Enhancing 3D building visualization and real-time monitoring in construction through IFC and IoT integration

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ABSTRACT

The integration of industry foundation classes (IFC) and internet of thing (IoT) addresses a key challenge in construction: real-time data visualization on specific building storeys. Traditional methods often struggle with data integration and timely monitoring. This study introduces a web-based platform that combines three-dimensional (3D) technology, IFC models, and IoT sensors to enhance visualization and monitoring in construction projects. Unlike prior approaches that focus on static visualization or lack real-time IoT integration, this platform delivers dynamic, storey -specific updates, enabling real-time monitoring of critical building parameters. A case study showed that file size significantly impacted loading speed, ranging from 0.17 kB/ms (97.3 kB model in 572 ms) to 11.72 kB/ms (7.2 MB model in 629 ms). Despite a slight drop in frame rate from 60 to 55 frames per second (FPS), the system maintained smooth user interactions. Memory usage increased from 180 MB to 314 MB to handle complex 3D models and IoT data in real time. These findings demonstrate that integrating IFC with IoT enhances data visualization, providing more efficient decision-making tools for construction stakeholders and improving on-site coordination and resource management.

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1. INTRODUCTION

Three-dimensional (3D) building visualization plays a pivotal role in the construction industry. It enables the accurate representation of design concepts and facilitates effective communication with stakeholders [1], [2]. Although traditional methods are widely used, they often suffer from limitations related to interoperability and data integration [3]–[6]. These limitations hinder seamless collaboration across diverse platforms and systems. The complex and fragmented nature of construction data further exacerbates these inefficiencies in the design and construction process.

Building information modeling (BIM) has emerged as a critical tool for addressing some of these issues [7]–[10]. It offers high-fidelity datasets that capture building elements and their spatial organization in great detail. The web of things standard simplifies the integration of building information from various sources [11]–[14]. However, despite effectively representing as-designed building information, BIM models are often constrained by proprietary formats and lack compatibility with other systems. A significant challenge remains in achieving efficient integration and real-time access to BIM data across various platforms.

Prior studies have shown that integrating BIM with the Web of Things enhances the communication of construction information [15], [16]. Despite advancements in web-based BIM tools, challenges persist in integrating multiple BIM models and enabling real-time interactions within web environments. The main obstacle is to ensure real-time updates while incorporating internet of thing (IoT) sensors that continuously monitor critical parameters like temperature, humidity, and structural integrity. Integrating industry foundation classes (IFC) into web platforms improves 3D visualization and supports efficient management of multiple BIM models [17]–[22]. However, current methods have not fully exploited the potential of combining IoT with BIM, particularly in achieving real-time data integration and dynamic control within a 3D web visualization framework.

IFC includes building story information useful for viewing specific building sections at designated levels [23]–[25]. This research leverages IFC's ability to represent building stories and enriches it with real-time IoT sensor data. The result is a dynamic platform where stakeholders can access updated building performance information for specific floors. In the construction project lifecycle, the absence of standardized, integrated methods for storing BIM files poses significant challenges. It hinders the exchange and sharing of information across various building application systems at different stages of a building's ecosystem [26].

To address the integration challenges between IFC and web technologies, recent research has focused on developing Web3D environments that merge IFC with IoT [27]. IFC uses the object-oriented EXPRESS data description language to ensure that detailed building elements can be shared across platforms without losing fidelity [28]. Frameworks like WebGL enable the integration of IFC into web platforms by rendering 3D models in real time. This allows users to interact directly with BIM models in web browsers [29].

This paper presents a novel solution by integrating IFC standards with an IoT platform. This enables real-time interaction with BIM models through a web-based interface. The IoT is a transformative technology that enables the integration of various objects, such as electronic devices and sensors, into diverse applications [30]-[33]. By incorporating IoT sensor data, our platform facilitates real-time monitoring and control of critical building parameters, such as temperature, humidity, and occupancy across different levels of a building.

The primary contribution of this research is the development of a web-based platform that bridges the gap between IFC and IoT integration, enabling continuous, story-specific monitoring. Our approach directly addresses the limitations of static BIM models and enhances real-time decision-making capabilities for construction stakeholders. The following sections outline the technical implementation of this system and demonstrate its effectiveness in improving construction project management and performance.

2. METHOD

This research integrates 3D technology with IoT for the construction industry, following a structured, multi-stage approach designed to ensure a comprehensive analysis and implementation process, as illustrated in Figure 1. These stages include projecting geolocation data into the 3D environment, layering IFC models, visualizing IoT sensor data, and conducting performance tests to evaluate the system's reliability and effectiveness.

