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Dual-Level Framework for OpenBIM-Enabled Design Collaboration

Ming Jin [1,2,*] and Baizhan Li [1]

1 Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China; baizhanli@cqu.edu.cn
2 China Southwest Architectural Design and Research Institute Corp. Ltd., Chengdu 610041, China
* Correspondence: jinmingcqu2018@163.com

Abstract: Design coordination and collaboration are crucial in the architecture, engineering, and construction (AEC) industries, necessitating the integration of diverse disciplines and expertise to achieve unified and functional designs. Traditionally, these disciplines operate in isolation, leading to a fragmented design process. Building Information Modeling (BIM), recognized for its collaborative capabilities, presents an opportunity to revolutionize traditional design practices. However, existing research on BIM primarily assumes an ideal environment where all major participants use BIM models, overlooking the dynamics of mixed 2D Computer-aided Design (CAD) and 3D BIM environments. Addressing this research gap, this study aims to establish a dual-level OpenBIM-enabled collaborative design framework, enhancing the design process across various disciplines. The study employs a case study approach, applying this framework to an airport project in Chengdu, China. The airport includes different corridors that are similar in scope and scale but distinct enough to allow for a comparative study. The results demonstrate a 27% faster completion rate, a 98% reduction in design errors, and improved user satisfaction with the proposed method. The paper concludes by discussing the limitations of the study and suggesting avenues for future research.

Keywords: BIM; collaboration; design

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1. Introduction

Design coordination is the art and science of harmonizing various design elements and professional inputs to achieve a unified architectural vision [1]. It entails managing the complexities of multiple disciplines—architectural, structural, mechanical, electrical, and plumbing, among others—ensuring that each component not only functions independently but also cohesively within the larger design framework. Effective coordination is crucial for avoiding design conflicts, optimizing resource allocation, and maintaining project timelines and budgets. Collaborative design, on the other hand, emphasizes the interactive and participatory aspects of the design process [2,3]. It involves stakeholders, including architects, engineers, clients, and sometimes end users, working together from the early stages of a project. This approach fosters a more holistic understanding of the project objectives, encourages innovation through diverse perspectives, and enhances the overall quality and functionality of the design.

Building Information Modeling (BIM) is a digital technology and process that has revolutionized the architecture, engineering, and construction industries. It serves as a collaborative platform where all geometric and non-geometric data are exchanged through three-dimensional models [4]. The use of BIM technology has proven effective and is able to help improve the efficiency and productivity in the project life cycle [2,4]. According to Wang and Chen [5], BIM has been widely integrated into management processes including information management, innovation and knowledge management, contract management, and project management. For project management, BIM capabilities are always discussed and mapped to a project life cycle, for instance, 3D modeling, where clash detection and design review are mapped to project design stage to improve project design management. The collaborative design process is an important factor for design productivity improvement, particularly using BIM technology [6]. However, despite its evident advantages, the integration and implementation of BIM in collaborative design still face significant challenges [7–9].

Research Gap 1: The Ideal vs. real-world BIM environment. A considerable amount of research has focused on BIM in an ideal project environment, where all key project participants are presumed to generate and utilize BIM models comprehensively. This assumption overlooks the complexities and variances encountered in actual project scenarios. In reality, many projects operate in a hybrid environment, incorporating both 2D Computer-aided Design (CAD) methodologies and BIM processes [10]. This gap in research leaves a critical question unanswered: which design coordination strategy is appropriate in a mixed 2D and BIM environment?

Research Gap 2: Data interoperability in BIM platforms. While a unified BIM-based platform promises to enhance the efficiency of data sharing, modification, and communication, achieving this level of integration in practice is fraught with challenges. The diversity of software tools used by different designers in a project creates a barrier to seamless data exchange and collaboration [11–13]. The development of a common BIM-based platform that can effectively bridge these diverse systems is a critical need. This platform must not only facilitate interoperability but also be user-friendly and adaptable to various designers' needs, ensuring that all designers can effectively manage and collaborate on projects.

