BIO Web of Conferences **183**, 050237 (2025) https://doi.org/10.1051/bioconf/2025183050237
ICoLIST 2025

Digital Twin for Smart Building Management: Integration of IoT and Cloud Technologies

Elezhbiev Bulat[1,*],

[1] Kadyrov Chechen State University, Grozny, Russia

Abstract. The concept of the digital twin has emerged as a transformative approach in smart infrastructure management, enabling real-time monitoring, simulation, and optimization of physical systems through virtual replicas. In the context of smart buildings, digital twins offer significant potential to enhance energy efficiency, improve occupant comfort, and streamline maintenance operations. This paper presents a novel architecture for a digital twin system designed for smart building management, integrating Internet of Things (IoT) sensors, cloud computing platforms, and data analytics tools. The proposed solution collects real-time data from heterogeneous IoT devices — including temperature, humidity, motion, and energy consumption sensors — and transmits it to a cloud-based platform for storage, processing, and visualization. A dynamic 3D building model, synchronized with live data, serves as the digital twin, enabling stakeholders to monitor conditions, simulate scenarios, and trigger automated control actions. The system is implemented using a scalable cloud infrastructure (AWS IoT Core and Amazon DynamoDB), a message broker (MQTT), and a web-based dashboard for user interaction. We evaluate the system in a real-world office building over a three-month period, demonstrating a 22% reduction in energy consumption through predictive HVAC control and occupancy-based lighting automation.

1 Introduction

The rapid urbanization and increasing demand for energy-efficient infrastructure have accelerated the development of smart buildings as a key component of sustainable cities. Modern buildings consume approximately 40% of global energy, contributing significantly to carbon emissions and operational costs. To address these challenges, building management systems (BMS) are evolving from static, rule-based control to intelligent, data-driven solutions capable of real-time adaptation and predictive decision-making. In this context, the concept of the digital twin —a dynamic virtual representation of a physical system that mirrors its state, behavior, and environment in real time—has emerged as a

* Corresponding author: bulat_elezhbiev@mail.ru

transformative paradigm in industrial automation, healthcare, and urban infrastructure. In smart building applications, digital twins enable continuous monitoring, simulation, fault detection, and optimization by integrating live data from sensors, historical records, and analytical models.

Despite growing interest, the practical implementation of digital twins in building management remains limited by several challenges, including data heterogeneity, system scalability, latency constraints, and the lack of integrated frameworks that bridge the gap between physical devices and cloud-based analytics. Traditional BMS often rely on isolated subsystems for HVAC, lighting, and security, resulting in fragmented data and suboptimal control strategies. Moreover, many existing solutions are vendor-locked, lack interoperability, and are difficult to scale across multiple buildings or adapt to changing usage patterns.

Recent advances in Internet of Things (IoT) and cloud computing technologies offer promising opportunities to overcome these limitations. IoT enables the deployment of low-cost, interconnected sensors that collect granular data on environmental conditions, occupancy, and energy usage. Cloud platforms provide scalable storage, high-performance computing, and advanced analytics capabilities, including machine learning and visualization tools. By integrating these technologies, it becomes possible to create a unified, real-time digital replica of a building that supports not only monitoring but also predictive maintenance, energy optimization, and emergency response planning.

This paper presents a comprehensive framework for a digital twin system tailored to smart building management, with a focus on the seamless integration of IoT and cloud technologies. The proposed architecture collects data from a heterogeneous network of sensors deployed throughout a building, transmits it via MQTT protocol to a cloud-based backend (AWS), and synchronizes a 3D digital model with real-time conditions. The system supports interactive visualization, scenario simulation, and automated control actions, such as adjusting HVAC settings based on occupancy predictions. A key innovation lies in the system's modularity, scalability, and use of open standards, enabling deployment across different building types and vendor ecosystems. The solution is evaluated in a real-world office environment over a three-month period, demonstrating measurable improvements in energy efficiency and operational responsiveness.

The main contributions of this work are: (1) a cloud-native digital twin architecture for smart buildings; (2) implementation and integration of IoT devices with AWS services (IoT Core, DynamoDB, Lambda, and API Gateway); (3) real-time synchronization between physical and virtual models; and (4) empirical validation of energy savings and system performance. The rest of the paper is organized as follows: Section 2 reviews related work in digital twins and smart building systems. Section 3 describes the system architecture and methodology. Section 4 presents the implementation and experimental results. Section 5 discusses limitations and future enhancements. Section 6 concludes the study and highlights practical implications.

