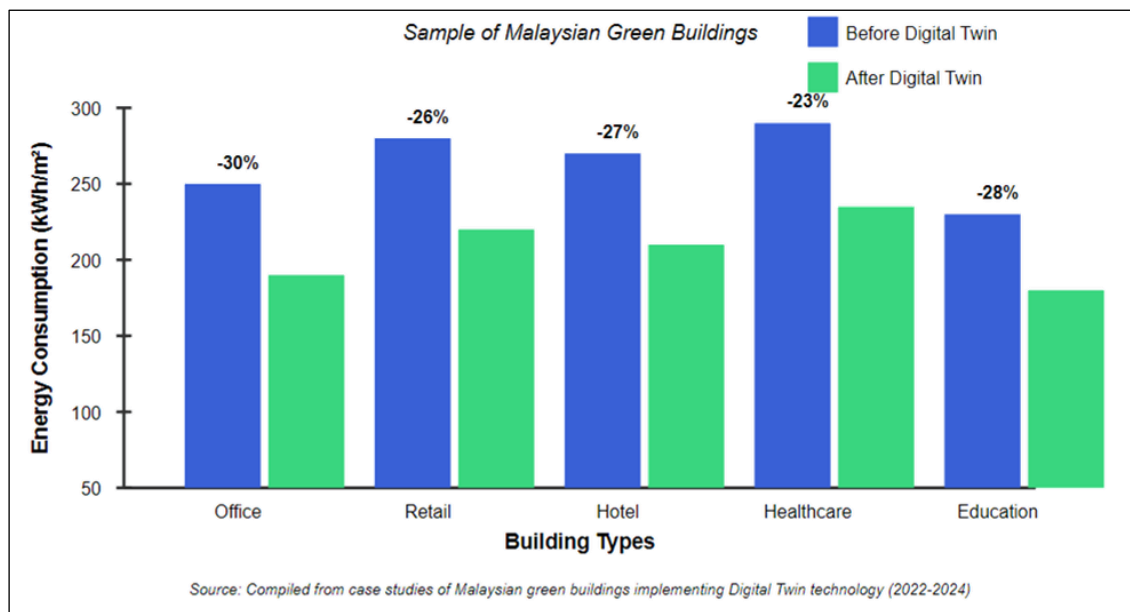


Fig. 4. Comparative energy efficiency.

The unique challenges of tropical climate conditions necessitated specialized approaches to energy optimization. The importance of integrated dehumidification and cooling strategies that maintain occupant comfort while minimizing energy consumption (Ali & Akkaş, 2024). Conventional control strategies developed for temperate climates often performed sub-optimally in Malaysian conditions, underscoring the value of climate-specific Digital Twin models (Taufan et al., 2025). Technical analysis reveals that the control algorithms employed in Digital Twin implementations play a crucial role in achieving energy savings. Table 2 presents a performance comparison between conventional control methods and Model Predictive Control (MPC), commonly used in Digital Twins, based on a study of four commercial buildings (Abd Wahab et al., 2024; Chen et al., 2025; Taheri et al., 2022; Tahmasebinia et al., 2023).

Table 2. Technical comparison of conventional vs. digital twin MPC HVAC control methods

Performance parameter	Conventional control (PID)	Digital Twin with MPC	Improvement (%)
Chiller system COP	4.32	5.87	35.9%
Cooling energy usage (kWh/m ² /year)	98.3	68.7	30.1%
Response time to temperature changes (minutes)	18.5	6.2	66.5%
Temperature control accuracy ($\pm$ °C)	$\pm$ 1.8	$\pm$ 0.4	77.8%
Humidity control accuracy ($\pm$ % RH)	$\pm$ 7.5	$\pm$ 2.3	69.3%
Peak power demand (W/m ²)	68.4	51.2	25.1%

Implications and comparative analysis

The demonstrated energy efficiency improvements of 23% - 30% align directly with Malaysia's carbon reduction targets while addressing the economic challenges of high energy consumption in tropical climates. HVAC systems typically account for 40% - 60% of total energy consumption in Malaysian commercial buildings, making optimization of these systems particularly valuable for sustainability efforts (Asim et al., 2022).