Therefore, this research aims to develop a dual-level OpenBIM-enabled collaborative design framework for improving the project design and collaboration process across multiple disciplines. This dual-level framework encompasses both the single discipline level (i.e., individual design team level) and the multiple discipline level (i.e., project level). At the single discipline level, designers are equipped to work with both 2D CAD and 3D BIM tools, whereas at the multiple discipline level, all design outputs are consolidated into 3D BIM models. The framework leverages OpenBIM standards [14] as a foundational element to manage the entire lifecycle of BIM data, ranging from data requirements to data exchange and validation. The proposed framework was a result of continuing testing (trial and error approach) and fine-tuning based on the authors' personal experience in BIM and design process. Subsequently, a case study approach was adopted and the scope focuses on the design stage of the project. The savings in terms of duration and design performance were analyzed and highlighted based on the conducted comparative study.

2. Related Works

2.1. BIM-Based Design Coordination and Collaboration

BIM has fundamentally transformed the architecture, engineering, and construction industries, offering a groundbreaking collaborative design framework. Central to BIM is the facilitation of design coordination and collaboration, allowing diverse stakeholders to collaboratively work on a unified building information model.

2.1.1. The Essence of Clash Detection and Design Coordination

Clashes are identified through quality checks by designers before releasing models for downstream processes. The resolution of such clashes often involves collaborative efforts among designers, modelers, and constructors. The root causes of project clashes include design uncertainties, such as placeholders for unresolved components; breaches in design rules leading to spatial conflicts; model accuracy and tolerance issues; and outright design errors, like incorrect dimensions or locations [15–19].

Both clash avoidance and detection are widely recognized and practiced in the BIM projects, offering immediate advantages. This is supported by Wang et al. [20] who found that design coordination and clash detection are the most common BIM uses in construction. BIM integrates different disciplines—architecture, structural engineering, and mechanical, electrical, and plumbing (MEP) systems—thereby fostering a more efficient and error-free design process. This integration is critical in identifying and resolving design clashes early on, preventing costly errors during the construction phase.

Chen et al. [21] highlighted that early detection of clashes through design coordination can significantly reduce conflicts during the construction phase, which tend to be more costly. Riley and Horman [22] contended that progressing to the construction phase should only occur after achieving a consensus on the design, coordinated among all involved stakeholders. Eadie et al. [23] noted that clash detection is a widely used practice in construction, employing BIM. Wang and Leite [24] described effective clash detection as a repetitive procedure in which project conflicts are identified, categorized, assessed, and resolved. This process continues until a model is produced with either minimal or an acceptable level of clashes. However, Wang [4] observed that the current industry practice often involves developing discipline-specific models in isolation before any coordination or clash detection.

2.1.2. MEP Design Coordination: A Critical Focus

MEP design coordination is often viewed as a straightforward, yet essential application of BIM. This process, however, involves intricate and sophisticated coordination. The complexity of MEP design necessitates a delicate balance between spatial constraints and economic considerations [4]. As MEP designs become more complex, the need for advanced coordination strategies increases. The challenge is compounded by the fact that multiple trades with different interests must converge on a single coordinated design solution. This inter-organizational coordination is crucial for minimizing design errors and improving project performance [25].

Studies have shown that the outcome of a project using BIM can vary significantly based on the chosen coordination strategies [26]. A range of strategies has been suggested to minimize or avoid design problems [27]. These include the development of a component-dependent network in BIM projects for clash detection improvement [28] and the proposal of effective BIM coordination steps [29]. The sequence of coordination between MEP elements is another critical factor. Teams responsible for each MEP component must communicate effectively to ensure that their designs are compatible and do not interfere with each other.

In summary, while BIM has proven to be a valuable tool in design coordination and collaborative design, its effectiveness is heavily dependent on the chosen coordination strategies, the complexity of the design, and the ability of project participants to effectively utilize its features for communication and collaboration. In addition, most of the previous studies have presupposed a perfect BIM project setting where all key designers create and utilize 3D BIM models. However, they have overlooked the effects of varying coordination tactics within an environment that combines both 2D CAD and 3D BIM. This scenario is more typical in current projects and is likely to persist in the future as well [10].

