Research Article

Integrating Dynamic Data Modelling for Non-Structural Components within a BIM-based Digital Twin Framework for Enhanced Emergency Evacuation in Buildings

Muhammad Farhan Jahangir[1], Carl Peter Leslie Schultz[2], and Aliakbar Kamari[1]

1 DIGIT, Department of Civil and Architectural Engineering, Aarhus University, Denmark
2 DIGIT, Department of Software Engineering & Computing, Aarhus University, Denmark
Correspondence: mfj@cae.au.dk

Abstract

Disasters, whether natural or human-induced, pose serious threats to human safety and infrastructure. In buildings such as hospitals, airports, and industrial facilities, timely and well-coordinated emergency evacuation is essential to safeguard occupants and assets. However, managing the performance of non-structural components, such as mechanical, electrical, and auxiliary systems, under such conditions remains a critical challenge, especially given their crucial role in ensuring operational continuity and occupant safety.

This paper introduces a dynamic, BIM-integrated Digital Twin (DT) framework tailored for the real-time simulation and management of non-structural components in complex buildings. Non-structural systems, including electrical, mechanical, HVAC, and auxiliary installations, play a crucial role in ensuring operational continuity and occupant safety, particularly during emergencies. Despite their criticality, these systems are often underrepresented in building simulations and asset management strategies. The proposed framework addresses this gap by leveraging Building Information Modelling (BIM) as a central, data-rich environment, with Industry Foundation Classes (IFC) employed to facilitate standardized, cross-domain data exchange.

The methodology enables a bi-directional, iterative exchange of data between the BIM environment and simulation units, using Building Simulation Identity Cards (BSIC) to standardize simulation parameters, data requirements, and system attributes. This approach enables seamless data exchange and cross-domain integration for non-structural system simulations. Each simulation not only extracts domain-specific data but also feeds updated results back into the BIM model. This continuous feedback loop maintains model currency and analytical fidelity, enabling adaptive, real-time modelling of system behavior.

Keywords: Digital Twin, Building Information Modelling (BIM), Non-structural Systems, Emergency Evacuation, Building Simulation Identity Card

Highlights

- Dynamic data modelling within the BIM framework.
- Proposes a BIM–Digital Twin framework for real-time simulation-driven model updates.
- Integrates BSIC standards to ensure interoperability across multi-domain simulations.
- Demonstrates evacuation simulation updating BIM with non-structural component changes

1 Introduction

In the changing landscape of smart building design and emergency preparedness, Building Information Modelling (BIM) has become a fundamental approach for digital transformation in the Architecture, Engineering, Construction, and Operation (AECO) industry (Zawada et al., 2024). As an innovative, data-rich platform, BIM allows the organized integration of multidimensional information throughout the entire lifecycle of built environments, from initial concept and construction to facility management and emergency response. This capability is significant in infrastructure such as hospitals, airports, and large commercial buildings, where the integrity and coordination of both structural and non-structural systems are crucial for maintaining operations and ensuring occupant safety (Adibi et al., 2024).

While BIM has traditionally served as a static digital model of architectural and engineering assets, the need to expand its capabilities toward real-time, dynamic modelling has gained significant momentum (Manzoor et al., 2025). This shift is primarily driven by the increasing demand to simulate and react to real-world scenarios such as natural disasters, equipment failures, and human-made emergencies (Jahangir et al., 2025). In these situations, non-structural components, including mechanical, electrical, HVAC, and auxiliary systems, are crucial for enabling quick, safe, and intelligent evacuation strategies. However, these systems are still underrepresented in conventional BIM analyses, resulting in a critical gap in the accuracy and effectiveness of emergency preparedness plans.

The integration of Digital Twin (DT) technology enhances this capability by enabling a continuously evolving, data-rich representation of the built environment, where real-time simulation outputs and sensor data directly inform model updates (Jahangir et al., 2024). Within this context, the Building Simulation Identity Card (BSIC), a standardized data schema that defines the input, output, and metadata requirements for each simulation, ensures that simulation data is structured, semantically consistent, and interoperable across multiple hazard and system domains, enabling reliable cross-simulation communication. (Jahangir et al., 2025).

