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Article

ADVANCING DIGITAL TWIN AND BIM INTEGRATION FOR SUSTAINABLE AND INTELLIGENT BUILT ENVIRONMENTS: IMPLICATIONS FOR ENERGY EFFICIENCY AND ENVIRONMENTAL PERFORMANCE

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Abstract: Building Information Modeling (BIM) and Digital Twin (DT) technology solutions are shown to be effective tools in the creation of Sustainable and Intelligent Built Environments. The study aims to explore how the integration of BIM and Digital Twin can enhance building energy efficiency and environmental performance by enabling real-time monitoring, data collection from Internet of Things (IoT) devices, and analysis using machine learning. A BIM model is embedded into a Digital Twin platform to enable ongoing monitoring of buildings and forecasting of energy use with LightGBM algorithm. The simulation results show the energy saving, indoor environment performance, maintenance management and carbon emission reduction, as compared with the conventional building management approaches. The results indicate that the application of BIM and Digital Twin can be an effective paradigm to support the sustainable operation of buildings, smart facility management.
Keywords: Building Information Modeling (BIM), Environmental Performance, Intelligent Built Environments, LightGBM

1. INTRODUCTION

Sustainable and intelligent built environments are in urgent demand due to the rapid urbanisation and rising energy demand. Energy consumption and carbon emissions in buildings constitute a substantial part of the global energy demand and carbon emissions and efficient building management is an important part of sustainable development. Traditional building management systems make insufficient use of dynamic information and periodic inspections, reducing their capacity to deal with dynamic operational conditions. There is, therefore, an increased interest in new and advanced digital technologies that will facilitate real-time monitoring, intelligent decision making and continuous optimization of building performance. Two game-changing solutions that can tackle these issues and drive greater operational efficiency, energy savings, and environmental stewardship are Building Information Modeling (BIM) and Digital Twin technology.

BIM (Building Information Modeling) is a digital representation of a building that incorporates all aspects of architecture, structure, mechanical systems, electrical systems, and building operation over a building's life. It helps in effective planning, design, construction, and facility management by allowing stakeholders to accurately visualize and efficiently share information. But BIM models are more typically static and are not automatically updated as buildings become operational. Digital Twin technology is capable of addressing this challenge by generating a virtual, representative copy of the physical asset that evolves over time, in real time, with data from IoT sensors. This integration allows for real-time monitoring, predictive analysis, fault detection and intelligent control of building systems. The combination of BIM and Digital Twins presents new ways to make smart built environments that support sustainable building operations.

Real-time monitoring of energy use, indoor environment, equipment performance, and occupancy can be achieved by combining real-time sensor data with detailed BIM models, allowing building managers to gain a comprehensive understanding of the environment at any given moment. In addition, the use of cloud computing, edge computing, and artificial intelligence (AI) helps Digital Twins process vast

amounts of operational data and make precise forecasts for energy optimization and maintenance planning.

The use of machine learning algorithms, like Light Gradient Boosting Machine (LightGBM), also enhances the predictive performance by uncovering intricate patterns in the environmental, operational, and energy factors, which assists in informed decision-making and sustainable energy management within buildings. Although BIM and Digital Twin techniques are becoming more and more popular, their joint use for enhancing energy efficiency and environmental performance is still a new field of research. Existing studies mainly consider visualization, construction management or individual energy monitoring, but the intelligent management of a building that integrates BIM, Digital Twin technology, IoT sensing and machine learning is comparatively little studied.

This is the only way to attain sustainable building operation, minimize CO2 emissions, enhance the IEQ and facilitate long-term building management goals. This study thus explores the use of BIM and Digital Twin technology for sustainable and intelligent built environments, focusing on energy efficiency and environmental performance. The proposed practice will integrate BIM-based information management, real-time Digital Twin monitoring, IoT-based data acquisition, cloud-edge computing and light GBM-based predictive analysis to analyse building operational performance. The results show the potential of these cutting-edge digital technologies to assist in intelligent decision making, optimize energy use and reduce maintenance needs, while also helping to create environmentally sustainable and smart buildings.

