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Building Performance Improvement Based on BIM Reverse Modeling and Digital Twin

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Abstract. It proposes a framework which combines scan-to-BIM and digital twin technologies to improve the performance of today's existing buildings. Firstly, 3D laser scanning and photogrammetry are applied to construct accurate Building Information Models (BIMs) of existing buildings. Real-time data are then streamed into the BIM from Internet of Things (IoT) sensors (temperature, humidity, structural, occupancy sensors) to create an operational digital twin. This combined model is applicable to various services, including: energy optimization (based on real-time Heating, Ventilation and Air Conditioning (HVAC) control & retrofit strategy evaluation), structural health monitoring (continuous assessment & predictive maintenance), crowd management of buildings: dynamic evacuation routing, etc. Advantages of integrated data integration through proactive control, more accurate building management. It also identifies challenges as lack of automation, gaps in interoperability and lack of standards. It concludes with the suggestion of future works on multi-source data fusion and advanced analytics to contribute to intelligent operation & maintenance and low-carbon retrofit strategies.

Keywords: BIM reverse modeling, Digital twins, Building performance, Energy consumption optimization, Structural safety

1. Introduction

The construction industry is undergoing a digital transition now, and Building Information Modeling (BIM) in conjunction with digital twin technologies is now a crucial part of lifecycle management [1]. BIM combines geometry and information about a building to stimulate interdisciplinary cooperation and simulation analysis [1]. However, many existing buildings lack digital models, limiting effective operation and maintenance (O&M) as well as performance optimization. It tackles the challenge by scanning by 3D laser and using photogrammetry to complete BIM reverse modeling (scan-to-BIM) and create top-quality digital models of these buildings [2]. A digital twin originally came from manufacturing, and connects a physical asset with a virtual model using data connections. Through IoT devices, the twin offers real-time mapping, monitoring and control of the building operations. In building management, digital twins create the capability to monitor the use of energy in real-time, structural health and occupant flow condition to allow intelligent analysis and management methods [3,4]. This research discusses the implementation of BIM's reverse modeling with digital twin as a dual tool in enhancing existing building performance, the two-step application

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scenarios (energy optimization, structural safety, pedestrian evacuation) and the advantages, limitations and future development paths.

2. Literature review

2.1. BIM and building performance

BIM integrates information across the building lifecycle, facilitating collaboration and enhancing p

BIM centralizes information management, enabling collaboration and performance management throughout the building lifecycle [1]. BIM combined with energy simulation in previous works has been shown to optimize design schemes and operational strategies [5]. BIM-based simulations may predict energy consumption and evaluate retrofits much earlier in planning [5]. Literature reviews show that BIM has already been found to be used for energy forecasting, performance tuning, and life-cycle cost analysis activities. Despite this, the role of BIM in the operation and maintenance of existing buildings remains limited [6], with insufficient functionality and lack of unified standards for performance improvement.

2.2. Reverse modeling

Scan-to-BIM reconstructs the BIM model of an existing building using 3D point clouds. Automated workflows that process the registration, filtering, feature extraction, and geometric fitting of objects still necessitate much manual work [2]. Volk et al. note that point cloud-to-BIM accuracy and automation remain challenging and in need of improvement [6]. Recently, some computer vision and deep learning algorithms have been tested in order to produce components automatically and generate BIM elements themselves. However, large-scale Scan-to-BIM processes still struggle for the right balance between efficiency, accuracy, and generality, and full automation of reverse modeling remains immature [2,6].

2.3. Digital twins

Digital twins have a physical asset, virtual model and data links between them. Boje et al. [3] proposed a semantic digital twin framework, focusing on the fusion of BIM data and real-time information for construction and facility management. Cespedes-Cubides and Jradi looked into how digital twins improve building energy efficiency, and highlighted crucial applications like component monitoring, anomaly detection, operational optimization, predictive maintenance, and scenario simulation [4]. All in all, adoption rate for digital twins in the built environment is still in its infancy: standardization remains limited, few large-scale deployments exist, and it lags behind the use of digital twins in manufacturing [3,4].

2.4. Research gaps

Overall, the previous studies have prepared the ground: the positive aspects of BIM for information integration are well known [1], scan-to-BIM techniques are facilitating the digitization of existing buildings, and digital twins hold great potential in improving energy efficiency and safety. However, gaps remain. First, scan-to-BIM automation is limited: it is not yet possible to efficiently create high-fidelity models. Second, the architectures, data standards, and integration methods of building digital twins vary widely, which limits interoperability. Thirdly, integrated use of BIM and digital twins for performance enhancement is less studied, including real-time data for dynamic

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optimization of energy models or simulation strategies. Such problems drive the context of the present issue.