In complex building operations, current BIM-based simulation workflows face a fundamental limitation: they are static, linear, and cannot adapt to changing real-world conditions. After a simulation runs, it usually depends on a fixed BIM model version, missing updates related to structural damage, system failures, or occupant movement that may happen during or after the simulation. This static approach weakens decision-making reliability, especially in high-stakes areas like hospitals or airports, where quick changes in non-structural systems such as HVAC, electrical, or communication networks can significantly impact evacuation results. Although DT technologies have advanced, there is still no integrated framework that allows BIM to act as a continuously updated, simulation-aware system. Specifically, the lack of mechanisms to dynamically feed simulation results back into the BIM model creates a gap between the virtual and physical building states. For example, in the case of evacuation, outdated BIM models may still show unblocked exits, while simulation-driven updates reveal obstructed pathways and displaced non-structural elements, directly affecting safe egress planning.

This results in outdated analyses, poor coordination across simulation domains, and less effective emergency responses. To address this, a shift toward dynamic data modelling within BIM is necessary, where model updates automatically trigger new simulation cycles.

This study addresses this issue by proposing a BIM-integrated DT framework specifically designed for the dynamic modelling and simulation of non-structural components during emergency evacuations. At the heart of this approach is the use of BIM not just as a visualization or documentation tool, but as an active, bidirectional data environment. By integrating Industry Foundation Classes (IFC) (Du et al., 2024) and Building Simulation Identity Cards (BSIC) (Jahangir et al., 2025), the framework establishes a standardized, interoperable infrastructure for simulation-driven decision-making, demonstrated through a proof of concept. This enables iterative feedback loops, where real-time sensor data, simulation results, and domain-specific updates are continuously incorporated back into the BIM model, transforming it into a living digital entity capable of adaptive analysis and predictive control.

2 Related Work

Dynamic data modelling in BIM has garnered significant attention as the architecture, engineering, and construction (AEC) industry moves toward more integrated and intelligent workflows. Existing research has explored various strategies to enhance the adaptability, interoperability, and real-time responsiveness of BIM data structures. For instance, Singh et al., (2025) explored BIM automation for reinforced concrete slab design using Python and IfcOpenShell, demonstrating real-time update mechanisms via IFC editing. Similarly, Chatsuwan et al.,(2025) proposed a BIM-IoT integration platform that leveraged IFC-to-JSON conversion via IfcOpenShell for facilities management, highlighting the importance of open data workflows for spatial updates.

Stoitchkov, (2020) developed a Python-based retrieval system for IFC model data that aligns with the current research objective of structured IFC manipulation through semantic parsing of placements. Meanwhile, Spielhaupter, (2021), compared multiple IFC transformation workflows, recognizing Python/IfcOpenShell as one of the most effective strategies for restructuring BIM data. Moreno et al., (2022), developed a BIM–FM prototype that integrates dynamic data, environmental sensor readings, and maintenance records into Autodesk Revit for facility management of a university building. The system enables real-time updates through Excel and Azure IoT integration, allowing non-BIM users to interact with and update building data. It enhances usability through a Power BI dashboard, providing intuitive data visualization and informed decision-making.

BIM and DT technologies have been widely studied for their applications in structural health monitoring, disaster resilience, and facility management. Renault et al.,(2025), proposed an intelligent structural health monitoring (iSHM) approach that integrates BIM and DT for real-time assessment of arbitrary non-structural elements, ensuring operational safety in buildings. This study emphasizes the importance of integrating real-time data with BIM models to ensure the stability of both structural and non-structural components under hazardous conditions.

The research by Deng et al., (2021), outlines the progressive evolution of BIM into intelligent, real-time Digital Twins (DTs). It identifies critical technological transitions, particularly the integration of live data streams and simulation capabilities, that underpin contemporary facility management and emergency decision-making systems. The study establishes the theoretical basis for dynamic BIM-DT convergence. Building on Deng et al.'s framework, a review by Khallaf et al. (2022) emphasizes the application of DTs in operational phases of buildings. The authors analyse real-time data loopbacks and the integration of IoT-enabled sensory inputs into BIM models, highlighting the shift from representational modelling to predictive, behaviour-aware modelling relevant to evacuation and dynamic asset monitoring. Yang et al. (2025), in their work, introduced a 4D Digital Twin framework that integrates IFC-based BIM with Synthetic Aperture Radar (SAR) interferometry to detect façade and roof deformation. Using machine learning for PS-point integration, the study advances dynamic update mechanisms for semi-structural and non-structural elements. A paper by Abdelalim et al., (2025), identifies a critical gap between static

BIM use and the dynamic demands of emergency planning. It proposes AI-augmented DTs capable of integrating and analysing live asset states (e.g., non-structural systems like ventilation, emergency lighting) during crisis simulations. Similarly, Hakimi et al. (2023), in their study, introduce a digital twin data-fusion framework enabling bidirectional data flows between sensors and BIM models. It outlines how different simulation units can use updated datasets. In another study by Almatared et al., (2023), this research explores DTs in real-time fire simulations, focusing on how environmental and asset data updates (e.g., blocked pathways, sensor failures) directly influence evacuation decisions.

