BIM-BASED DIGITAL TWIN INTEGRATION FOR ENHANCING ENERGY EFFICIENCY IN MULTI-STOREY RESIDENTIAL BUILDINGS: A SYSTEMATIC LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

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Abstract: *The rapid digital transformation of the architecture, engineering, and construction (AEC) industry has created new opportunities for improving the sustainability of multi-storey residential buildings. Building Information Modeling (BIM), Internet of Things (IoT), and Digital Twin technologies collectively enable intelligent building design, real-time monitoring, and data-driven operational management. This study investigates BIM-based Digital Twin integration for enhancing energy efficiency in multi-storey residential buildings through a systematic literature review and comparative analysis of contemporary studies.*

The findings indicate that BIM-based Digital Twin systems significantly improve energy efficiency through real-time monitoring, adaptive control, and intelligent decision-making. Key challenges include high implementation costs, interoperability issues, cybersecurity risks, and limited technical expertise, particularly in developing countries. The study proposes a conceptual framework integrating BIM, IoT, and Digital Twin technologies into a unified system for intelligent residential building management, contributing valuable insights for researchers, practitioners, and policymakers.

Keywords: *Building Information Modeling (BIM); Digital Twin; Internet of Things (IoT); smart buildings; energy efficiency; multi-storey residential buildings; sustainable construction; smart city; facility management.*

INTRODUCTION

Rapid urbanization has significantly increased demand for multi-storey residential buildings, while the construction sector has become one of the largest consumers of energy globally. Residential buildings account for a substantial share of carbon emissions, intensifying the need for sustainable and energy-efficient building management. In this context, digital technologies are becoming central to improving building performance and resource management.

Building Information Modeling (BIM) has emerged as a transformative technology in the AEC industry, enabling integrated data management, interdisciplinary coordination, and lifecycle-oriented building analysis. Simultaneously, Digital Twin technology has gained attention as a virtual replica of physical buildings that continuously processes real-time data from IoT sensors and monitoring systems, enabling predictive maintenance, energy analysis, and intelligent control.

Despite growing research interest, the integrated application of BIM-based Digital Twin technologies in multi-storey residential buildings remains insufficiently systematized. Most studies focus either on BIM during the design phase or on Digital Twin in industrial and commercial settings. This study therefore investigates BIM-based Digital Twin prospects for improving energy efficiency in residential buildings, analyzes integration mechanisms, identifies challenges, and proposes a conceptual framework for intelligent residential building management.

Literature Review

Building Information Modeling (BIM) Technologies

BIM is an intelligent digital representation of a building integrating geometric, technical, functional, and operational information into a unified data environment. Unlike conventional CAD systems, BIM enables multidimensional data management throughout the entire building lifecycle. Modern BIM systems span from 3D spatial modeling through 4D construction scheduling, 5D cost estimation, 6D sustainability analysis, to 7D facility management, supporting operational optimization and lifecycle assessment.

In residential construction, BIM enables clash detection, simulation, and integrated data analysis across engineering networks, ventilation, structural, and energy systems. BIM also supports energy performance analysis including daylight simulation, HVAC optimization, and environmental performance assessment. Despite its advantages, BIM adoption still faces barriers such as high software costs, interoperability issues, and resistance to digital transformation, particularly in developing countries.

Recent studies indicate BIM is transitioning from a design-oriented tool into a comprehensive digital ecosystem integrated with IoT, cloud computing, artificial intelligence, and Digital Twin technologies, positioning it as a central component of future smart residential environments.

Digital Twin Concept in Smart Buildings

A Digital Twin is a virtual representation of a physical system that continuously exchanges data with its real-world counterpart. Originally developed in manufacturing and aerospace, the concept has gained widespread adoption in the AEC sector for improving operational efficiency and building performance management. In smart buildings, Digital Twin systems integrate real-time data from IoT sensors covering temperature, humidity, lighting, ventilation, energy usage, and occupancy behavior, enabling live visualization and analysis of building conditions.