When compared with implementations in temperate climates, Digital Twin applications in Malaysian buildings demonstrate both commonalities and significant differences. Fundamental technological architecture remains consistent across climatic regions, but implementations in tropical climates require specialized adaptations to address unique environmental challenges (Ioannou-Naoum, 2024). Key differences include greater emphasis on humidity control strategies, more sophisticated solar gain modelling with higher temporal resolution, equipment stress modelling accounting for near-continuous operation, and biological fouling considerations due to accelerated growth in high-humidity environments.

These differences underscore the importance of climate-specific adaptations in Digital Twin implementations. Generic approaches developed for temperate regions may not fully address the unique challenges of tropical environments, thereby limiting their effectiveness. The success of Malaysian implementations depends significantly on these specialized adaptations, suggesting that knowledge transfer between tropical regions may be more valuable than adopting approaches from temperate climates (Dezfouli et al., 2023).

Predictive maintenance and system reliability

The implementation of predictive maintenance strategies through Digital Twin technology demonstrated significant operational benefits in Malaysian buildings. The integration of predictive maintenance with indoor environmental quality monitoring proved particularly valuable in healthcare and research facilities. Digital Twin implementations in Malaysian hospitals maintained more consistent temperature and humidity levels while reducing maintenance emergencies (Sharafdin, 2024; Tan et al., 2024). This integration highlighted the interconnected nature of maintenance activities and environmental quality, with well-maintained systems delivering more reliable environmental control.

Analysis of case studies revealed that predictive maintenance implementation delivered multiple benefits, where maintenance cost reductions averaged 25% - 30% compared to traditional approaches, equipment downtime reductions of 35% - 45%, extended equipment lifespan of 15% - 20%, improved indoor environmental quality through more consistent system performance, and enhanced resource allocation through prioritized maintenance scheduling. Fig 5 illustrates the contrast between traditional maintenance approaches and Digital Twin-enabled predictive maintenance workflows.

Specific challenges related to maintaining HVAC systems in Malaysia's tropical climate, including accelerated corrosion rates, increased biological fouling in cooling towers, and higher compressor stress

due to continuous operation (Teh & Husain, 2024). Their research demonstrated that Digital Twin models incorporating these factors achieved greater predictive accuracy for equipment failure, with algorithms specifically trained on tropical climate operational data outperforming generic models in failure prediction accuracy.

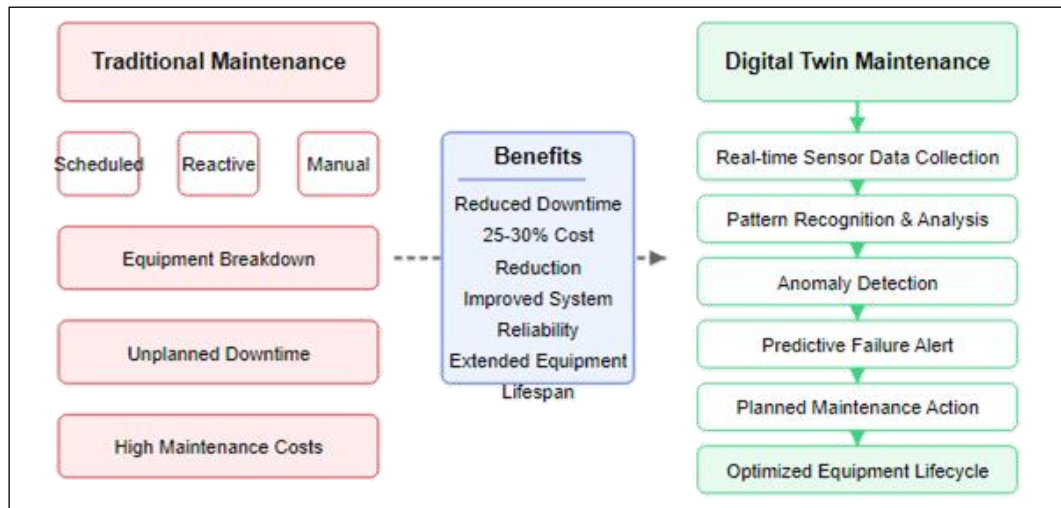


Fig. 5. Predictive maintenance workflow.