2. LITERATURE REVIEW

Piras et al. (2024) highlight that the advent of Digital Twin (DT) technology offers distinctive prospects for society by enabling instantaneous data transmission from the physical realm to its digital equivalent. Despite breakthroughs in several industries including aerospace, the Architecture, Engineering, Construction, and Operation (AECO) sector still need more growth, particularly in embracing modern technology instead of conventional methods. The implementation of these technologies need to be normalised instead of being considered a sophisticated procedure. This document seeks to fill the current void by offering an all-encompassing framework that amalgamates technology and ideas sourced from purpose-oriented case studies and research across many sectors. The framework aims to provide optimal methodologies for the AECO industry. Furthermore, it seeks to emphasise the capacity of digital transformation for enhancement by supervising and digitally managing the constructed environment throughout the whole life cycle of facilities, including design, building, operation, and maintenance. It is based on a comprehensive literature analysis and offers an integrated perspective on delineating the functions of Building Information Modelling (BIM), Geographic Information Systems (GIS), Internet of Things (IoT), and other essential facilitators within the Digital Transformation (DT) landscape. These computerised instruments enable the concurrent assessment of related advantages, including resource conservation and future opportunities, such as tracking project sustainability goals.

Alnaser et al. (2024) This comprehensive literature analysis examines the convergence of AI-enabled digital twins and IoT in fostering a sustainable architectural ecosystem. An extensive examination of 125 articles centers on four primary issues. Initially, digital twins are analysed within the realms of building, facility management, and their contribution to promoting sustainability and intelligent urban environments. The convergence of IoT and AI with digital twins and energy optimisation for net-zero buildings is examined. Secondly, the use of artificial intelligence and automation in manufacturing, especially within Industry 4.0 and cyber-physical systems, is assessed. Third, the emphasis is placed on nascent technologies in urban development, such as blockchain, cybersecurity, and EEG-based systems for eco-friendly structures. The research highlights the significance of data-centric methodologies in enhancing flood resilience and urban digital environments. This evaluation aids sustainability by pinpointing the ways in which digital technologies and AI might improve energy efficiency and bolster resilience in urban and industrial settings.

Muhudin and colleagues (2026) The amalgamation of Building Information Modelling [BIM] and Digital Twins [DT] has become a pivotal catalyst for digital change within the design, engineering, and construction industry. Nevertheless, its overarching influence is limited by conceptual disunity and inconsistent institutional implementation. This research integrates current BIM–DT scalability to pinpoint prevailing technical and application aspects, scrutinise the governance factors influencing scalability, and provide an analytical framework that enhances comprehension beyond technology-focused analyses. A bifurcated analytical framework was used, integrating bibliometric keyword co-occurrence analysis of 1295 Scopus-indexed entries with a systematic qualitative synthesis of 56 peer-reviewed journal papers released from 2020 to 2025, according to PRISMA principles. The present BIM–DT research environment is defined by six interconnected analytical dimensions: breakthroughs and applications in BIM–DT integration; interoperability and visualisation; improvements in safety; energy efficiency; data-informed decision making; and cooperation among stakeholders. In these areas, a continual discord is evident between technological proficiency and organisational preparedness, with shortcomings in standards, governance, and sociotechnical integration being the primary obstacles to extensive implementation. The results reconceptualise the convergence of BIM and DT not just as a separate technological enhancement, but as the construction of an integrated socio-technical information ecosystem encompassing the whole building lifespan. This research enhances comprehension of how digital twins broaden BIM from design coordination to operational governance by emphasising governance conditions, data stewardship, and institutional coordination, thereby laying the groundwork for more systematic deployment of intelligent, resilient, and sustainable built-environment systems.

Venkateswarlu and colleagues (2025) In the modern digital era, the constructed environment experiences substantial transformations due to technology advancements that boost building management, maximise operational efficiency, and elevate total output. Digital Twin technology has become a crucial instrument for improving indoor environmental quality and maximising energy efficiency in current structures. This illustrates its resemblance to many Sustainable Development Goals, whereby digital twin technology plays a crucial role in fulfilling numerous objectives, particularly those pertinent to our study: Affordable and sustainable energy; optimal health and wellness are the principal results of our research; Our approach emphasises industry innovation and infrastructure; also, our study contributes to sustainable cities and communication. Nonetheless, some difficulties need more contemplation. Initially, to evaluate the techniques and instruments used to observe and depict environmental variables. Secondly, to examine prior research on Digital Twin technology concerning energy efficiency and indoor environmental quality. This research meticulously analysed 261 scholarly papers to tackle these issues, pinpointing 17 pertinent studies that explore the use of Digital Twin in improving energy efficiency and indoor environmental quality inside structures. The study highlights Building Information Modelling, the Internet of Things, and Big Data, which together enhance the oversight and administration of physical assets via real-time data duplication. Our study demonstrates the need of a multidisciplinary approach to thoroughly examine Digital Twin applications, since a holistic comprehension of the implications of this technology demands the amalgamation of several disciplines. The assessment highlights the limited usage of sensors for environmental monitoring, the significance of inhabitants' subjective perceptions, and the need for more