2 Research methodology

This study adopts a design science research approach to develop and evaluate a digital twin system for smart building management, integrating Internet of Things (IoT) technologies with cloud computing infrastructure. The methodology is structured around four core phases: (1) system requirements analysis and use case definition, (2) architectural design and component selection, (3) implementation and integration of physical and virtual layers, and (4) deployment, testing, and performance evaluation in a real-world environment. The research focuses on creating a scalable, real-time, and interoperable digital twin framework capable of monitoring, simulating, and optimizing building operations through continuous data synchronization between the physical and virtual domains. The system architecture is divided into three main layers: the perception layer , the cloud processing layer , and the application layer . The perception layer consists of a heterogeneous network of IoT sensors deployed across a multi-floor office building, including temperature, humidity, CO_2, motion (PIR), and smart energy meters. These devices are based on ESP32 and Arduino platforms, configured to sample data at 5–30 second intervals depending on the parameter, and connected via Wi-Fi to a local gateway. The collected data is transmitted using the lightweight MQTT protocol over TLS encryption to ensure secure and efficient communication. The cloud processing layer is hosted on Amazon Web Services (AWS), chosen for its scalability, reliability, and native IoT support. Data ingestion is managed by AWS IoT Core, which authenticates devices and routes messages to AWS DynamoDB—a NoSQL database used for time-series storage. AWS Lambda functions process incoming data in real time, triggering alerts for anomalies (e.g., abnormal CO_2 levels) or initiating predictive analytics workflows. A digital building model, developed in Unity3D and integrated with AWS API Gateway, serves as the virtual counterpart—the digital twin—updated every second via RESTful APIs to reflect current sensor readings. The application layer provides a web-based dashboard for facility managers and occupants, enabling real-time visualization of environmental conditions, historical trends, and 3D navigation through the building. The dashboard also supports scenario simulation: users can adjust virtual HVAC settings or simulate occupancy changes to observe predicted impacts on energy consumption, powered by a lightweight regression model trained on historical data. To evaluate system performance, a three-month pilot was conducted in a 1,200 m^2 office space with 45 occupants. Key performance indicators included end-to-end latency, data accuracy, system availability, and energy efficiency gains. Latency was measured as the time from sensor sampling to data update in the digital twin, using timestamped logs across all components. Energy savings were assessed by comparing baseline consumption (pre-deployment) with post-deployment data under optimized control strategies, such as occupancy-driven lighting and predictive HVAC scheduling. Data integrity was verified through periodic cross-checks with calibrated reference instruments. All components were designed with modularity and open standards (MQTT, JSON, REST) to ensure interoperability and ease of integration with third-party systems. The entire implementation is open-sourced to promote reproducibility and further research. This methodological framework ensures a practical, evidence-based validation of the digital twin concept in real building management scenarios, bridging the gap between theoretical models and operational deployment.

3 Results and Discussions

The digital twin system was successfully deployed and operated continuously over a three-month period in a real-world office building, demonstrating robust performance in data acquisition, synchronization, visualization, and operational optimization. The experimental results confirm the feasibility and effectiveness of integrating IoT and cloud technologies to create a responsive and scalable digital twin for smart building management. A total of 187

IoT sensors were deployed across seven zones, generating approximately 1.2 million data points per day. The system achieved an average data ingestion success rate of 98.7%, with less than 1.3% packet loss, primarily occurring during brief Wi-Fi outages or device reboots. The end-to-end latency—from sensor measurement to visualization in the 3D digital twin—averaged 850 ms, with 95% of updates delivered within 1.2 seconds. This level of responsiveness is sufficient for non-critical monitoring and control tasks such as environmental tracking and lighting automation, though it may require optimization for safety-critical applications like fire detection. The cloud infrastructure demonstrated high availability, with AWS services maintaining 99.95% uptime during the testing period. Data consistency was verified through cross-referencing with calibrated instruments, showing a mean absolute error of 0.4°C for temperature, 2.1% for humidity, and less than 3% for energy metering, which falls within acceptable tolerances for building management applications. The digital twin interface enabled facility managers to detect anomalies in real time, such as a malfunctioning HVAC unit in Zone 3, which was identified through sustained high CO_2 levels and temperature deviations. This led to a 40% reduction in mean time to repair (MTTR) compared to previous manual reporting procedures. In terms of energy efficiency, the implementation of occupancy-based control strategies—automatically switching off lights and reducing ventilation in unoccupied zones—resulted in a 22% decrease in overall electricity consumption, equivalent to 1,850 kWh saved over the trial period. Predictive HVAC scheduling, driven by historical occupancy patterns and weather forecasts, contributed to an additional 8% reduction in heating and cooling costs. User feedback from the web dashboard indicated high satisfaction with the visualization capabilities, particularly the 3D navigation and real-time heatmaps of environmental conditions. However, some users reported a learning curve associated with scenario simulation tools, suggesting a need for improved user guidance in future versions. A key finding of this study is that the integration of MQTT and AWS services enables a highly scalable and secure architecture: the system seamlessly accommodated new devices and data streams without requiring backend reconfiguration, and TLS encryption ensured data confidentiality during transmission. The modular design also facilitated integration with external systems, such as the building's existing access control platform, through REST API bridges. Compared to traditional building management systems, which often operate in silos and rely on periodic manual checks, the proposed digital twin provides a unified, dynamic, and proactive approach to facility management. These results align with recent studies on digital twins in smart environments but extend them by demonstrating long-term stability, real-time performance, and measurable energy savings in a live operational setting. While the system shows strong promise, limitations include dependency on stable network connectivity and the computational cost of maintaining high-fidelity 3D models on low-end client devices. Future work will explore edge computing integration to reduce latency and cloud dependency, as well as the incorporation of machine learning models for more advanced predictive maintenance and occupant behavior analysis. Overall, this research validates the digital twin as a powerful tool for sustainable and intelligent building management, offering both operational efficiency and environmental benefits.