3 Framework

The proposed framework for dynamic data modelling of non-structural components in buildings within a BIM-based DT architecture integrates real-time monitoring, predictive maintenance, and emergency evacuation support. It establishes a structured approach to managing critical non-structural assets, ensuring system integrity and safety under operational and emergency conditions. Figure 1 represents the DT Framework, which incorporates dynamic data modelling in BIM.

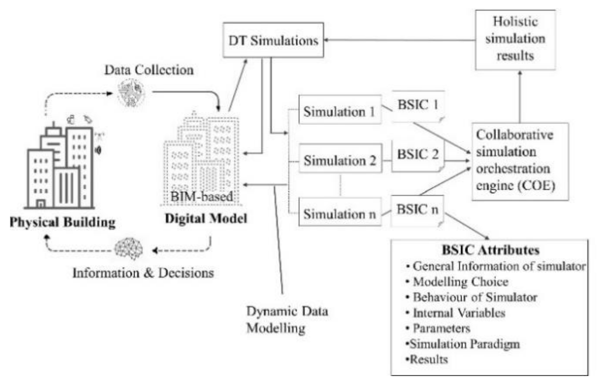


Figure 1: DT Framework facilitating co-simulation

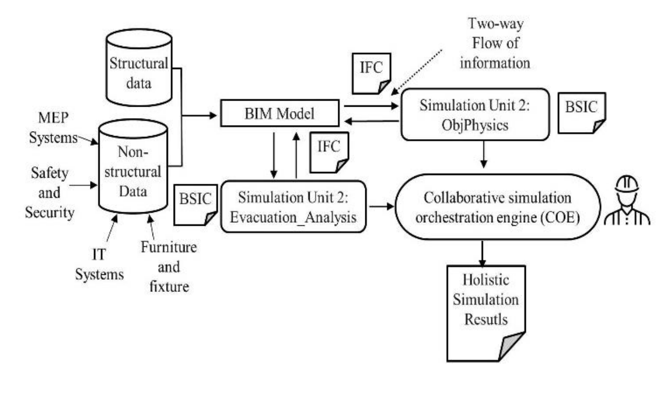


Figure 2: Dynamic data modelling within the BIM framework.

The proposed framework establishes a collaborative and integrated simulation environment leveraging BIM to facilitate multi-domain analysis in buildings. At its core, the BIM Model serves as a centralized data repository, incorporating both structural and non-structural data essential for comprehensive simulation processes, as represented in Figure 2. The framework employs IFC as a standardized data exchange format, ensuring seamless interoperability between the BIM model and various domain-specific simulation units.

A key feature of this framework is its dynamic two-way flow of information, where each simulation unit not only extracts data from the BIM model but also updates it iteratively. This continuous updating process ensures that subsequent simulations operate on the most up-to-date state of buildings, thereby enhancing analysis accuracy and informed decision-making. For instance, in seismic analysis, structural vulnerabilities and potential modifications are identified. This updated information is then utilized in evacuation analysis, ensuring that emergency egress simulations reflect real-time structural conditions.

This proof of concept focuses explicitly on integrating and updating non-structural data critical to building operations. These include equipment, control panels, safety barriers, ventilation systems, emergency lighting, and other essential components of infrastructure. The location and status of these non-structural components are dynamically updated after both structural and evacuation simulations, ensuring that subsequent analyses are based on real-time, high-fidelity data. The proposed framework enables the BIM model to evolve continuously, ensuring that future simulations reflect the most recent state of the buildings.