comparative research on energy consumption estimating techniques. For further research, augmented global cooperation is essential to advance the academic inquiry into Digital Twin in this domain. Ultimately, the constructed environment may gain considerable advantages from the use of Digital Twin technologies. Nevertheless, the obstacles need to be tackled prior to technology realising its whole capacity for developing sustainable and energy-efficient structures.

Zahedi et al. (2024) assert that Digital Twin (DT) technology, as an advancement of Building Information Modelling (BIM), has arisen to tackle worldwide issues related to the ecological effects of the building sector and to fulfil sustainability criteria. Notwithstanding the plethora of research focused on the amalgamation of digital transformation and sustainability, a significant void exists in establishing a thorough summary of the initiatives and prospective trajectories in this domain. Consequently, this study seeks to provide a scientometric evaluation and a thematic overview of 235 articles sourced from the Scopus database. These articles, released from 2017 to 2024, examine past initiatives, contemporary trends, and prospective avenues for using the Digital Twin in sustainable building. Furthermore, 34 articles that received over 20 citations were categorised by the application into four distinct groups: simulation, technology integration, smart systems, and literature review. Moreover, concerning the utilisation of intelligent systems in sustainability, the authors examined the implementations of BIM-DT in intelligent construction, intelligent buildings, intelligent infrastructures, and intelligent cities as derived from the most-cited literature. Consequently, five areas of inquiry were identified and proposed for further exploration. The study provides a comprehensive understanding of the prevailing trend of digital transformation among scholars, past accomplishments, and prospective pathways.

2.1 Research Gap

Previous research has underlined the potential of these technologies: Building Information Modeling (BIM), Digital Twin (DT), Internet of Things (IoT), and Artificial Intelligence (AI) to enhance the performance of buildings, but most of the research has been directed at single technologies, systematic reviews, or at specific application, e.g., construction management, facility management, and energy monitoring. However, the few existing studies have offered an integrated model incorporating BIM, Digital Twin, IoT, cloud-edge computing and machine learning, to improve energy and environmental performance in intelligent built environments simultaneously. Furthermore, existing studies have paid relatively less focus on the integration of predictive energy management, real-time environmental monitoring and sustainable building operation in a digital framework. Thus, this study seeks to fill this gap by examining an integrated approach of BIM–Digital Twin coupled with the use of IoT devices to collect real-time data and LightGBM predictive analytics for energy efficiency, environmental performance, and intelligent building management.

3. OBJECTIVES OF THE STUDY

- To analyze the use of Building Information Modeling (BIM) and Digital Twin technology in smart built environment.
- To assess the contribution of BIM and Digital Twin integration to enhance the energy efficiency of buildings.
- To evaluate the environmental performance of buildings with Digital Twin.

4. METHODS

4.1 BIM Model Construction and Information Integration

A Digital Twin within Sustainable and Intelligent Built Environments is built upon the BIM model. Three-dimensional building information was obtained at the data acquisition stage with a high-resolution 3D laser scanner of ±2 mm accuracy and a multi-view photogrammetry system of single-pixel positioning error of ±5 mm. The joint scanning process allowed the generation of high density point clouds with a scanning resolution of 5mm and the overlap rate of the pictures was over 80% of the total area.

High density scanning, with a point spacing of 2 mm, was used to obtain accurate geometric representation of complex architectural elements and building services. The acquired point cloud data were registered and merged with the Improved Iterative Closest Point (ICP) algorithm, with an average registration error of less than 3 mm, representing a Level of Development (LOD) 400 BIM model that provides component-level modeling accuracy for facility management and operational analyses. The result is a BIM model that includes not only the architectural and structural elements, but also the mechanical, electrical and plumbing systems, and maintains the spatial and functional characteristics of the built environment.