2.2. Data Communication for BIM Collaborative Design

BIM data communication stands as a cornerstone, ensuring effective collaboration across various professional disciplines involved in a building project. The seamless exchange of information among architects, engineers, and construction managers is essential for the successful implementation of BIM.

The evolution of BIM models has garnered considerable attention from researchers. Studies by Fernando et al. [30] and Huang et al. [31] have made significant strides in exploring the design communication facets of BIM. These studies, while comprehensive, have not encapsulated all the necessary functions for full-scale collaborative design. On the other hand, the contributions of Chen and Hou [32] and Edwards et al. [33] in developing online collaborative platforms and file synchronization systems have markedly improved the capabilities of remote design teams working on complex, multi-disciplinary BIM models.

Interoperability, particularly through the Industry Foundation Classes (IFC) standard [34], has been a major research focus. This interoperability is vital for enabling collaborative efforts among diverse professionals, such as architects, structural engineers, and MEP engineers [35]. Initiatives like those proposed by Lee and Jeong [36] have aimed to support remote interactions and distributed collaborative design, underscoring the importance of semantic interoperability and the adoption of a flexible, process-based model.

Despite these advancements, challenges persist in the domain of data sharing and communication within BIM projects, especially during design changes. The BIM Collaboration Format (BCF) [37] developed by buildingSMART offers a potential solution, yet issues with data consistency remain a concern. To address these challenges, the development of a common BIM-based platform has been suggested by Lai et al. [7]. Such a platform would enhance the efficiency of data sharing, modification, and communication processes, leading to more effective project design management and collaboration. However, how to develop the common BIM-based platform between different software tools and stakeholders in practice is still challenging [7,38–40]. OpenBIM provides a potential solution to build an open and neutral environment for the exchange of information, allowing for better interoperability among the diverse software tools used in the industry [41,42]. By embracing OpenBIM standards, the industry can move towards a more collaborative and efficient way of working, overcoming the barriers of proprietary formats and fostering a more inclusive approach to project development [43–47].

3. Framework of the Dual-Level OpenBIM-Enabled Collaborative Design Platform

Building design is a multifaceted process that involves various disciplines, each with its own preferences and methodologies for creating and visualizing design elements. For instance, architects often favor 3D BIM for its comprehensive and detailed approach. BIM allows architects to create highly detailed and accurate three-dimensional representations of buildings, enabling them to visualize not just the aesthetic aspects but also the functional characteristics of a structure. This visualization is crucial in understanding how different components of a building interact and integrate with each other. On the other hand, disciplines like plumbing often opt for 2D CAD due to its efficiency and straightforward nature. 2D CAD provides a clear and concise view of plumbing layouts, making it easier to plan and implement complex piping systems. This preference is rooted in the practicalities of plumbing design, where the focus is more on the accuracy of spatial relationships and connections rather than on the three-dimensional interplay of spaces.

The proposition of a dual-level design collaboration framework (as shown in Figure 1) in building design addresses the diverse needs and preferences of different disciplines while ensuring effective coordination and integration of the overall project. At the first level, within each individual discipline, designers have the flexibility to choose between 2D CAD, 3D BIM, or a mixed approach, depending on what best suits their specific design requirements and workflows. This level of autonomy allows each discipline to work in the format they find most efficient and comfortable, whether it is the detailed modeling of BIM or the straightforward layouts of 2D CAD. However, at the second level, which involves cross-discipline collaboration, there is a transition towards a unified format. If a discipline initially used 2D CAD, their outputs are converted into 3D BIM models for coordination and clash detection purposes. This conversion is crucial for visualizing how different aspects of the project interact in a three-dimensional space, ensuring that any potential conflicts are identified and resolved early in the design process. Conversely, if the collaborating discipline still relies predominantly on 2D CAD, the outputs can be converted to this format for ease of reference and integration. This two-tiered approach ensures that while individual disciplines can work in their preferred formats, the final collaborative process is streamlined, efficient, and conducive to producing a cohesive and conflict-free design. Additionally, this platform provides robust standards that govern the exchange of design data, ensuring interoperability and minimizing data loss or misinterpretations. Beyond mere design collaboration, the platform also boasts an array of functions tailored for advanced design analysis, empowering stakeholders to make informed and optimized decisions throughout the project lifecycle.