A key advantage of Digital Twin systems is predictive maintenance: by continuously evaluating sensor data, potential malfunctions can be identified before critical failures occur, reducing costs and minimizing downtime. Digital Twin platforms also optimize HVAC, lighting, and energy distribution in real time, substantially reducing energy consumption and carbon emissions. Additionally, simulation capabilities allow operators to test different operational scenarios virtually before physical implementation, improving decision-making and sustainability planning.

Remaining challenges include high implementation costs, data interoperability issues, cybersecurity risks, and lack of standardized frameworks for residential Digital Twin development. Nevertheless, Digital Twin technologies are expected to become a central component of future smart cities when integrated with BIM, AI, cloud computing, and IoT.

Energy Efficiency in Multi-Storey Residential Buildings

Multi-storey residential buildings consume substantial energy for HVAC, lighting, water supply, and other operations, significantly contributing to greenhouse gas emissions. Factors influencing energy consumption include building orientation, construction materials, insulation quality, glazing, occupancy patterns, and climatic conditions. Inefficient coordination among these components leads to operational waste, making integrated digital technologies increasingly essential for building performance management.

BIM supports energy-efficient design through simulation, daylight assessment, and thermal performance evaluation during early design stages. The integration of BIM, IoT sensor networks, and Digital Twin systems enables real-time energy monitoring and intelligent control, allowing dynamic adjustment of HVAC and lighting based on occupancy and environmental conditions. Adaptive energy management approaches significantly outperform traditional fixed-schedule building management systems. Despite these advances, high investment costs and limited digital infrastructure remain barriers in developing countries.

Integration of BIM, IoT, and Digital Twin

The integration of BIM, IoT, and Digital Twin technologies creates a unified digital ecosystem for comprehensive building lifecycle management. BIM provides the foundational platform with geometric, structural, and engineering data. IoT sensors collect real-time operational data — temperature, occupancy, energy consumption, equipment performance — transmitted to centralized digital platforms. Combining IoT data streams with BIM models creates the basis for Digital Twin systems, transforming static information models into dynamic, real-time operational environments.

This integration delivers major benefits: improved energy management through real-time monitoring and adaptive HVAC and lighting control; predictive maintenance that reduces failures and operational costs; and enhanced decision-making through virtual scenario simulation before physical intervention. Technical challenges remain, including data interoperability between platforms, cybersecurity concerns, high costs, and insufficient digital infrastructure in developing regions. Nevertheless, research confirms that BIM-IoT-Digital Twin convergence will become a fundamental component of future smart buildings and sustainable urban development.