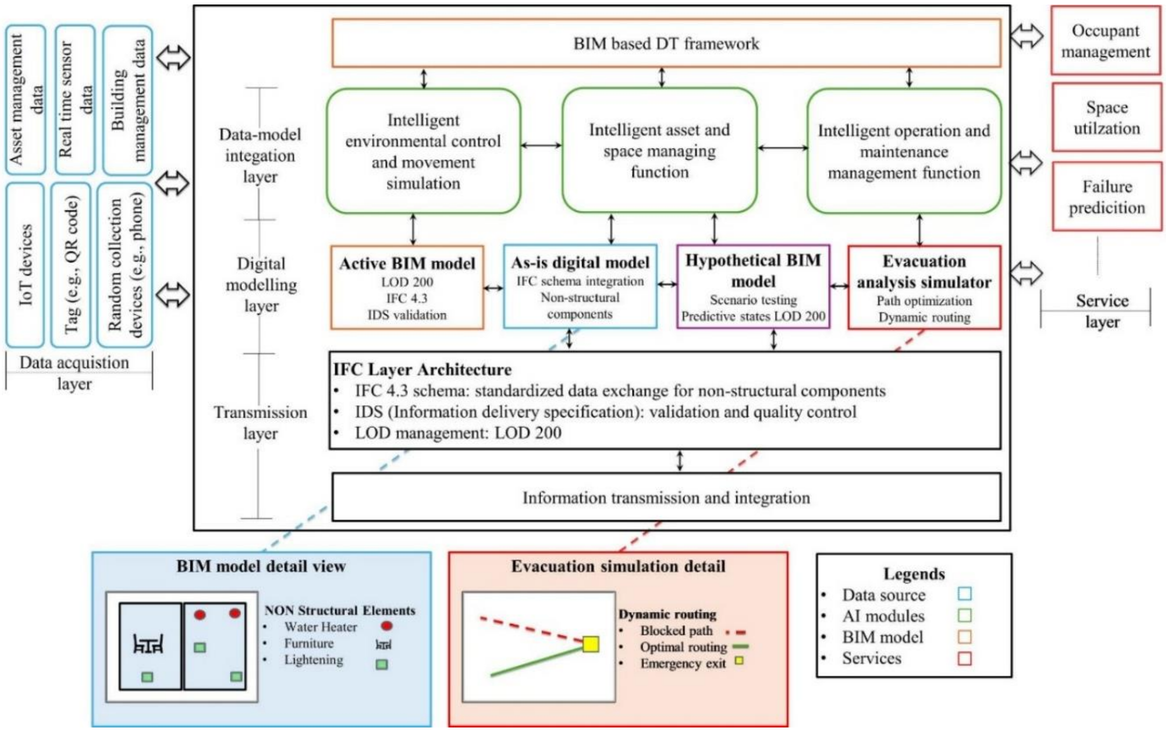


Figure 3 BIM-based DT Framework for Non-Structural Component Management (inspired by (Lu et al., 2022))

The Digital Twin framework shown in Figure 3 presents an advanced BIM-based architecture designed for managing non-structural components during emergency evacuations. At its core is the IFC Layer Architecture, utilizing the IFC 4.3 schema to standardize data exchange for elements such as furniture, emergency lighting, and safety barriers. The integration of the Information Delivery Specification (IDS) (de Marco et al., 2024) ensures data consistency and accuracy throughout the feedback process. The Active BIM model, operating at the level of detail (LOD) 200 (Elmurodov et al., 2025), represents the current state of the building with full IFC 4.3 and IDS validation. The As-is digital model serves as a hub for managing non-structural components and their status updates via BSIC parameters. Meanwhile, the Hypothetical BIM model is used for scenario testing and predictive modelling.

3.1 Integration of Co-Simulation Approaches

Within the proposed BIM–Digital Twin framework, a key design decision relates to how various simulation units (FMUs) communicate during co-simulation. Generally, there are two integration approaches: (i) direct FMU-to-FMU communication, where simulators share data in real time through a master algorithm, and (ii) FMU–IFC–FMU communication, where the BIM model via IFC serves as the central hub for information exchange.

In this study, the FMU–IFC–FMU pathway was adopted. This choice reflects the objective of maintaining BIM as a central source of information. By embedding simulation-driven updates (e.g., displaced non-structural elements or obstructed egress routes) directly into the IFC model, subsequent simulations operate on the most current representation of the building state. This demonstrates the feasibility of embedding simulation outputs within a semantically enriched BIM environment, a capability that has not been adequately addressed in prior approaches.