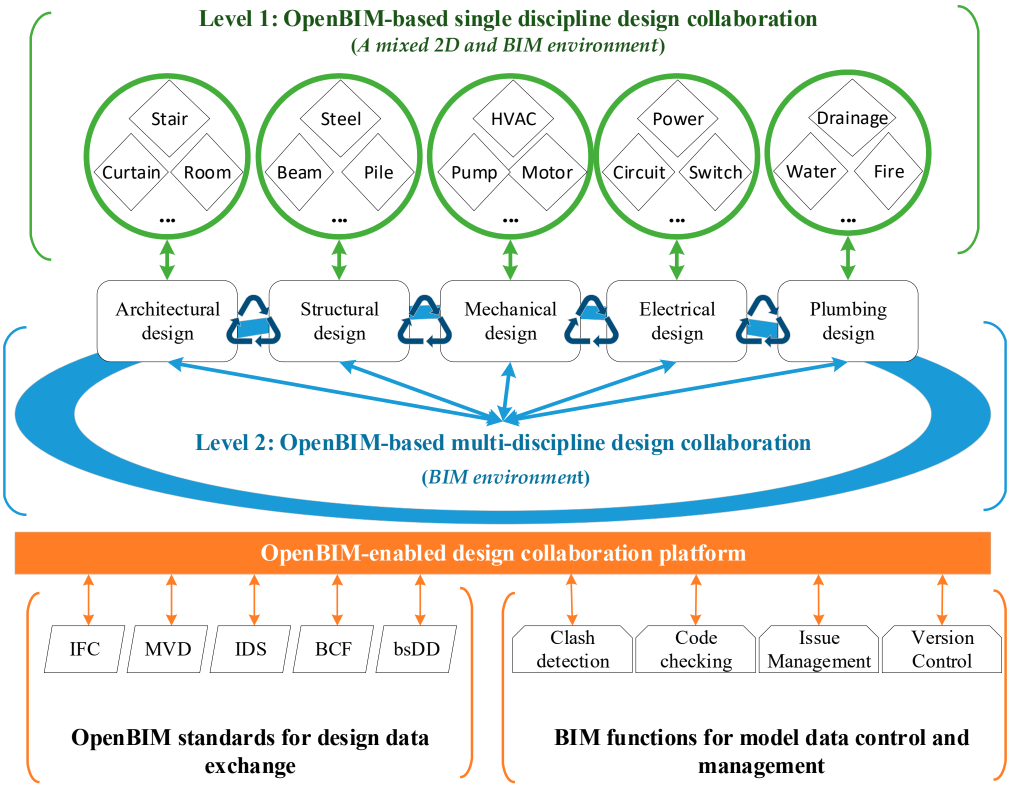

Figure 1. Framework of the dual-level OpenBIM-enabled collaborative design platform.

3.1. OpenBIM-Based Single Discipline Design Collaboration (A Mixed 2D and BIM Environment)

Single discipline design collaboration, when executed within the OpenBIM framework, signifies a laser-focused integration tailored to specific domain data models. For instance, if the stakeholders are primarily from the architectural realm or the structural engineering field, the platform accommodates and centralizes their domain-centric data models. This focus allows for an in-depth exploration of design intricacies, often leading to a more granular level of detailing and accuracy. In this approach, professionals within the same discipline collaborate closely using either BIM or CAD tools, depending on the the team's expertise. When utilizing BIM, the collaboration focuses on creating detailed 3D models. When employing CAD, particularly 2D CAD, the collaboration revolves around creating precise drawings and layouts. Regardless of the tool used, single discipline design collaboration aims to harness the collective expertise of the team to create designs that are not only technically sound but also innovative and efficient. One of the standout benefits of this approach is the significant diminution of data loss and discrepancies. This ensures not just a smoother design trajectory but also fosters an environment where professionals within that chosen discipline can harmoniously align their efforts. Real-time updates become a staple in this setup, ensuring that every member has access to the latest shared resources and design modifications. This not only elevates the quality of the design but also cuts down iterative redundancies.