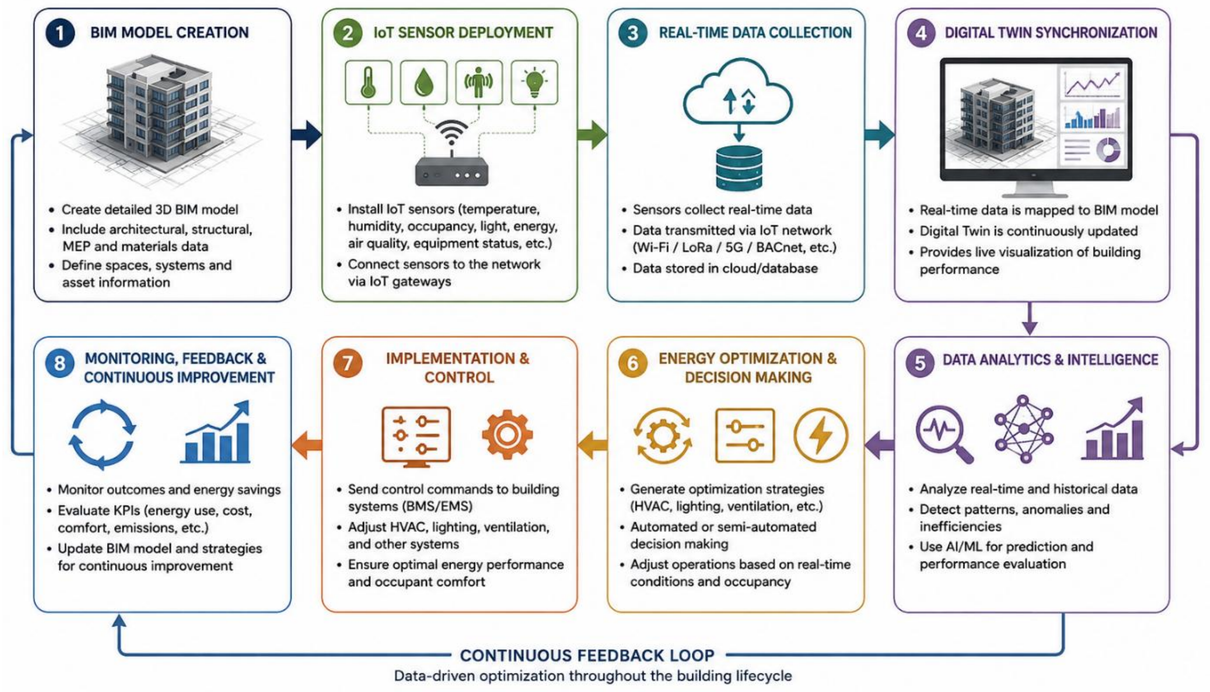

Figure 1. BIM–IoT–Digital Twin Integration Workflow for Energy Efficiency Management in Multi-Storey Residential Buildings

Research Methodology

This study employs a systematic literature review and comparative analysis of scientific publications related to BIM, Digital Twin, IoT, smart buildings, and energy-efficient residential building management. Literature was sourced from Scopus, Web of Science, ScienceDirect, Springer, and MDPI databases using keywords including "Building Information Modeling", "Digital Twin", "IoT in buildings", "energy efficiency", and "BIM-based Digital Twin". Studies from the last decade were prioritized for contemporary relevance.

Selected literature was analyzed thematically, systematically categorizing technological frameworks, implementation strategies, advantages, and limitations of BIM-based Digital Twin systems. Duplicate, non-peer-reviewed, and unrelated publications were excluded. Based on this analysis, a conceptual framework was developed illustrating the relationship between BIM, IoT data acquisition, Digital Twin environments, and energy-efficient building management processes.

Advantages of BIM-Based Digital Twin Systems

BIM-based Digital Twin systems offer several interconnected advantages for multi-storey residential building management:

Real-time monitoring and transparency: Continuous data collection from IoT sensors enables immediate identification of operational anomalies and equipment inefficiencies, replacing periodic inspection-based management approaches.

Energy optimization: Dynamic adjustment of HVAC, lighting, and ventilation based on real-time occupancy and environmental data reduces unnecessary energy consumption and operational costs.

Predictive maintenance: Continuous performance data analysis enables detection of potential equipment malfunctions before critical failures, reducing downtime and extending system lifespan.

Enhanced decision-making: Unified digital ecosystems allow stakeholders to simulate operational scenarios and make data-driven decisions across building management, engineering, and maintenance domains.

Occupant comfort and sustainability: Intelligent environmental control based on occupancy patterns improves indoor quality while supporting greenhouse gas emission reduction and sustainable urban development objectives.

Challenges and Limitations

Several challenges constrain large-scale adoption of BIM-based Digital Twin technologies in residential buildings:

High implementation costs: Advanced software, IoT devices, sensor networks, and cloud infrastructure require substantial financial investment, particularly limiting adoption in developing countries.

Interoperability issues: Different software standards and communication protocols across BIM, IoT, and Digital Twin platforms create data integration complexity, reducing system efficiency.

Cybersecurity risks: Continuous real-time data collection and transmission increase vulnerability to cyberattacks and data breaches, requiring advanced security infrastructure.

Skills shortage: Effective implementation requires interdisciplinary expertise in architecture, engineering, IT, data analytics, and IoT systems — professionals that remain scarce in many regions.

Retrofitting complexity: Integrating digital systems into existing residential buildings not originally designed for smart technologies is technically demanding and costly.

Ongoing advances in cloud computing, AI, IoT standardization, and digital infrastructure are expected to progressively reduce these barriers.