4 Conclusions

This study presents the design, implementation, and evaluation of a digital twin system for smart building management, leveraging the integration of Internet of Things (IoT) and cloud computing technologies. The proposed framework enables real-time synchronization between a physical building and its virtual counterpart through a scalable, secure, and interoperable architecture. By collecting data from a heterogeneous network of IoT sensors and processing it in the cloud using AWS services, the system provides continuous monitoring, anomaly detection, scenario simulation, and automated control capabilities. Experimental results from a three-month deployment in a real office environment demonstrate a 22% reduction in energy consumption through occupancy-driven automation and predictive HVAC scheduling, with an average end-to-end latency of 850 ms and high data reliability (98.7% ingestion success rate). The web-based 3D dashboard enhances situational awareness for facility managers, enabling faster diagnostics and improved decision-making, while the modular, open-standard design ensures adaptability across different building types and vendor ecosystems. The research confirms that digital twins, when combined with modern IoT and cloud infrastructure, can significantly enhance the efficiency, sustainability, and responsiveness of building operations. Unlike traditional building management systems, this approach offers a unified, dynamic, and proactive platform for intelligent infrastructure control. The work contributes to the advancement of smart city technologies by providing a reproducible and scalable model for digital twin deployment. Nevertheless, challenges remain, including network dependency, client-side rendering performance, and the need for more advanced predictive analytics. Future research will focus on incorporating edge computing to reduce latency, integrating machine learning models for occupant behavior prediction, and extending the system to multi-building urban-scale deployments. As cities move toward digitalization and decarbonization, the integration of digital twins into building management systems will play a pivotal role in achieving energy efficiency, occupant comfort, and operational resilience.

References

1. Y. Cheng, D. Wang, P. Zhou, and T. Zhang, "A Survey of Model Compression and Acceleration for Deep Neural Networks," IEEE Transactions on Neural Networks and Learning Systems , vol. 31, no. 12, pp. 4983–5000, Dec. 2020, doi: 10.1109/TNNLS.2020.2976311.
2. S. Han, H. Mao, and W. J. Dally, "Deep Compression: Compressing Deep Neural Networks with Pruning, Trained Quantization and Huffman Coding," in Proceedings of the International Conference on Learning Representations (ICLR) , 2016. [Online]. Available: https://arxiv.org/abs/1510.00149
3. B. Jacob et al., "Quantization and Training of Neural Networks for Efficient Inference in Embedded Systems," in Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) , 2018, pp. 2710–2719, doi: 10.1109/CVPR.2018.00287.
4. G. Hinton, O. Vinyals, and J. Dean, "Distilling the Knowledge in a Neural Network," arXiv preprint arXiv:1503.02531 , 2015. [Online]. Available: https://arxiv.org/abs/1503.02531
5. C. Tai, T. Xiao, Y. Zhang, X. Wang, and E. P. Xing, "Convolutional Neural Networks with Low-Rank Regularization," in Proceedings of the International Conference on Learning Representations (ICLR) , 2016. [Online]. Available: https://arxiv.org/abs/1511.06067
6. M. Tan and Q. V. Le, "EfficientNet: Rethinking Model Scaling for Convolutional Neural Networks," in Proceedings of the International Conference on Machine Learning (ICML) , 2019, pp. 6105–6114. [Online]. Available: https://arxiv.org/abs/1905.11946

7. A. Howard et al., "Searching for MobileNetV3," in Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV) , 2019, pp. 1314–1322, doi: 10.1109/ICCV.2019.00140.
8. J. Redmon and A. Farhadi, "YOLOv3: An Incremental Improvement," arXiv preprint arXiv:1804.02767 , 2018. [Online]. Available: https://arxiv.org/abs/1804.02767
9. NVIDIA, "TensorRT Documentation," 2023. [Online]. Available: https://docs.nvidia.com/deeplearning/tensorrt/
10. Google AI, "TensorFlow Lite," 2023. [Online]. Available: https://www.tensorflow.org/lite
11. Microsoft, "Neural Network Intelligence (NNI)," 2023. [Online]. Available: https://github.com/microsoft/nni
12. W. Shi et al., "Edge Computing: Vision and Challenges," IEEE Internet of Things Journal , vol. 3, no. 5, pp. 637–646, Oct. 2016, doi: 10.1109/JIOT.2016.2579198.