The BIM model includes information on building geometry, construction materials, HVAC systems, electrical networks, occupancy profiles, operational schedules, and sustainability attributes, providing a comprehensive overview of the building.The BIM model includes information about the building geometry, construction materials, HVAC systems, electrical networks, occupancy profiles, operational schedules, and sustainability attributes, providing a comprehensive overview of the building. The adoption of the Industry Foundation Classes (IFC) open standard will allow seamless interoperability between BIM and external applications and convert data to and from various software applications with ease.

Moreover, construction materials' thermal properties such as thermal conductivity, density and specific heat capacity have been incorporated into building energy simulation models in order to determine heating and cooling loads. As HVAC systems, lighting systems, renewable energy systems and indoor environmental sensors operate, their data is continually synced with the BIM model, creating an accurate digital representation of the physical building. It is an integrated BIM framework that creates a complete digital platform for life cycle management, predictability maintenance and sustainability evaluation during the building operation phase.

4.2 Real-Time Monitoring and Data Collection of Digital Twin Technology

The Digital Twin platform is connected to the physical building via an Internet of Things (IoT) sensing network and continuously pulls in real-time operational data. Various environmental and energy sensors are installed across the building to measure indoor temperature, relative humidity, carbon dioxide (CO2) level, particulate matter (PM2.5), illumination level, occupancy, electricity consumption, HVAC performance and generation of renewable energy. LoRa wireless communication and MQTT messaging are used to feed data from sensors to a cloud-based Digital Twin platform. Cloud computing resources are responsible for storing data in the cloud and offering large-scale analytical power, whereas edge computing is about managing data at the edge of the network to reduce communication latency and enhance real-time responsiveness.

The sensor data collected is subjected to various pre-processing stages prior to analysis. Sliding window technique with observation interval of 5 minutes is used to remove outliers. The temporal and spatial synchronization of multi-source sensor streams is based on temporal and spatial alignment, and the Kalman filter is used to remove the noise in the measurement. Z-score standardization was used to

normalize data to remove dimensional inconsistencies between variables. The Fourier Transform method is then used to detect periodicities in environmental data while the Dynamic Time Warping (DTW) method is used to identify energy consumption patterns during the day and week, despite the temporal variations. A hybrid prediction model combining LSTM and ARIMA is used to predict the performance of buildings in the future. Long Short-Term Memory (LSTM) network is used to capture the nonlinear temporal dependency in the monitoring data, and ARIMA is used to represent linear time-series characteristics.

Optimal hyperparameters of a hybrid prediction model are selected by Bayesian Optimization which enhances the forecasting accuracy and computational efficiency. The evolving Digital Twin keeps in sync with the physical building and allows real-time visualization, intelligent decision making, predictive maintenance, occupancy-aware control and dynamic optimization of building operations. This live synchronization enables energy saving, better indoor environmental quality and sustainable energy facility management.

4.3 Energy Consumption Analysis and Optimization Strategy Based on LightGBM

The cleaned environmental operational data is used to understand the energy consumption pattern of the building and to optimize operation strategies using algorithm Light Gradient Boosting Machine (LightGBM). LightGBM also offers the following advantages: fast training speed, highly computational efficient, scale well to large datasets, and powerful in modeling complicated nonlinear relationships between multiple building variables. The process of feature engineering involves the initial selection of relevant parameters that are present in the environment, occupancy and operational conditions that have significant impact on building energy consumption. To lower the computational complexity, continuous variables are discretized by histogram based binning techniques without compromising the predictive power. The input features of the LightGBM model are historical monitoring data, which include indoor temperature, humidity, occupancy, HVAC operating status, lighting intensity, electricity consumption, weather, renewable energy generation, and time-based features. Target Variable is the actual building energy use with various operating conditions.

The objective function of the LightGBM model is expressed as

$$Obj = \sum_{i=1}^{n} l(y_i, \hat{y}_i) + \sum_{k=1}^{K} \Omega(f_k) \qquad (1)$$

where $l(y_i, \hat{y}_i)$ denotes the prediction loss function, while $\Omega(f_k)$ represents the regularization term controlling model complexity and preventing overfitting.