3. Research on inverse modeling methods

3.1. 3D data acquisition

Point cloud data recorded on a single building location are acquired using terrestrial laser scanning (TLS) and photogrammetry. TLS enables accurate millimeter measurements for detailed scans (indoor and outdoor), while mobile laser scanning (MLS) can capture larger areas of the scene with somewhat lower accuracies. In photogrammetry, many angle/wide shots are collected via Structure-from-Motion (SfM) and Multi-View Stereo (MVS) to reach high spatial coverage. Thus, a combination of TLS/MLS and photogrammetry ensures more complete point clouds. Upon data capture, the point clouds are registered (aligned) using reference targets or alignment algorithms, filtered to eliminate noise and outliers, and segmented by geometry into categories (walls, beams, columns, etc.) [2]. Each part's shape can then be reconstructed by geometric fitting (e.g., planes fit to the surfaces of the walls). Finally, the resulting geometry and topology are imported into BIM software, where corresponding model elements with attributes are created to complete the point cloud-to-BIM reconstruction.

3.2. BIM modeling strategies

BIM reverse modeling is usually done in a semi-automated manner. The program initially batch-fits routine objects such as regular walls or slabs, and at the same time manually modifies irregular or complex objects. Modeling typically follows a “whole-to-part” model process, where the primary structure — grid, floors, main frame — is built, and elements such as walls, columns, and beams are created, finishing with doors, windows, mechanical/electrical fixtures, and more. The point cloud is taken as a reference in the modeling environment for BIM model matching with reality. There has been a recent rise of smart tools (such as rule-based automatic room generation) aimed at increasing efficiency [7]. However, Scan-to-BIM has not reached fully automatic performance, and more advanced high-precision modeling algorithms are required.

4. Digital twin building

4.1. IoT sensor deployment

Digital twin requires deploying IoT sensors throughout the physical building. Sensors used to measure energy and environment include temperature, humidity, CO_2, utility meters and other conditions. This also includes strain gauges and accelerometers on key load-bearing elements for structural health. For people flow, occupancy sensors (infrared counters, cameras, or RFID readers) are positioned at entrances, corridors and stairwells. Real-time streaming of data to one central platform from all sensors (Each sensor’s location in the BIM model is referenced for correlated analysis).

4.2. Data platform architecture

These multi-source inputs are then pooled and processed by the data platform. This consists of data interfaces (e.g., via MQTT, HTTP, OPC protocols), time-series storage, and analytics modules

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connected to the BIM model. The incoming data of each sensor is pre-processed, integrated and processed into a visual representation; mapping is used for 3D plotting of the images at higher level. For instance, one solution further extends the IFC (Industry Foundation Classes) schema to include live sensor readings in a BIM architecture, ensuring that the building components can be linked to real-time sensor data and the virtual model maintains consistency with the physical state [4]. The platform makes dashboards (or 3D data representations for O&M staff) and creates alerts or recommendations to enable better decisions.

4.3. Virtual and real interaction mechanism

A digital twin exists because of the two-way exchange between a virtual model and a real building. Real-time sensor data drive updates in the BIM-based model (like a room in the model highlighted when the actual temperature exceeds a certain threshold). The building's control systems can, on the other hand, draw upon simulation and analysis results from the virtual model. For instance, this twin can automatically adapt HVAC setpoints or provide optimized evacuation instructions based on the simulations. The closed-loop is realized through real-time communication and rule-based decision logic, providing automated performance optimization while still allowing manual oversight when needed.

5. Applications for building performance improvement

5.1. Energy consumption simulation and energy-saving strategy evaluation

Energy usage plays a central role in both operational cost and carbon emissions. Traditional energy simulations typically center on the design phase, while digital twins allow for ongoing assessment of a building's lifecycle. An energy digital twin combines real-time information — temperature, occupancy, power usage—and BIM-based reverse modeling to provide accurate, geometric and thermal models. It routinely compares actual consumption with simulated forecasts, identifies anomalies, and tests energy-saving strategies (for instance, HVAC scheduling or insulation upgrades). Facility managers use it to estimate savings and payback periods for retrofits. Studies demonstrate such advantages: Iqbal et al. used machine learning for developing a BIM-IoT twin for autonomously optimizing indoor comfort, and Cespedes-Cubides and Jradi showcased five primary uses—monitoring, anomaly detection, optimization, predictive maintenance, and scenario simulation—to demonstrate how energy twins are turning the management of the structure from static design to dynamic and adaptive control [4,8].

5.2. Structural security and operation and maintenance management

Structural safety is a critical consideration. By integrating a network of structural sensors with the BIM model in a digital twin, real-time structural assessment and early warning become possible. Beams and columns are equipped with sensors that continuously provide stress and vibration data to the twins' platform. When an anomaly is identified (for instance, excessive strain or unusual vibration), the twin automatically generates an alert and highlights the affected element in the BIM model, which allows the engineers to identify the problem in record time. This can find any possibility of problems due to load or age much sooner than the occasional manual inspection. Digital twins move structural maintenance from a reactive to a predictive domain: e.g., analysis of gathered stress data can inform the construction of preventive reinforcements. Furthermore, twins can simulate building response to extreme events (e.g., earthquakes) and, using real sensor data

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post-event, swiftly assess actual damage to ensure the emergency operations are informed. In general, a structural digital twin offers 24/7 detailed monitoring, which significantly promotes faster and enhanced maintenance speed and accuracy [7,9].