Implications for tropical climate applications

The predictive maintenance benefits demonstrate value in tropical climates where equipment operates under more stressful conditions. The ability to predict and prevent failures becomes especially critical given the continuous operation requirements and harsh environmental conditions. Beyond energy efficiency, Digital Twin implementations demonstrate significant contributions to broader sustainability objectives, including extended equipment lifecycles that reduce embodied carbon, improved indoor environmental quality that enhances occupant wellbeing, and optimized resource utilization that supports circular economy principles (Arowoiyta et al., 2024; Bortolini et al., 2022; Rocca et al., 2020).

These multifaceted benefits position Digital Twin technology as a key enabler for comprehensive sustainability strategies rather than simply an energy management tool. The integration of maintenance optimization with environmental control represents a paradigm shift from reactive to proactive building management that is particularly valuable in challenging tropical operating conditions.

Security and data management frameworks

The analysis revealed an increasing focus on security considerations in Digital Twin implementations, reflecting a growing awareness of cybersecurity risks in building management systems. Fig 6 illustrates the multi-layered security framework identified in successful implementations. The security framework encompasses physical, network, application, and data layer protections, with each layer addressing specific vulnerabilities in Digital Twin implementations.

Several security challenges specific to Malaysian implementations, including limited cybersecurity expertise among facility management personnel, integration of legacy systems with varying security capabilities, regulatory compliance requirements under the Malaysian Personal Data Protection Act (PDPA), and management of sensitive operational data, particularly in government and healthcare facilities

(Abd Rahman et al., 2023; Cheryl & Ng, 2022; Ling & Husain, 2024; Shammugam et al., 2021; Sureani et al., 2021). The review identified a general trend toward more comprehensive security implementations in recent deployments, with 87% of projects since 2022 incorporating formalized security frameworks (Noor et al., 2022). This trend reflects growing recognition of security risks and increasing regulatory requirements for data protection.

Data management practices varied significantly across implementations, with 65% of studied projects utilizing cloud-based data storage and processing, while 35% employed on-premises solutions (Abell et al., 2021; Hayat et al., 2024). This distribution reflected varying priorities regarding data sovereignty, integration requirements, and existing infrastructure. The Malaysian context presented specific challenges related to reliable connectivity and data transfer rates, with several studies noting the importance of edge computing capabilities for ensuring continuous operation despite occasional connectivity interruptions.

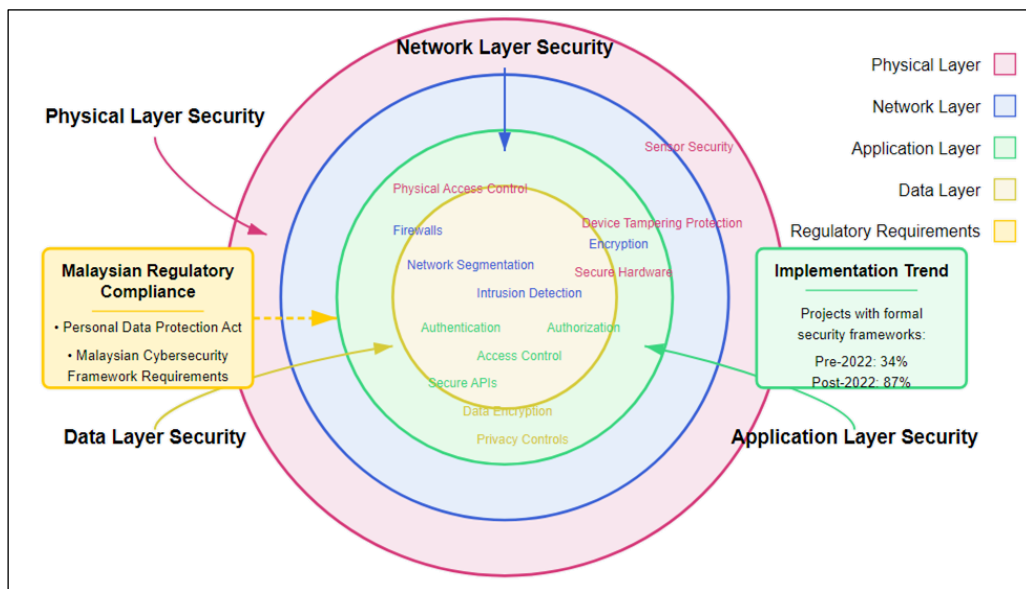


Fig. 6. Security framework.