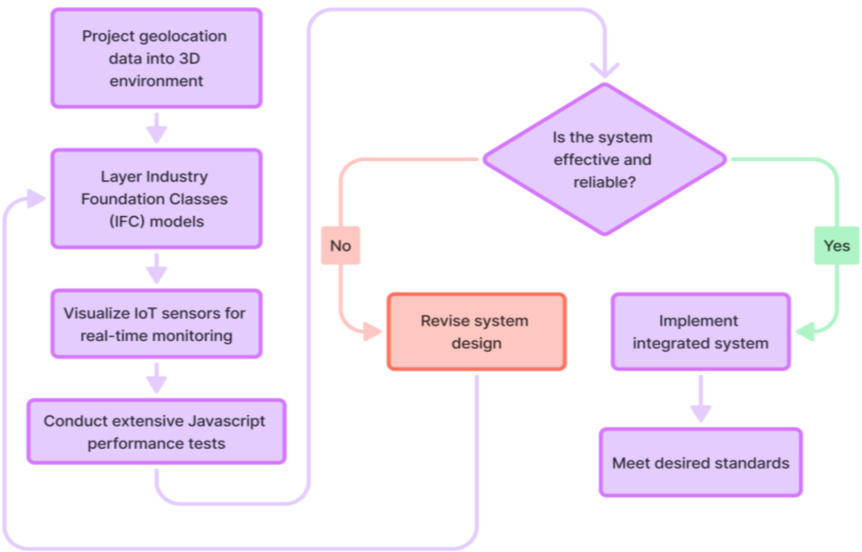


Figure 1. 3D web IoT design method flow

2.1. Building projection into a 3D environment

The initial step involves projecting geolocation data into a 3D environment to provide accurate spatial context for the construction site. The Haversine formula was used to calculate the distance between two points on Earth's surface, ensuring precise spatial projections [34]. This method is widely recognized for its accuracy in mapping geolocation data into 3D coordinates, which is crucial for aligning the construction site accurately in the virtual space. Additional parameters roll, pitch, and heading further refine the building orientation within the scene. The formula used for this projection is presented in (1).

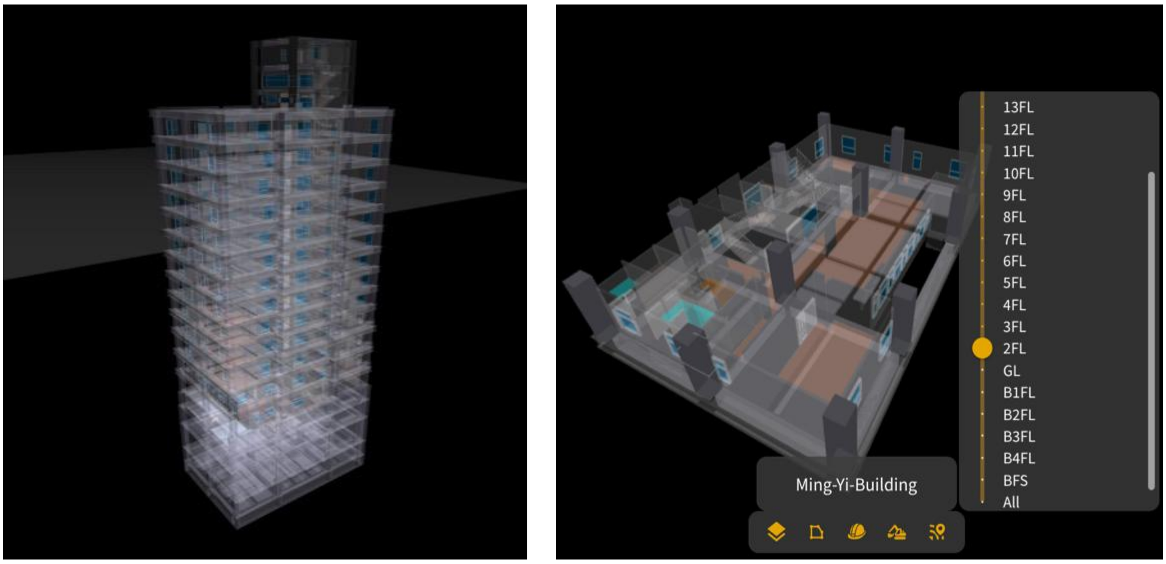
$$\begin{aligned} a &= \sin^2(\Delta\varphi/2) + \cos\varphi 1 \cdot \cos\varphi 2 \cdot \sin^2(\Delta\lambda/2) \\ c &= 2 \cdot atan2(\sqrt{a}, \sqrt{(1-a)}) \\ d &= R \cdot c \end{aligned} \tag{1}$$