Prospects for Implementation

Future residential buildings are expected to operate as self-regulating digital environments integrating BIM, Digital Twin, AI, and IoT for continuous energy and comfort optimization. AI and machine learning will enhance Digital Twin analytical capabilities — processing large real-time data volumes to predict system failures and optimize building performance automatically. Integration of renewable energy systems including solar panels, storage, and smart grids into Digital Twin platforms supports the transition to net-zero-energy residential buildings.

Cloud computing and big data will accelerate implementation through centralized remote monitoring, real-time synchronization, and scalable analysis. Broader integration with smart city infrastructure — transportation, environmental monitoring, and utility networks — positions BIM-based Digital Twin platforms as components of comprehensive urban management systems. In rapidly urbanizing regions, adoption of these technologies offers significant potential for improving residential construction quality, though progress depends on digital infrastructure investment, professional education, and supportive policy frameworks.

Conceptual Framework

The proposed conceptual framework structures BIM-IoT-Digital Twin integration around four interconnected layers for multi-storey residential building management:

Layer 1 – BIM Digital Foundation: The core digital information platform containing geometric, structural, technical, and operational building data, establishing the informational basis for integrating real-time technologies.

Layer 2 – IoT Data Acquisition: Smart sensors installed throughout the building continuously collect indoor temperature, humidity, occupancy, lighting, HVAC performance, air quality, and energy consumption data, transmitted to centralized digital platforms.

Layer 3 – Digital Twin Environment: Real-time operational data synchronizes with the BIM virtual model to create a live digital representation of the physical building. AI and machine learning algorithms support predictive maintenance, anomaly detection, occupancy analysis, and adaptive environmental control.

Layer 4 – Intelligent Energy Management: Based on real-time analysis, the integrated system optimizes HVAC, lighting, ventilation, and energy distribution according to occupancy patterns and environmental conditions, reducing consumption, lowering costs, and improving occupant comfort. Continuous monitoring also supports proactive maintenance and lifecycle-oriented facility management.

Figure 2. The 5-Layer Conceptual Framework for Smart Building Management

This conceptual framework provides a theoretical basis for future empirical studies and practical implementation strategies. Further research should investigate interoperability standards, AI integration, economic feasibility, and real-world operational performance across different urban and climatic contexts.

Conclusion

This study investigated the prospects of BIM-based Digital Twin technologies for enhancing energy efficiency in multi-storey residential buildings. The analysis demonstrated that BIM provides a comprehensive foundation for building information management and lifecycle analysis, while Digital Twin systems supported by IoT enable real-time monitoring, predictive maintenance, and intelligent operational control.

The integration of these technologies creates significant opportunities for optimizing energy consumption, improving occupant comfort, reducing operational costs, and supporting sustainable building management. Key challenges — including high implementation costs, interoperability limitations, cybersecurity risks, and skills shortages — remain barriers to large-scale adoption, particularly in developing countries. However, ongoing advances in cloud computing, AI, and sensor technologies are expected to improve feasibility and accessibility over time.

The proposed four-layer conceptual framework illustrates how integrated BIM-IoT-Digital Twin ecosystems can contribute to predictive maintenance, adaptive energy control, and sustainable residential building management. BIM-based Digital Twin technologies hold significant potential for shaping intelligent, energy-efficient residential environments as essential components of future smart cities and sustainable urban infrastructure.

REFERENCES:

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2018). BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, and Contractors. Wiley.

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. Automation in Construction, 38, 109–127.

Bo’ronov N.S. BIM: Uchinchi avlod texnologiyalari. — Toshkent, 2025. — 200 p.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179.

Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to Digital Twins: A systematic review of enabling technologies. Advanced Engineering Informatics, 47, 101200.

Zafar Matniyazov, Jurat Tajibaev, Samidullo Elmurodov, Nizomjon Buronov, & Zilola Rakhmatillaeva. (2025). Artificial Intelligence–Based 3d Model Generation For Architectural Design: A Review Of Current Approaches [Data set]. In Latin American Journal of Education (Vol. 5, Issue 07, pp. 388–397). Zenodo. https://doi.org/10.5281/zenodo.17934870.