Nevertheless, the limitations of the IFC schema must be acknowledged. Phenomena such as physiological impacts of smoke inhalation during evacuation cannot be represented through IFC updates, highlighting scenarios where direct FMU-to-FMU communication is more suitable. Table 1 represents the comparative advantages and trade-offs of these approaches.

Table 1 Comparative Assessment of Co-Simulation Strategies

Dimension	Direct FMU-to-FMU Communication	FMU–IFC–FMU Communication
Data Exchange Mechanism	Real-time exchange between FMUs via master algorithm	Indirect exchange through IFC-based BIM updates
Analytical Fidelity	Captures dynamic, non-BIM phenomena (e.g., human physiology, toxic exposure)	Limited to data expressible within IFC schemas
Consistency & Traceability	Weak – results not embedded in BIM	Strong – BIM preserved as a single source of truth
Interoperability	Low – requires bespoke integration	High – leverages standardized IFC formats
Computational Efficiency	High – minimal latency, no serialization overhead	Lower – IFC read/write introduces delays
Applicability	Real-time, domain-specific simulations	Multi-domain coordination, documentation, and governance
Research Contribution	Enables dynamic extensions beyond the BIM scope	Demonstrates embedding of simulation outputs into semantically enriched BIM, advancing Digital Twin fidelity

4 Proof of Concept

To demonstrate the feasibility of the proposed framework, we developed a proof-of-concept prototype that integrates simulation-driven updates of non-structural components within a BIM-based DT environment. This implementation targets a simplified yet representative building model, a single-story structure comprising two adjacent rooms, each measuring 20 by 30 feet, yielding a total floor area of 1200 square feet, as represented in Figure 5(a) and (b). The proposed simulation-driven methodology integrates BIM-based DT technology with multi-domain simulation for dynamic modelling of non-structural components in buildings. The process begins with a reference IFC-based BIM model, which stores both spatial and non-structural elements (e.g., equipment, furnishings, ventilation units). An IFC Handler is used to extract and update object locations in real-time, serving as the interface between the simulation results and the BIM model in Figure 4 represents the class diagram for dynamic data modelling in BIM.

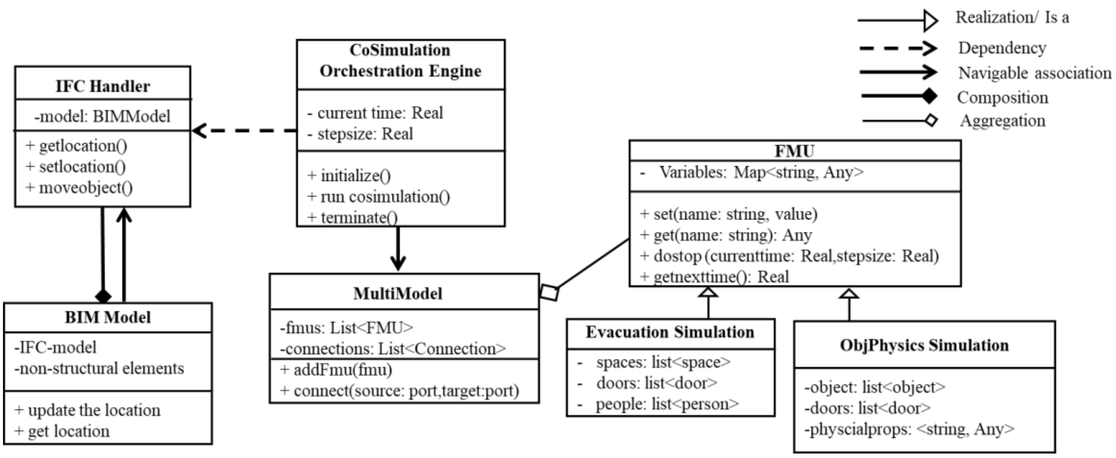


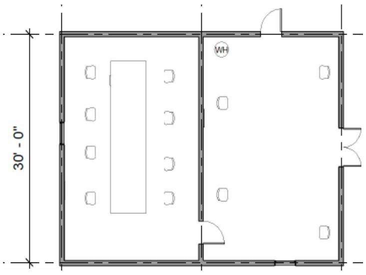
Figure 4: Simulation Architecture for Dynamic BIM Updates

Simulation orchestration is governed by a master algorithm that coordinates multiple FMU-based modules defined within a multi-model architecture. Key simulation domains include Evacuation Simulation, which models occupant movement toward exits while interacting with movable objects, and ObjPhysics Simulation, which applies physics-based responses such as collision detection and force propagation. The Simulation Engine manages time-stepped execution, synchronizing these modules and feeding dynamic object interactions back into the BIM model via the IFC Handler.