Feature importance is evaluated using the cumulative information gain of each feature across all decision trees and is calculated as

$$FI(f) = \sum_{t=1}^{T} Gain(f, t) \qquad (2)$$

where $Gain(f, t)$ represents the information gain contributed by feature f in decision tree t.

Hyperparameter tuning is done using a three-stage optimization method: Bayesian Optimization, Grid Search and Early Stopping. Bayesian Optimization is used to find the suitable range of parameters, Grid Search is used to find the best parameter values, and the Early Stopping method reduces overfitting and enhances the generalization of the model. To provide more interpretable models, SHAP (Shapley Additive Explanations) values are used to measure the individual contribution of the features to the prediction of energy consumption, and LIME (Local Interpretable Model-Agnostic Explanations) values are used to explain individual prediction outcomes under the different environmental conditions. The optimized LightGBM model can be used to accurately predict building energy consumption, pinpoint key variables that impact building energy efficiency, and enable dynamic optimization measures such as HVAC scheduling, intelligent lighting controls, renewable energy utilization, occupancy-based energy management, and predictive building maintenance. The optimization approaches are linked to the energy-efficient and environmentally friendly operation of smart and sustainable built environments.

5. RESULTS AND DISCUSSION

5.1 Simulation

The effectiveness of the proposed Digital Twin and BIM integration framework was assessed using the benchmark comparison method against the conventional building management methods. The intelligent building was selected as a representative building and energy efficiency, environmental performance, IEQ and maintenance cost were evaluated due to the improvements. The main performance criteria were energy use (kWh), IEQ index, carbon emissions ($kgCO_2$), maintenance cost and total energy saving percentage. The three-dimensional building model developed through BIM was combined with the Digital Twin platform and the simulation was carried out. The BIM model included information on building geometry, construction materials, HVAC systems, lighting systems, occupancy schedule and renewable energy elements, and facility management information.

The Digital Twin continually updated the virtual building with data from the physical world through IoT sensors that tracked the temperature, humidity, CO_2 levels, light, occupancy and electricity usage. The sensor information was propagated via the LoRa communication network in the form of MQTT message and processed through the cloud and edge computing platforms for real-time analytics. The simulation was carried out with a 12-month operating period on a workstation with an NVIDIA RTX 4060 graphical processor unit (GPU). In the simulation, the responses of various building performance indicators were continually tracked, recorded and contrasted with those achieved in a conventional building management strategy throughout the simulation.

5.2 Experimental Results

Real-Time Monitoring Data

Table 1. Real-Time Environmental and Energy Monitoring Data

Time	Temperature (°C)	Humidity (%)	CO_2 (ppm)	Light Intensity (lux)	Occupancy (%)	Energy Consumption (kWh)
08:00	22.8	46	465	320	42	0.82
12:00	25.6	41	540	1180	88	1.18
16:00	24.9	43	515	830	76	1.03
20:00	23.9	49	485	480	58	1.42
00:00	21.4	54	425	90	8	0.56

The real-time monitoring data showcase the platform's ability to gather environmental and operational data from scattered IoT sensors in real-time. Environmental parameters, occupancy and energy usage are synced with the BIM model to keep a correct virtual model of the physical building. The up-to-date monitoring information is used for the intelligent prediction of energy consumption, the assessment of the building's environmental performance, and adaptive building control strategies.

LightGBM Prediction Performance

Table 2. LightGBM Energy Consumption Prediction Results

Feature	Feature Importance Score	Predicted Energy Consumption (kWh)	Actual Energy Consumption (kWh)	Error (kWh)
Temperature	0.43	1.24	1.30	0.06
Humidity	0.29	0.98	1.04	0.06
Light Intensity	0.17	0.84	0.89	0.05
Occupancy	0.07	1.46	1.53	0.07
HVAC Load	0.04	1.11	1.16	0.05

The optimized LightGBM model has been able to predict building energy consumption with high accuracy with different environmental and occupancy situations. The most critical feature influencing energy demand was temperature, and then humidity and lighting intensity. The energy variation is also due to occupancy and HVAC load, but to a lesser extent, as indicated by the relatively low energy variation importance value. The prediction errors were kept below 0.07 kWh for each of the features evaluated, indicating a high level of robustness of the optimized model for intelligent energy management of built environment in the context of Digital Twin.