Zafar Matniyazov, Samidullo Elmurodov, Zilola Rakhmatillaeva, Tajibayev Jurat, Nizomiddin Buronov. (2025). Integration Of Generative Design And Bim Technologies In Architectural Design: State Of The Art And Future Directions [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17941174.

Zafar Matniyazov, Samidullo Elmurodov, Nizomiddin Buronov, Tajibayev Jurat, & Zilola Rakhmatillaeva. (2025). Comparative Analysis Of Traditional Architectural Design And Generative Design: Quality Metrics, Timeframes And Labour Intensity [Data set]. In Latin American Journal of Education (Vol. 5, Issue 07, pp. 398–414). Zenodo. https://doi.org/10.5281/zenodo.17940629.

Nizomiddin Buronov, Zafar Matniyazov, Samidullo Elmurodov, Tajibayev Jurat, & Zilola Rakhmatillaeva. (2025). Optimizing Building Energy Efficiency Using Ai And Digital Technologies: A Comprehensive Analytical Review [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17941193.

Lu, Q., Xie, X., Heaton, J., Parlikad, A. K., & Schooling, J. (2020). From BIM towards Digital Twin: Strategy and future development. Automation in Construction, 115, 103199.

Zheng, Z., Fischer, M., & Froese, T. (2019). A conceptual framework for BIM-based Digital Twin in construction. Journal of Information Technology in Construction, 24, 1–21.

Kensek, K. (2014). Integration of environmental sensors with BIM: case studies on energy efficiency. Journal of Building Performance Simulation, 7(1), 1–15.

Zafar Matniyazov, Zilola Rakhmatillaeva, Samidullo Elmurodov, Samidullo Elmurodov, & Tajibayev Jurat. (2025). Ai-Based Digital Methods For Construction Documentation Examination [Data set]. In Latin American Journal of Education (Vol. 5, Issue 07, pp. 376–387). Zenodo. https://doi.org/10.5281/zenodo.17934814.

Jurat Tajibaev, Zafar Matniyazov, Samidullo Elmurodov, Nizomjon Buronov, & Zilola Rakhmatillaeva. (2025). Comparative Analysis Of Parametric And Traditional Architecture Based On Form Freedom, Economic And Ecological Efficiency Criteria [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17941044.

Jurat Tajibaev, Zafar Matniyazov, Samidullo Elmurodov, Nizomjon Buronov, & Zilola Rakhmatillaeva. (2025). The Importance Of Affordance, Design, And Cultural Analysis Methods In Organizing Children's Playgrounds Based On National Identity [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17941213.

Buronov, N., Rakhmatillaeva, Z., Matniyazov, Z., Arabi, F., & Husainov, M. (2025). Advancing the understanding and application of building information modeling. American Journal Of Education And Learning, 3(3), 998-1006.

Matniyazov Z. et al. Requirements For The Preparation Of Design Documentation Based On Building Information Modeling (Bim) Technology // American Journal Of Education And Learning. – 2025. – Vol. 3. – No. 3. – pp. 985-991.

Chen, X., & Shi, Z. (2022). IoT-enabled smart buildings: energy optimization using Digital Twin systems. Energy and Buildings, 255, 111589.

Ahmed, Q., & Ali, M. (2021). Smart building energy management using BIM and IoT integration. Sustainable Cities and Society, 70, 102905.

Zhao, X., Hwang, B. G., & Lee, H. (2020). Identifying barriers to BIM adoption in construction industry. Engineering, Construction and Architectural Management, 27(6), 1437–1457.

Tajibaev, J., Matniyazov, Z., Elmurodov, S., Buronov, N., & Rakhmatillaeva, Z. (2026). Integration of parametricism and BIM: Opportunities and limitations of digital design of complex forms in high-rise residential construction. Educator Insights: A Journal of Teaching Theory and Practice, 2(5), 198–220.

Grieves, M. (2016). Origins of the Digital Twin concept. Florida Institute of Technology Report.

Bilal, M., et al. (2023). Digital Twin applications in smart cities and sustainable buildings: A review. Renewable and Sustainable Energy Reviews, 170, 112942.