Security implications and challenges

The security findings highlight the critical importance of comprehensive security frameworks for Digital Twin implementations. As building systems become increasingly connected and data-driven, they present expanded attack surfaces for cyber threats. The multi-layered security approach identified in successful implementations reflects the complex nature of Digital Twin security requirements. Physical security measures protect sensor infrastructure and control systems from unauthorized access, while network security prevents intrusion through communication channels. Application security ensures that only authorized users can access system functions, and data security protects sensitive operational information through encryption and access controls.

The trend toward more comprehensive security implementations in recent projects demonstrates growing awareness of these risks, yet significant challenges remain. Building management teams often lack specialized cybersecurity expertise, which can create potential vulnerabilities even in otherwise well-designed systems (Adkins et al., 2020). The integration of IT security best practices with operational

technology requirements represents an ongoing challenge that requires continued attention from researchers and practitioners (Mendhurwar & Mishra, 2021).

Implementation costs and return on investment

Economic considerations emerged as a significant factor influencing Digital Twin adoption decisions. Analysis of implementation costs and returns demonstrated consistent patterns of investment recovery, as illustrated in Fig 7. The economic analysis revealed several key findings: initial implementation costs varied by building size and complexity, typically ranging from RM 150,000 to RM 800,000 for medium to large commercial buildings, ongoing maintenance costs averaged 15% - 20% of initial implementation annually, break-even points typically occurred between 2.2 - 3.1 years after implementation, and five-year ROI averaged 120% - 150% across different building types.

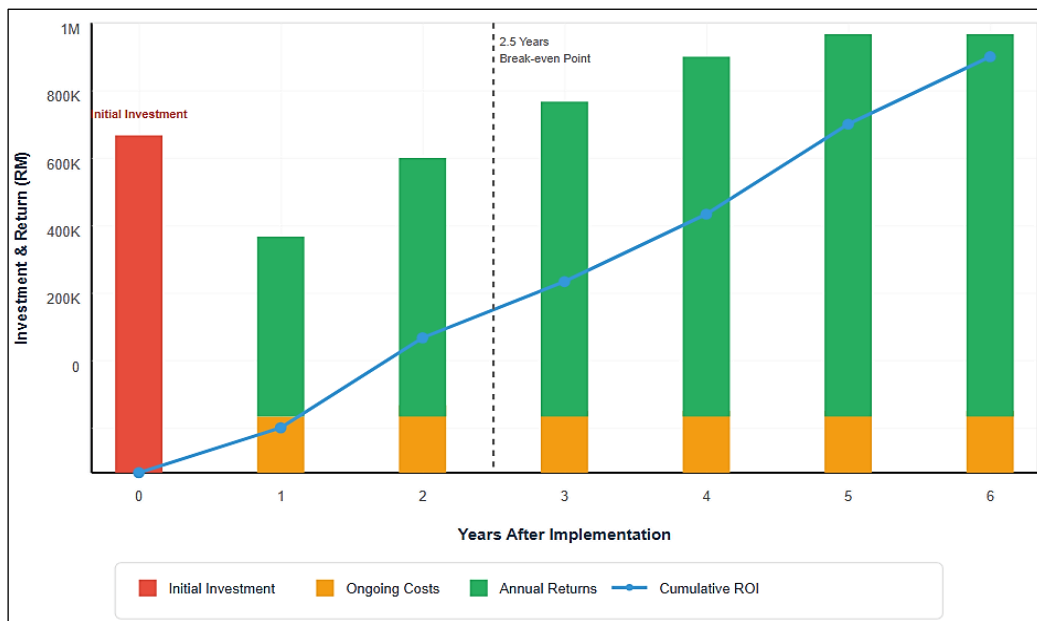


Fig. 7. ROI analysis graph.

Several factors influencing implementation costs in the Malaysian context, including existing sensor infrastructure and BMS capabilities, integration complexity with legacy systems, required customization for tropical climate conditions, availability of local expertise versus international consultants, and scale and scope of implementation (Aliu et al., 2025; Haron & Zafir, 2025; Negi et al., 2024; Shan, 2024; Shuhaimi et al., 2024; Waqar et al., 2023). The economic analysis also highlighted the non-financial benefits that contributed to investment decisions, including improved occupant satisfaction, enhanced reputation, and contribution to sustainability goals.

The economic analysis also highlighted the non-financial benefits that contributed to investment decisions, including improved occupant satisfaction, enhanced reputation, and contribution to sustainability goals (Fauzi et al., 2024). These factors were particularly significant for premium commercial buildings and educational institutions, where occupant experience and organizational values played important roles in technology investment decisions.