The pseudo-code shown illustrates the process of calculating distances between geographical points (latitude and longitude) and converting them into 3D coordinates for spatial analysis:

```
const R = 6371e3; // meters
const φ1 = lat1 * Math.PI/180; // φ, λ in radians
const φ2 = lat2 * Math.PI/180;
const Δφ = (lat2-lat1) * Math.PI/180;
const Δλ = (lon2-lon1) * Math.PI/180;
const a = Math.sin(Δφ/2) * Math.sin(Δφ/2) +
 Math.cos(φ1) * Math.cos(φ2) *
 Math.sin(Δλ/2) * Math.sin(Δλ/2);
const c = 2 * Math.atan2(Math.sqrt(a), Math.sqrt(1-a));
const d = R * c; // in meters
```

2.2. 3D building layering using industry foundation classes

The second stage involves layering the IFC models within the 3D environment. IFC provides a standardized way to represent and exchange building information, enabling detailed and comprehensive representations of each component (e.g., floors, walls, and doors). Through the DasIoT platform, IFC models are visualized, allowing for detailed segmentation of building elements. This layered approach supports the integration of IoT applications, enabling real-time monitoring and analysis of each building storey [35]. As shown in Figure 2, this method allows us to extract and visualize different building layers, offering users the ability to focus on specific floors or segments. Figure 2(a) shows the entire multi-storey BIM project, while Figure 2(b) illustrates the layering achieved using IFC, enabling storey-specific visualization.



(a) (b)

Figure 2. Displaying 3D scene of; (a) all floor multi-storey BIM building and (b) after layering with IFC (source: screenshot of 3D scene of DasIoT platform)

2.3. Internet of thing sensor data visualization

Following the integration of the IFC models, the next step involves visualizing IoT sensor data within the 3D environment. This stage is essential for real-time monitoring of critical construction parameters such as temperature, humidity, structural integrity, and indoor positioning. IoT sensor data is mapped onto the corresponding building storeys, providing stakeholders with real-time insights into site conditions [35]. The dynamic nature of the system allows for continuous updates as new data streams in, offering enhanced decision-making capabilities and improved construction site management.

2.4. Performance testing

To assess the performance and scalability of the integrated 3D visualization and IoT platform, a case study was conducted across three active construction projects: two located in Taipei, Taiwan (project 1 and project 2), and one in Fukuoka, Japan (project 3). The selection of these projects was deliberate, as they provide representative examples of large-scale construction environments with significant numbers of workers and substantial data generation. This real-world complexity and high volume of IoT data capture make them suitable for evaluating the platform's practical application and performance under demanding conditions. Each project utilized buildings modeled using IFC, allowing for standardized data representation and analysis.

Performance metrics were collected using the stats.js library, an advance JavaScript-based tool chosen for its capability to deliver real-time performance insights. Key metrics evaluated include frame rates, memory usage, and processing times, allowing for a comprehensive performance analysis of the platform's visualization and data integration capabilities. The system was tested on several fronts:
- Rendering efficiency: the speed and accuracy with which the platform renders complex 3D building models.
- IoT integration: the effectiveness in visualizing and monitoring real-time sensor data across the platform.
- System scalability: the platform's capacity to manage multiple large-scale BIM models without experiencing significant performance deterioration.

The findings from these performance tests were analyzed to provide insights into the system’s scalability, reliability, and overall usability. This comprehensive evaluation underscores the platform’s capacity to handle real-world construction scenarios, offering valuable recommendations for future improvements and applications in the construction industry.

3. RESULTS AND DISCUSSION

In the results and discussion section, we conduct a comprehensive evaluation of the system's performance by examining key metrics, including response time when loading building models, the frames per second (FPS) during 3D rendering, and memory usage throughout the process. The assessment focuses on how efficiently the system handles these tasks under various operational conditions, such as different building sizes, levels of detail, and user interactions.

3.1. Response time

To understand the overall performance of the 3D website, we measure the response time or loading time of the 3D model. This measurement is crucial as it provides insights into the efficiency and speed of the website in displaying 3D content to users. Table 1 shows the response time for loading BIM. The data indicates that there is a direct correlation between the file size and load time.