3.2. OpenBIM-Based Multi-Discipline Design Collaboration (3D BIM Environment)

Diverging from the singular focus of the previous approach, multi-discipline design collaboration in an OpenBIM setting epitomizes the amalgamation of diverse domain-centric models. It is not just about juxtaposing these models but intricately weaving them to produce an integrated, cohesive design tapestry. This method fosters a dynamic interaction matrix that encompasses a spectrum of disciplines—from architects sketching out the spatial narratives, mechanical engineers optimizing Heating, Ventilation, and Air Conditioning (HVAC) systems, electrical engineers illuminating spaces, to structural engineers fortifying the built form. This collaborative ethos ensures that these diverse models harmonize in their objectives and design language. One of the pivotal benefits here is the substantial reduction in design clashes, often a challenge in large, complex projects. By facilitating a platform for interdisciplinary feedback, professionals can anticipate potential design challenges and recalibrate in advance. This not only optimizes design efficiency but champions a holistic, inclusive design methodology where every discipline contributes to and shapes the final built form.

3.3. OpenBIM Standards for Design Data Exchange

The seamless integration and exchange of design data are crucial for any successful BIM project. Multiple standardized tools and protocols are established to enhance the interoperability of data among different software platforms. To elucidate the significance of these standards, Figure 2 shows a typical data exchange scenario through OpenBIM standards.

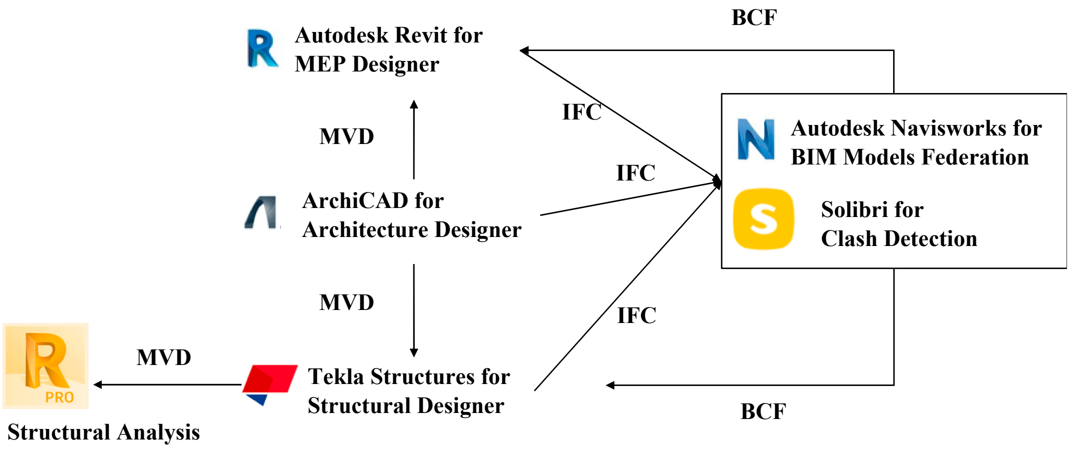

Figure 2. OpenBIM standards for design data exchange.

In a complex project scenario, a multi-disciplinary team collaborates using specialized tools for specific tasks. The architectural division, utilizing ArchiCAD 26, has formulated a design intended for dissemination to the structural department operating Tekla Structures 2022, and the MEP group employing Revit 2022. To synergize these contributions into a coherent whole, Navisworks 2022 is employed to establish a federated BIM for design coordination. Further refinement is achieved using Solibri 9.12 for rigorous design code validation, while the structural integrity is assessed through Autodesk Robot Structural Analysis software 2022.