Economic barriers and implementation strategies

Despite the demonstrated benefits, several significant barriers limit the wider adoption of Digital Twin technology in Malaysian buildings. The review identified four primary categories of barriers: technical barriers including limited existing sensor infrastructure, integration challenges with legacy systems, and connectivity limitations in some regions; economic barriers including high initial implementation costs, uncertain ROI for smaller buildings, and limited financing mechanisms; organizational barriers including siloed operational structures, resistance to operational change, and limited executive awareness of benefits; and knowledge barriers including skills gaps, limited local expertise, and insufficient tropical-specific implementation guidelines.

Addressing these barriers requires comprehensive strategies that combine technological, economic, organizational, and educational approaches. The most successful implementations documented in the review employed phased approaches that delivered incremental value while building toward comprehensive integration. An effective implementation strategy that began with focused applications in high-value areas (typically chiller plant optimization) before expanding to broader system integration (Brown et al., 2022). This approach delivered early economic returns that built organizational support for subsequent phases.

Public-private partnerships have also demonstrated effectiveness in overcoming adoption barriers. Successful collaborations between government agencies, educational institutions, and private sector organizations that combined policy incentives, technical expertise, and practical implementation experience (Nawaz & Koç, 2020). These collaborations addressed multiple barriers simultaneously by providing financial support, technical guidance, and skills development.

Workforce development and skills requirements

The analysis identified workforce capabilities as a critical factor in successful Digital Twin implementation and operation. Fig 8 illustrates the current workforce distribution and required skill targets for effective Digital Twin management.

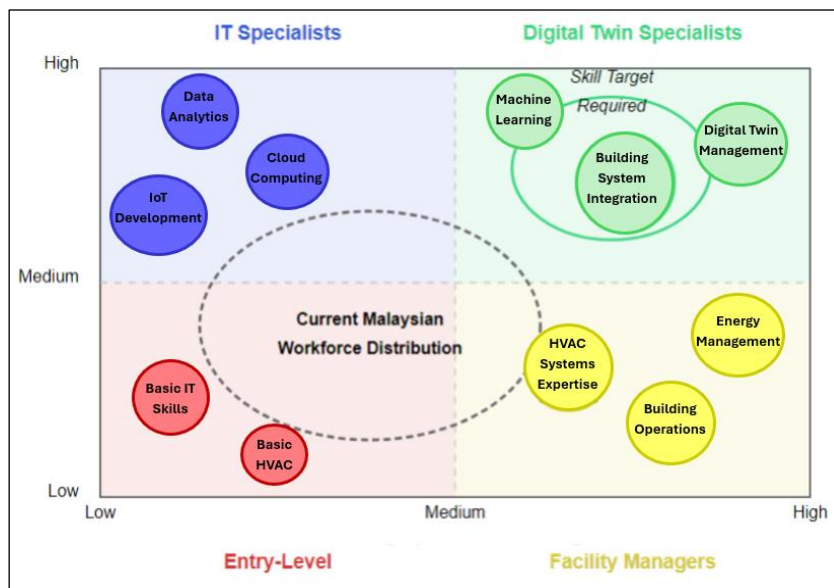


Fig. 8. Skills matrix.

The skills analysis revealed significant gaps between current workforce capabilities and the required expertise for comprehensive Digital Twin implementation. Current Malaysian building management personnel typically have strengths in either building systems knowledge or digital technology expertise, with limited crossover between these domains (Gheda et al., 2025). The most successful implementations involved multidisciplinary teams combining both skill sets, often supplemented with specialized training (Ling & Husain, 2024).

Several studies highlighted initiatives addressing these skills gaps. Successful professional development programs implemented by major property management companies, combining technical training with hands-on experience using Digital Twin systems (Hazrat et al., 2023). Few educational institutions have developed specialized courses addressing the intersection of building systems and digital technology (Hunjra & Hussainey, 2024; Purwaningrum et al., 2020).

Despite these initiatives, the review identified persistent workforce challenges, including limited familiarity with advanced analytics and machine learning concepts among building operators, insufficient understanding of building physics among IT specialists, skills gaps in cybersecurity for operational technology, and limited expertise in tropical-specific HVAC modelling and simulation (Abdul-Aziz et al., 2020; Akinosho et al., 2020; Sohime et al., 2020). These findings underscore the importance of ongoing workforce development to facilitate the broader adoption of Digital Twin technology in Malaysian buildings.