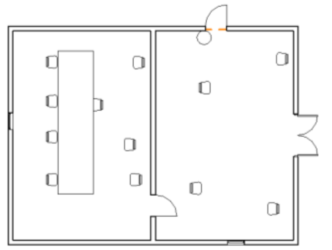
The script performs the following critical operations:

IFC Parsing: Leveraging ifcOpenShell and related Python libraries, the script reads and parses the IFC model to identify and extract metadata and spatial coordinates of target non-structural elements.

IFC Model Editing: The affected elements are programmatically modified within the IFC schema.



a : Building floor plan from the reference BIM model before the dynamic updates.



b : Building floor plan from BIM model reference after dynamic updates.

Figure 5 Building floor from the BIM model before and after dynamic data modelling.

Simulation-Driven Update: Output data from external simulations (e.g., Evacuation flow disruptions or localized equipment failures) is processed to determine required updates in location, status, or orientation of non-structural elements.

4.1 Analysis

The proof-of-concept implementation demonstrates the viability and effectiveness of the proposed BIM-based DT framework for dynamic modelling and simulation-driven management of non-structural components during emergency evacuations. The system's core advantage is to establish a real-time, bi-directional data exchange between simulation engines and the IFC-based BIM environment, significantly enhancing fidelity and operational relevance in emergency preparedness scenarios.

Table 2 Comparative Evaluation of Static BIM Workflows and the Proposed Framework for Dynamic BIM Workflows

Category	Static BIM Workflows	Proposed Dynamic DT Framework	Impact on Emergency Preparedness
Model Adaptability	One-time, static model	Continuous real-time updates from simulation feedback	Enhances the accuracy of evacuation simulations and resource planning
Simulation Interoperability	Siloed, domain-specific tools with minimal coordination	Integrated FMU-based architecture with standardized BSIC	Facilitates cross-domain decision-making and synchronized actions
Update Propagation Mechanism	Manual, error-prone BIM updates	Automated update via Python + IfcOpenShell IFC Handler	Reduces latency; ensures model fidelity across simulations
Component Behaviour Modelling	Geometric only; lacks physical or dynamic properties	Includes dynamic interactions via the ObjPhysics simulation engine	Captures real-world behaviours, such as collisions and displacement.
Simulation Coordination	Sequential	Orchestrated multi-module simulation scheduling via a Master Algorithm	Optimizes critical path execution and dependency management
Scalability to Large Models	Degrades significantly with scale; high manual overhead	Modular, Python-driven workflow; compatible with distributed setups	Enables deployment in multi-storey hospitals, airports, and industrial sites
Post-Simulation Reusability	Requires manual reset or duplication of models	Automatic state preservation and evolution of BIM after each simulation	Supports predictive modelling and iterative improvement cycles

The framework also demonstrates strong potential for scalability. Although tested on a two-room prototype, the modular, API-driven architecture enables it to scale to high-density environments such as airports, hospitals, and industrial plants. Furthermore, the system's interoperability with open standards and readiness for integration with IoT inputs position it well for full-scale facility implementations.

The comparative evaluation in Table 2 reinforces these points by systematically contrasting the proposed framework with traditional BIM workflows. Key differentiators include real-time update mechanisms, automated simulation coordination, and semantic richness via IDS, all of which contribute to reduced human error, enhanced fidelity, and improved emergency readiness.

5 Discussion

The evacuation simulation implemented in this study validates the central proposition of the proposed BIM-integrated Digital Twin (DT) framework: that the continuous updating of a BIM model with simulation outputs is not only important but essential for achieving accurate emergency analyses. The proof-of-concept demonstrates how simulation-driven updates, such as occupant-object interactions, obstacle displacements, and altered circulation paths, are directly written back into the IFC file, ensuring that the BIM model serves as a living, operationally relevant representation of the building.

This capability addresses the core limitation identified in the literature regarding the static nature of conventional BIM-based emergency workflows. The study by Moreno et al., (2022) and Hakimi et al., (2023) have underscored the benefits of integrating sensor feeds and environmental data into BIM for operational management, but these approaches often remain descriptive rather than prescriptive. In emergency contexts, this limit can lead to dangerous discrepancies, such as evacuation routes planned on outdated layouts or fire suppression strategies designed without accounting for newly blocked egress points.