1. IFC: Initially, the architectural team exports their design into an IFC file, a neutral and open file format. IFC ensures that irrespective of the originating software, the design's information and geometric attributes are preserved, making it accessible for other platforms.
2. Model View Definition (MVD): Before sharing the file, they extract specific views of the data set using MVD. MVD allows for defining specific subsets of the information contained in the IFC model, ensuring that the structural team and MEP team receives only pertinent information, making the data exchange more efficient and reducing the potential for information overload.
3. BCF: After federating multi-discipline IFC models and running clash detection and code checking, the design coordination team has certain queries and suggestions. Instead of communicating these through lengthy emails or reports, they use BCF to pinpoint specific issues directly on the model. BCF encapsulates these issues within the context of the model views, enabling precise and context-aware communication.
4. Information Delivery Specification (IDS): Given the iterative nature of design, if one team requires specific information from other teams for their further design, they

utilize IDS to formally define and request this exact set of data. IDS streamlines the process of information requisition, ensuring clarity and precision in communication.
5. Building Smart Data Dictionary (bsDD): During the entire collaborative process, there might be terms or specifications that vary across disciplines or regional standards. bsDD acts as a universal dictionary, ensuring that all stakeholders have a common understanding of terms, units, and definitions, fostering clearer communication.

In essence, this scenario highlights the interplay of various standards in ensuring smooth, efficient, and precise data exchange in a BIM environment. By leveraging IFC, MVD, BCF, IDS, and bsDD, stakeholders can overcome software limitations, improve collaboration, and enhance the overall design process across multiple disciplines, diverse project types and geographical regions.

3.4. BIM Functions for Model Data Control and Management

The OpenBIM-enabled collaborative design platform integrates a plethora of functions that are pivotal in streamlining design processes and facilitating effective communication across various disciplines. These functions empower stakeholders to address challenges in real time, maintain documentation coherency, and adhere to industry standards. Some fundamental functions inherent in the platform are explained below.

1. Clash detection: One of the most vital tools in a multi-disciplinary design project, clash detection identifies and pinpoints intersections or 'clashes' between different elements from various domains. For instance, an HVAC duct running through a structural beam can be promptly identified. Such proactive detection ensures that potential design conflicts are addressed in the design phase itself, saving substantial time and resources during construction.
2. Code checking: This function automatically verifies if the design adheres to local building codes and standards. Leveraging a database of rules and guidelines, the BIM platform can automatically scrutinize a design for code compliance, highlighting areas that may breach stipulated norms. This not only ensures adherence to regulations but also expedites the approval processes.
3. Issue management: In the dynamic environment of design collaboration, issues, discrepancies, or suggestions may arise. The issue management function allows team members to log, categorize, assign, and prioritize these issues directly within the BIM environment. Coupled with tools like BCF, this ensures that feedback is contextually relevant and can be addressed efficiently.
4. Version control: With numerous stakeholders contributing to a design, maintaining the coherency and integrity of documentation becomes pivotal. The version control function ensures that every change made to the model is logged, timestamped, and attributed to a user. This provides a chronological record of all alterations, enabling teams to revert to previous versions if needed, thereby preventing data loss and ensuring the integrity of the design evolution.

4. System Architecture and Prototype

In order to implement the proposed framework explained in Section 3, this section presents a comprehensive exploration of the system's architecture and the prototype of the OpenBIM-enabled design collaboration platform. Figure 3 shows the three-tiered structure of the system.