Monthly Energy Consumption Analysis

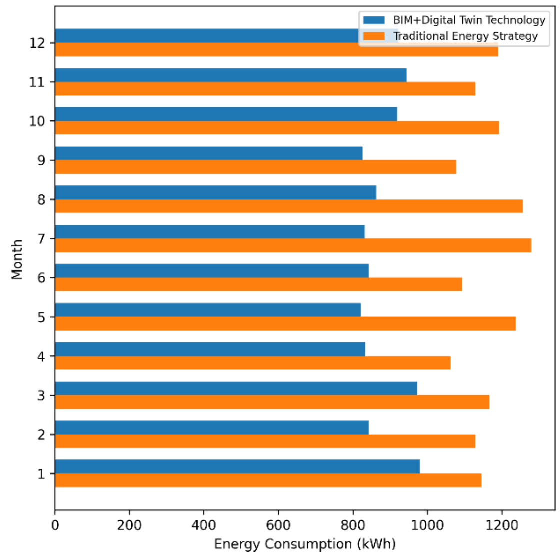

Figure 1. Monthly Energy Consumption Comparison

The monthly energy consumption comparison illustrates that the building energy consumption using the Digital Twin-BIM framework was always lower during the 12-month period of the simulation. The proposed framework led to substantial savings in annual energy consumption, compared to traditional building management approaches, via real-time monitoring, predictive analytics, occupancy-aware HVAC control, and intelligent lighting management. The monthly energy use of the buildings was significantly reduced under the proposed framework, proving it to be effective to enhance energy efficiency of the buildings.

Environmental Performance Analysis

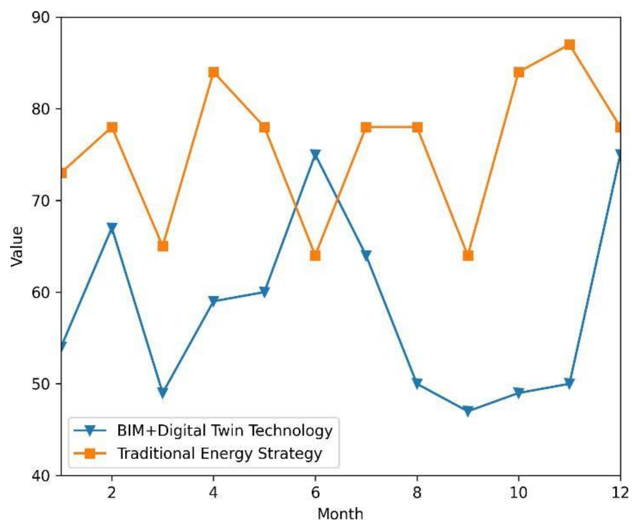

Figure 2. Environmental Performance / Indoor Environmental Quality

The environmental performance evaluation was done based on four parameters: indoor temperature, relative humidity, concentration of CO2, air quality and lighting condition. The Digital Twin continually optimized environmental management strategies based on the incoming data from the sensors, leading to more consistent indoor conditions and higher comfort for the occupants. The proposed framework

was able to provide the good indoor environmental quality and also reduce the unnecessary energy consumption, which was not obtained by the conventional approach.

Maintenance Cost Analysis

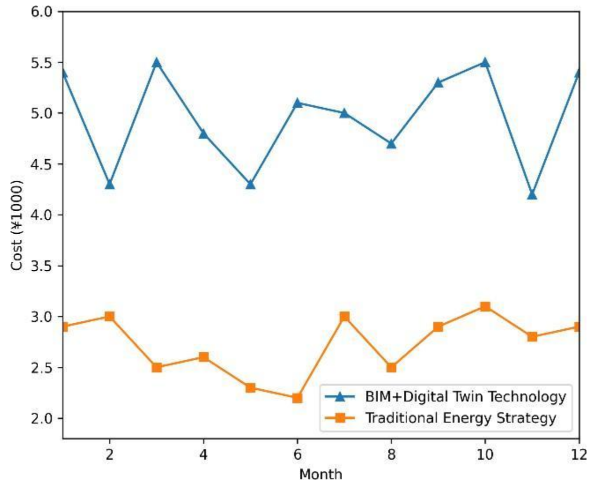

Figure 3. Maintenance Cost Comparison

The cost comparison of the maintenance suggests that incorporating BIM into the Digital Twin approach has led to substantial savings in operational and maintenance costs through predictive maintenance and intelligent asset management. The continuous monitoring allowed for timely fault detection, optimized maintenance plans and reduced unscheduled equipment failures. As a result, the proposed framework led to lower maintenance costs, higher building reliability and building operational efficiency.