Figure 6 illustrates the framework's operational flow, where the BIM environment is positioned at the core of a multi-simulation ecosystem. Inputs from the physical environment, ranging from motion and thermal sensors to current and displacement measurements, are processed via the Interface layer and translated into actionable simulation triggers. Simulation modules, including Evacuation Simulation, ObjPhysics Simulation, and Seismic Simulation, interact bidirectionally with the BIM model. Crucially, updated spatial and semantic data are reintegrated into the model before subsequent simulations are executed. This sequencing ensures that every simulation begins with the most current state of the building, maintaining fidelity and preventing the "model drift" observed in isolated, sequential workflows.

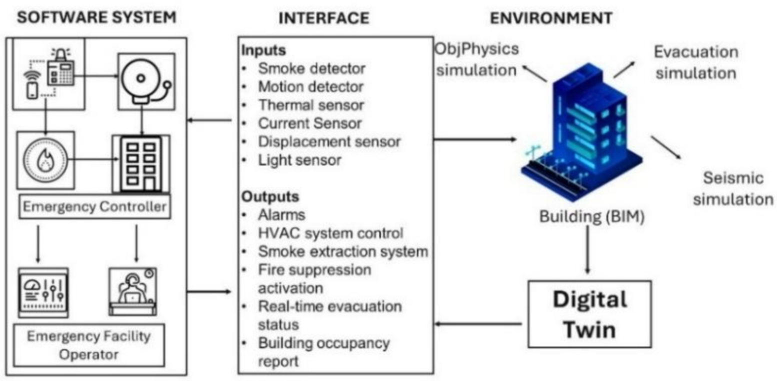


Figure 6 Conceptual Framework for BIM–DT Integration

The functional integration of Building Simulation Identity Cards (BSIC) within this framework further ensures semantic consistency and seamless data exchange across simulation domains, echoing the cross-domain integration strategies suggested by Abdelalim et al., (2025) and Khallaf et al., (2022). By providing a standardized data structure for each simulation's input and output requirements, BSICs eliminate ambiguities that can otherwise result in incompatible datasets or incomplete updates. This is especially critical when non-structural systems, such as emergency lighting, HVAC control, or safety barriers, are displaced or reconfigured in ways that materially affect other hazard domains.

The broader implication is that coordination among simulations is not the end goal in itself; rather, it is the updated BIM model, enriched by each simulation cycle. This shift from static to continuously updated modelling aligns with the operational aspirations of DT frameworks described by Deng et al., (2021) and Almatared et al., (2023), moving from representational to predictive, behaviour-aware modelling.

Furthermore, the architecture's modular, IFC-driven design makes it inherently scalable. While the proof of concept was tested on a simplified two-room layout, the same principles can extend to multi-storey hospitals, high-capacity airports, or industrial complexes. In such environments, the need for accurate, simulation-informed model updates becomes exponentially more critical, as decision latency or reliance on outdated layouts can lead to significant risks for both occupants and assets.

6 Conclusion

This study advances BIM–Digital Twin integration by introducing a real-time feedback mechanism that updates the BIM model with simulation results through a bidirectional, iterative exchange. This ensures subsequent analyses operate on the most current building state with high analytical fidelity. Through the proof-of-concept evacuation simulation, the framework demonstrated how non-structural components, often overlooked in emergency modelling, can be dynamically repositioned and reintegrated into the BIM model during evolving hazard scenarios.

Unlike static, domain-isolated workflows, the proposed approach maintains a single authoritative BIM model as the central hub for all simulation outputs. This enables adaptive, cross-domain integration for emergency planning, where evacuation and structural safety simulations draw from the same updated data. The inclusion of standardized BSIC structures ensures semantic consistency and seamless data exchange, making the system scalable while capturing realistic system behaviour.

Practically, the framework transforms BIM from a static documentation tool into a continuously evolving operational asset, capable of supporting predictive, simulation-informed decision-making in high-stakes environments. Future work will focus on integrating real-time IoT sensors, chaining multi-hazard simulations, and scaling to extensive, complex facilities while maintaining low update latency and high analytical fidelity.