5.3. Crowd simulation and emergency evacuation

In big public buildings, efficient people flow and effective evacuation are performance indicators. A digital twin of the crowd integrates live occupant data into real-time BIM-based simulation. For instance, people-count sensors at significant points of access (entrances, hallways, stairs) provide live data that monitor the movement of the occupants. If there is congestion or an emergency (for example, a fire alarm), the twin can calculate the optimal evacuation routes on the fly and issue real-time guidance. Indeed, studies have indicated that the dynamism of this method outperforms static evacuation plans in adjusting to a changing environment [10]. By correlating virtual simulations with live data, bottlenecks in a building's layout can be unearthed and signage or pathways can be improved. The people-flow twin also uses heatmap data to optimize facility placement and scheduling in daily operations. In short, a crowd-aware digital twin provides a deeper insight into occupant behavior to enhance efficiency and safety in emergencies [10].

6. Discussion and outlook

6.1. Advantages and comprehensive benefits

BIM reverse modeling and digital twin technologies together can achieve great benefits for improving existing building performance. With BIM reverse modeling, we could get a complete and accurate digital model of an older building, and real-time operational data can be fed into that model to use for visualization and analysis. As a result, the integration of real-world and virtual information allows for insights that conventional models may struggle to easily produce by quick identification of performance issues and optimizing control decisions. In fields such as energy management and safety, it transforms the nature of building operations from reactive responses to proactive prediction and optimization. Additionally, both BIM and digital twins focus on information integration and collaboration, which means their integration can eliminate information silos throughout the building lifecycle and, likewise, offer closed-loop feedback from design and construction to operation and maintenance.

6.2. Existing shortcomings

However, challenges remain even with these benefits. First, the technology and upfront investments required are high: high-precision scanning equipment is expensive, data processing demands are heavy, and implementing a full digital twin (sensors, networks, platforms) is a high barrier to entry. Second, standardized requirements are lacking: nowadays, Scan-to-BIM and digital twin data systems often rely on proprietary data formats or interfaces and no system standardization exists among various tools. This requirement for custom integration means that large-scale adoption is difficult for each project. Data security and privacy are also a problem: digital twins collect and transmit enormous amounts of real-time data, and insufficiently secured systems could be vulnerable to cyber-attacks or data leaks. Finally, there is a trade-off between the precision of data and the power of a real-time model: highly detailed models with frequent updates lead to data volumes and computation requirements, so the challenge is how to enhance responsiveness but with no loss of accuracy.

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6.3. Future development direction

On the horizon, a few areas are worth looking into. (1) Multi-source data fusion and AI: connect disparate data sources (laser scans, photogrammetry, drones, and IoT sensors) and employ innovative AI technologies to enhance automation in twin model creation and analysis. AI-powered algorithms (in particular large language models) could facilitate the automation of complex mapping between sensor data and BIM elements [11]. (2) Accuracy and robustness: develop algorithms able to achieve high accuracy under complicated or cluttered environments and also to incorporate adaptive mechanisms for sensor noise and uncertainty. (3) Standardization: develop unified data and interface standards for scan-to-BIM and digital twin systems (based on IFC format, for example) to facilitate integration and improve interoperability. (4) Application expansion: extend digital twins to new domains such as historic building preservation, smart city coordination, and carbon emission monitoring, and integrate twins with emerging systems like energy microgrids and storage to optimize overall building energy management. (5) Policies and business models: advocate for favorable government policies and industry standards and consider business models (e.g., performance contracting or energy savings sharing) which would encourage implementation of such technology.

7. Conclusion

This research explored how an adaptation of BIM reverse modeling in conjunction with digital twin technology can improve the performance of established buildings. Through our studies, we show that scan-to-BIM can generate high-precision digital representations of the existing structures and that, by incorporating real-time sensor data into these BIM models, real-time monitoring and feedback control of building work can be achieved. However, in practice, digital twin-based energy simulations and strategy evaluations can significantly reduce energy usage; the structural twin enables continuous health monitoring and proactive maintenance; and the people-flow twin improves daily operational efficiency and emergency evacuation. The integration of BIM with digital twins allows for increased benefits through information integration and proactive control, resulting in significant improvements in building energy efficiency, safety, and comfort. But there are still challenges (limited automation, lack of standards, etc.) and work remains in areas for R&D. With the maturing of associated technologies and standards, the deeper integration of scan-to-BIM and digital twins will enable new approaches to intelligent building operation, maintenance, and green retrofitting of buildings, which have a wide application spectrum.

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