Table 1. A duration comparison across buildings

Project	BIM No.	Size	Response time	Loading speed (kB/ms)
Project 1	1.	97.3 kB	572 ms	0.17
	2.	712 kB	387 ms	1.84
	3.	7.2 MB	1.40 s	5.14
	4.	20.5 MB	5.70 s	3.60
Project 2	1.	97.2 kB	273 ms	0.35
	2.	7.2 MB	629 ms	11.72
Project 3	1.	1.6 MB	534 ms	3.06
	2.	2.4 MB	917 ms	2.68

Previous research on 3D web visualization and IoT integration in BIM environments has largely focused on rendering and system performance [27], [36]. However, there is limited attention on real-time response and performance efficiency, particularly when handling large-scale BIM files. This study addresses this gap by examining the impact of varying file sizes on response times in a 3D visualization platform integrated with IoT. The findings show a clear correlation between file size and load time. For instance, smaller files like 97.3 kB and 712 kB were loaded in 572 ms and 387 ms, respectively. In contrast, larger files, such as 7.2 MB and 20.5 MB, required significantly longer, taking 1.40 seconds and 5.70 seconds to load (Table 1). Notably, project 2’s 7.2 MB file demonstrated a faster load time of 629 ms, likely due to improved server response and bandwidth during the testing phase. Figure 3 shows the performance metrics for three different projects during various phases of network communication, reflecting significant variations in size and response times.

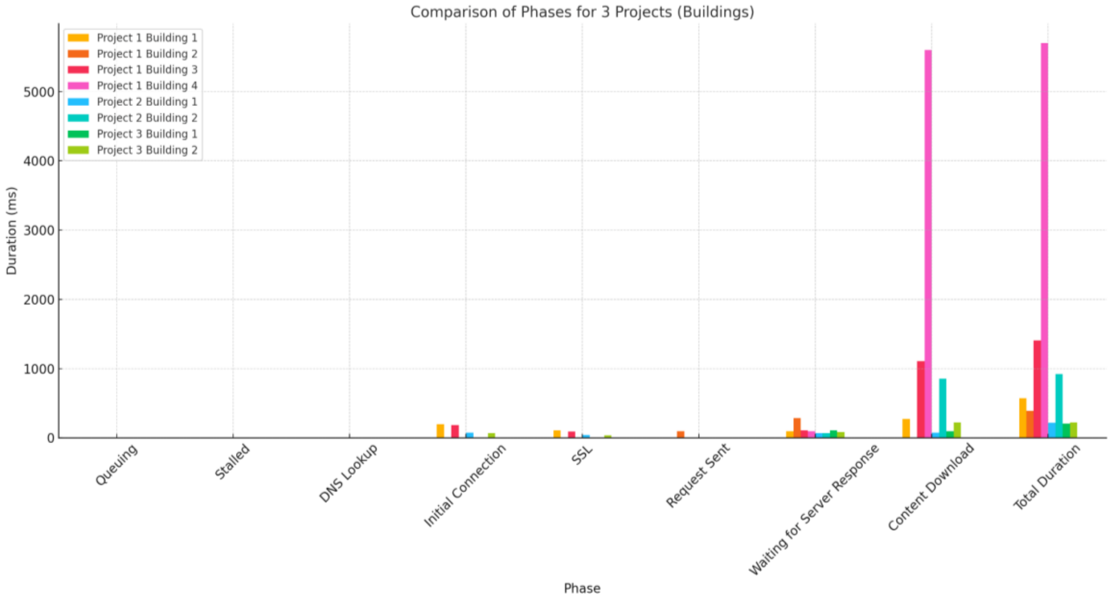


Figure 3. Graph of phase duration comparison across projects

There is a correlation between the file size and the total duration for loading. For instance, in project 1, building 1 (97.3 kB) took 572.62 ms to load, while building 4 (20.5 MB) took significantly longer at 5700 ms. Similarly, in project 2, building 1 (97.2 kB) loaded within 216.73 ms, whereas building 2 (7.2 MB) took 920.40 ms. This suggests that larger files, due to their increased complexity, require more time for data transmission and processing, impacting the user experience.

The content download time is the most substantial contributor to the total load time, especially for larger files. For example, building 4 in project 1 had a content download duration of 5600 ms, accounting for almost all the total duration. In contrast, smaller files like building 1 in project 3 (2.4 MB) had a much faster download time of 97.12 ms, underscoring the importance of optimizing file sizes and improving server performance.