Carbon Emission Reduction

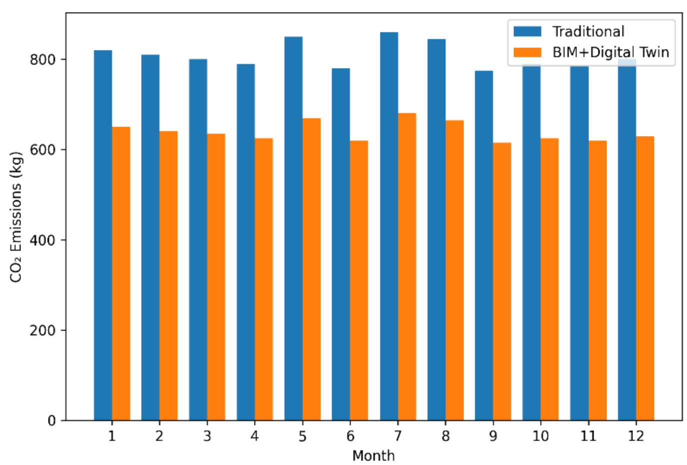

Figure 4. Annual Carbon Emission Comparison

Also, the suggested Digital Twin-BIM framework helped in significant reduction of carbon emissions produced during the building operation due to energy management and optimized HVAC system operation. The reduction in electricity use directly reduced greenhouse gas emissions, thus contributing to sustainable building operation and environmental conservation goals.

Overall Energy Saving Performance

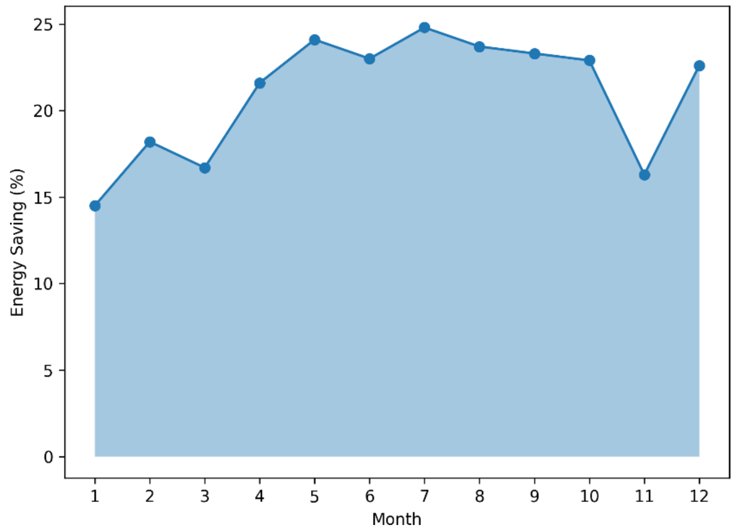

Figure 5. Energy Saving Percentage

The overall framework resulted in significant annual energy savings over conventional building management practices. Optimization of building operations was achieved through intelligent control of HVAC systems, lighting, occupancy scheduling and renewable energy usage. The enhancements highlight the synergy between BIM, Digital Twin, IoT sensing and machine learning in creating sustainable and intelligent built environments.

6. CONCLUSION

This study aimed to investigate the application of BIM and Digital Twin technology for sustainable and intelligent built environment with emphasis on sustainable energy and environmental performance. The proposed approach showed the feasibility of integrating BIM with real-time monitoring of Digital Twin and machine learning-based analysis to effectively manage buildings by continuous integration of data, prediction of energy consumption, and optimisation of their operation. The simulation results showed that a better energy efficiency, indoor environmental quality, maintenance cost reduction and carbon emission reduction have been achieved compared to the traditional building management strategies. Moreover, by incorporating IoT, cloud computing, edge computing and LightGBM, predictive capabilities were improved and informed decisions were made for sustainable facility management. In summary, the results demonstrate the potential of BIM and Digital Twin integration in the design of energy-efficient and environmentally sustainable smart buildings, as well as pioneering applications for smart cities, and their relevance in the future.

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