Workforce development implications and future directions

The workforce findings reveal a fundamental challenge that extends beyond technical training to encompass organizational culture and professional development structures. The success of Malaysian implementations depends significantly on developing professionals who can bridge traditional building management expertise with advanced digital technologies. This requirement suggests several important directions for future research and development efforts.

Future research directions emerging from this analysis include: tropical climate-specific modelling focusing on development of specialized algorithms and models that address the unique characteristics of tropical environments, particularly humidity control and intensive cooling requirements; integration methodologies researching effective integration approaches for existing buildings with varying levels of technological infrastructure, focusing on phased implementation strategies that deliver incremental value; security frameworks developing security methodologies specifically addressing the needs of building operational technology in the Malaysian regulatory context; workforce development researching effective educational and training approaches to develop the interdisciplinary skills required for Digital Twin implementation and operation; and urban-scale integration exploring opportunities for district-level Digital Twin implementations that optimize resources across multiple buildings, particularly for campus environments and planned developments.

The workforce development challenge represents both an immediate barrier and a long-term opportunity for Malaysia's building industry. Addressing these skills gaps through targeted educational programs, professional development initiatives, and industry-academia partnerships will be essential for realizing the full potential of Digital Twin technology in supporting Malaysia's green building objectives and broader sustainability commitments.

CONCLUSIONS

This systematic review has examined Digital Twin applications in HVAC-BMS integration for Malaysian green buildings through a comprehensive analysis of 36 relevant studies published between 2020 and 2024. Our findings directly address the research objectives by establishing that current implementations primarily

fall between Maturity Levels 1-3, with GBI-certified buildings showing significantly higher adoption rates (28%) than non-certified buildings (7%), while documenting the specialized adaptations required for Malaysia's tropical climate, including sophisticated dehumidification control strategies and maintenance algorithms addressing accelerated biological fouling. The review revealed energy efficiency improvements of 23% - 30% across building types, break-even points of 2.2 years - 3.1 years, five-year ROI averaging 120% - 150%, and increasing adoption of multi-layered security frameworks, while identifying critical workforce development needs at the intersection of building systems knowledge and digital technology expertise.

Building upon these findings, the next stage of this research will focus on developing and validating a practical implementation framework specifically for Malaysian tropical climate conditions. The significant energy efficiency improvements (23% - 30%) and demonstrated ROI (120% - 150%) documented in this review provide strong justification for advancing empirical validation through pilot implementations in selected GBI-certified buildings. This progression directly addresses the identified research gaps, particularly the lack of tropical-specific implementation guidelines and long-term performance data, while leveraging the finding that GBI-certified buildings demonstrate 28% higher adoption rates to maximize implementation success. The next phase will integrate the specialized dehumidification control strategies, enhanced security frameworks addressing PDPA compliance, and workforce development protocols identified as critical success factors, ultimately delivering validated tools to support Malaysia's green building transformation and carbon reduction objectives through evidence-based Digital Twin deployment strategies.

These findings support recommendations for phased implementation approaches, collaborative public-private partnerships, integration with renewable energy systems, and standardized ROI frameworks, contributing to the field by extending Digital Twin frameworks for tropical climate requirements and providing practical implementation guidance for Malaysian stakeholders. While limitations exist regarding long-term performance data, the research demonstrates that Digital Twin technology offers a powerful approach for enhancing building performance and sustainability in Malaysia when properly adapted to local conditions. Future research directions include longitudinal studies, tropical-specific algorithms, integration methodologies for existing buildings, and expansion to district and urban scales.

ACKNOWLEDGEMENTS/ FUNDING

Communication of this research is made possible through monetary assistance by Universiti Tun Hussein Onn Malaysia and the UTHM Publisher's Office via Publication Fund E15216.

CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts, and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Nur Muhamad Afif, Hamidun; data collection: Nur Muhamad Afif, Jeffery; analysis and interpretation of results: Mohd Hafizal, Nur Syafiqah Adha; draft manuscript preparation: Nursyazwani, Hamidun, Muhammad Arif. All authors reviewed the results and approved the final version of the manuscript.

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