Secure socket layer (SSL) connection times vary significantly, particularly in larger files where SSL overhead can delay the process. For example, in project 1, building 3 (7.2 MB) took 91.55 ms for SSL, while smaller files such as building 1 (97.3 kB) took 109.56 ms, showing that SSL times are not solely dependent on file size but also on network conditions. Similarly, domain name system (DNS) lookup times are minimal, but initial connection times and waiting for server response introduce additional delays, particularly with larger files. The fast loading speeds observed in smaller files will directly benefit construction admin or the managers by providing quick access to critical building data and real-time IoT sensor readings, allowing for faster on-site decision-making and reducing delays caused by data retrieval or model visualization. The integration of IoT and storey-specific monitoring allows stakeholders to pinpoint issues at particular building levels, adjust workflows based on real-time data, and ultimately improve the precision and execution of construction projects.

3.2. 3D statistical performance

In this section, we evaluated the performance of the 3D scene using advanced JavaScript performance monitoring tools to assess key metrics such as FPS, allocated memory, and rendering time per frame. These metrics provide insights into how well the system manages resources and renders complex 3D models efficiently in real-time. The performance under different loading conditions is summarized in Table 2.

Table 2. Performance monitor of before and after load

Project	Process	FPS	Allocated memory (MB)
Project 1	3D model loaded	55	314
	3D model not loaded	60	180
Project 2	3D model loaded	88	151
	3D model not loaded	89	171
Project 3	3D model loaded	86	151
	3D model not loaded	85	181

3.2.1. Frames per second

When the 3D models are not loaded, the system achieves 60 FPS in project 1, but this drops slightly to 55 FPS after the model is loaded. This slight drop is expected as the system consumes additional resources to fetch geometry data, textures, and set up shaders. Similarly, project 2 and project 3 show stable FPS values (88-89 FPS and 85-86 FPS), indicating efficient performance even after loading.

Our FPS findings align with previous studies in 3D visualization performance in web environments. For instance, previous study Wang *et al.* [4] showed that web-based 3D visualization platforms typically maintain FPS around 50-60 for moderate model complexity, although significant drops occur with larger models due to processing bottlenecks. Compared to their findings, our system shows minimal FPS degradation, indicating that it can handle even larger models with relative stability.

3.2.2. Allocated memory

In project 1, memory usage increases significantly from 180 MB (before the model is loaded) to 314 MB after the 3D scene is fully loaded. This is expected as the system needs to allocate more memory for handling complex 3D models. In project 2 and project 3, memory usage varies slightly, with project 2 consuming less memory overall (151 MB loaded vs. 171 MB not loaded), which might be due to optimizations in model complexity or texture sizes.

A comparison with prior study, Boje *et al.* [22] has argued that similar memory usage increases when rendering more complex BIM models, where memory consumption increases as the model complexity rises. However, in their study, systems experienced performance slowdowns due to memory management inefficiencies. In contrast, our research demonstrates efficient memory usage, even for complex models, preventing major slowdowns or crashes. Notably, even with increased memory usage, the system maintains stable performance with minimal degradation in FPS, ensuring a smooth user experience.

4. CONCLUSION

The integration of IFC enables detailed representation of building structures and supports real-time monitoring of multiple buildings within the platform. Our results demonstrate that the system manages a range of file sizes and varying model complexities with minimal disruption to user experience. While larger model sizes led to increased load times and memory consumption, the system maintained adequate performance levels, with frame rates decreasing slightly from 60 to 55 FPS and memory usage increasing from 180 MB to 314 MB. This indicates that the system is capable of processing complex 3D models without substantial performance deterioration. The adoption of IFC as an open standard fosters platform interoperability, facilitating advancements in the construction and facility management sectors. This improvement enhances user interaction and supports more informed, real-time decision-making in smart building environments. In conclusion, this study contributes significantly to advancing BIM visualization within an IoT framework and establishes a foundation for scalable adoption of these technologies in both academic research and practical applications in the construction industry and beyond. Future work could focus on optimizing BIM file sizes and developing advanced compression techniques to further improve load times and network performance.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Kannan Nataraj	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This research does not involve human participants, personal data, or any ethical concerns requiring formal approval. However, it complies with all relevant national and institutional guidelines for ethical research practices.

DATA AVAILABILITY

The data and source code utilized in this study were provided by Beeinventor Ltd. and have been approved for use by the company. Due to confidentiality agreements, these data are not publicly available but may be accessed upon reasonable request with permission from Beeinventor Ltd. Additionally, for the building projection into a 3D environment, the reference code used in this study is publicly accessible at https://www.movable-type.co.uk/scripts/latlong.html.

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