Acknowledgements

This study is supported by the Higher Education Commission of Pakistan, Aarhus University and Digit.

Funding

Funding for this Project is Provided by the Higher Education Commission of Pakistan

Data Availability Statement

Data can be available on request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdelalim, A. M., Essawy, A., Sherif, A., Salem, M., Al-Adwani, M., & Abdullah, M. S. (2025). Optimizing Facilities Management Through Artificial Intelligence and Digital Twin Technology in Mega-Facilities. *Sustainability*, *17*(5), 1826.

Adibi, S., Rajabifard, A., Shojaei, D., & Wickramasinghe, N. (2024). Enhancing healthcare through sensor-enabled digital twins in smart environments: A comprehensive analysis. *Sensors*, *24*(9), 2793.

Almatared, M., Liu, H., Abudayyeh, O., Hakim, O., & Sulaiman, M. (2023). Digital-twin-based fire safety management framework for smart buildings. *Buildings*, *14*(1), 4.

Chatsuwan, M., Ichinose, M., & Alkhalaf, H. (2025). Enhancing Facility Management with a BIM and IoT Integration Tool and Framework in an Open Standard Environment. *Buildings*, *15*(11), 1928.

de Marco, G., Slongo, C., & Siegele, D. (2024). Enriching building information modeling models through information delivery specification. *Buildings*, *14*(7), 2206.

Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction*, *26*.

Yang, C., Lee, J., & Kim, J. (2025). Fusion of BIM and SAR for innovative monitoring of urban movement—towards 4D digital twin. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 1627–1634.

Du, S., Hou, L., Zhang, G., Tan, Y., & Mao, P. (2024). BIM and IFC data readiness for AI integration in the construction industry: A review approach. *Buildings*, *14*(10), 3305.

Elmurodov, S., Kuchimov, M., Ikramov, S., Mirdjalalov, D., & Quvatova, M. (2025). Requirements for lod in BIM design. *AMERICAN JOURNAL OF EDUCATION AND LEARNING*, *3*(3), 966-971.

Hakimi, O., Liu, H., Abudayyeh, O., Houshyar, A., Almatared, M., & Alhawiti, A. (2023). Data fusion for smart civil infrastructure management: A conceptual digital twin framework. *Buildings*, *13*(11), 2725.

Jahangir, M. F., Kamari, A., & Schultz, C. P. L. (2025). Unified and interoperable digital twin models for emergency evacuation using building simulation identity cards. *Automation in Construction*, *175*, 106225.

Jahangir, M. F., Leslie Schultz, C. P., & Kamari, A. (2024). A review of drivers and barriers of Digital Twin adoption in building project development processes. *Journal of Information Technology in Construction*, *29*.

Khallaf, R., Khallaf, L., Anumba, C. J., & Madubuike, O. C. (2022). Review of digital twins for constructed facilities. *Buildings*, *12*(11), 2029.

Lu, Q., Xie, X., Parlikad, A. K., Schooling, J., & Pitt, M. (2022). *Digital twins in the built environment: Fundamentals, principles and applications*. ice Publishing.

Manzoor, B., Charef, R., Antwi-Afari, M. F., Alotaibi, K. S., & Harirchian, E. (2025). Revolutionizing Construction Safety: Unveiling the Digital Potential of Building Information Modeling (BIM). *Buildings*, *15*(5).

Moreno, J. V., Machete, R., Falcão, A. P., Gonçalves, A. B., & Bento, R. (2022). Dynamic data feeding into BIM for facility management: A prototype application to a university building. *Buildings*, *12*(5), 645.

Renault, P. L., Radisic, M., Michel, P., & Butenweg, C. iSHM-Intelligent structural health monitoring coupled with BIM. SMiRT 27,

Singh, T., Mahmoodian, M., & Wang, S. (2025). Advancing Smart Construction Through BIM-Enabled Automation in Reinforced Concrete Slab Design. *Buildings*, *15*(3), 343.

Spielhaupter, O. (2021). *BIM to BEM transformation workflows:: A case study comparing different IFC-based approaches* Technische Universität Wien].

Stoitchkov, D. (2020). Automated retrieval of shared IFC model data based on user-specific requirements.

Zawada, K., Rybak-Niedziółka, K., Donderewicz, M., & Starzyk, A. (2024). Digitization of AEC industries based on BIM and 4.0 technologies. *Buildings*, *14*(5), 1350.