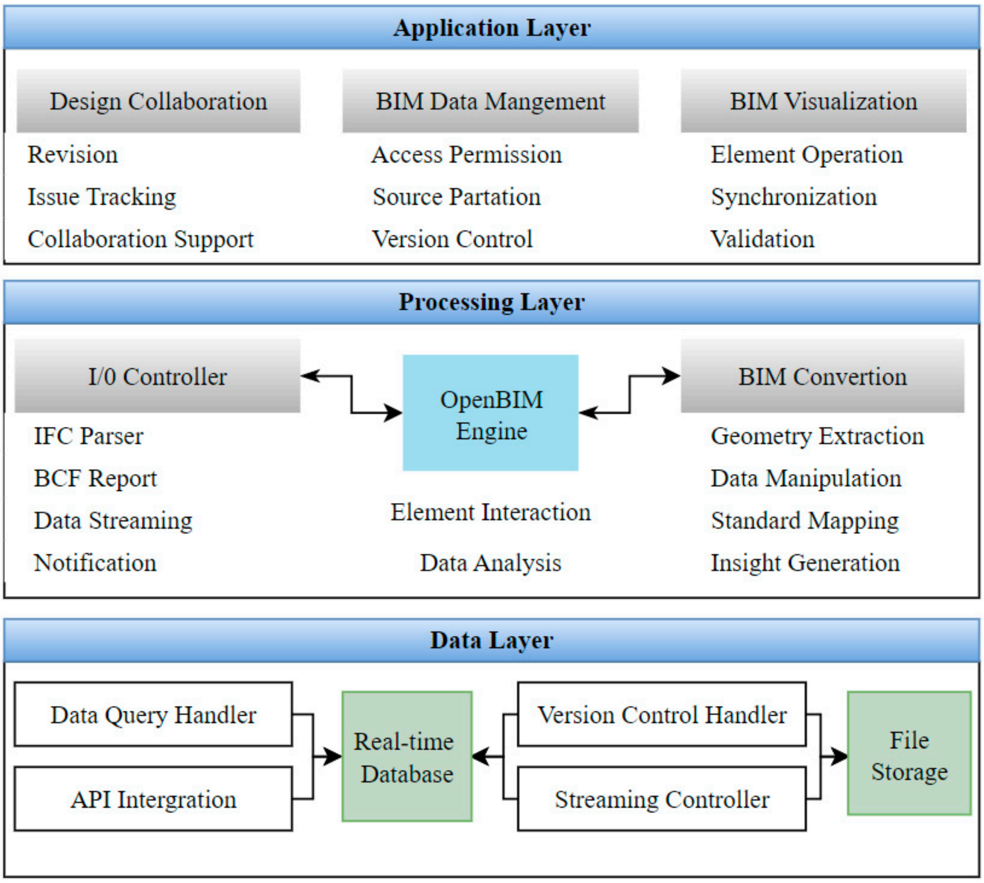

Figure 3. System architecture.

This platform is fundamentally anchored in the OpenBIM standards. When combined with a strong emphasis on user experience, it stands on the verge of reshaping the way project stakeholders unite and work collectively. The specifics of each layer are elaborated upon as follows:

1. Data layer: Sitting at the very heart of the platform, the data layer stands as the guardian and manager of all project-centric data. It integrates a state-of-the-art real-time database, promising simultaneous data storage and on-the-spot retrieval, ensuring users always have the latest information at their fingertips. Alongside, the version control handler operates with precision, ensuring all project iterations are systematically managed. Another feather in its cap is an advanced file storage mechanism, pledging both robust data security and unhampered accessibility. In a bid to fine-tune data transactions, an integrated data query handler is meshed with a seamless API system, which, in tandem, ensures data interactions are both flexible and efficient.
2. Processing layer: Acting as a pivotal conduit between untouched data and end-user interaction, the processing layer plays a quintessential role in data metamorphosis and facilitation. A savvy I/O controller stands at its helm, directing all system-related input and output functionalities. Adding to its prowess is the IFC parser, which ingeniously transforms standardized IFC BIM files, rendering them suitable for the platform's processing demands. Adding depth to its operations is the OpenBIM engine. Paired with high-grade BIM conversion tools and adept geometry extraction features, it guarantees an unparalleled precision in design data processing.
3. Application layer: Serving as the platform's front end, the application layer is the gateway for users, providing a suite of tools tailor made for design collaboration, issue pinpointing, and vivid BIM data representation. It employs fortified data management protocols, ensuring the data remains uncorrupted and genuine. Moreover, it houses

revision controls, which act as beacons, guiding users through the labyrinth of design changes. In the spirit of fostering a cooperative environment, access permissions are meticulously assigned, striking the right balance between data protection and honoring project confidentiality.

Figure 4 shows the system prototype interface, which has been crafted based on in-depth research and extensive feedback from industry professionals. The interface is characterized by a clean layout, with menus and toolbars strategically positioned for ease of access. The user dashboard prominently showcases real-time project updates, ensuring that stakeholders are always in the loop with the latest developments. Advanced filtering options have been incorporated, enabling users to sift through vast amounts of data swiftly and hone in on specific details without hassle.

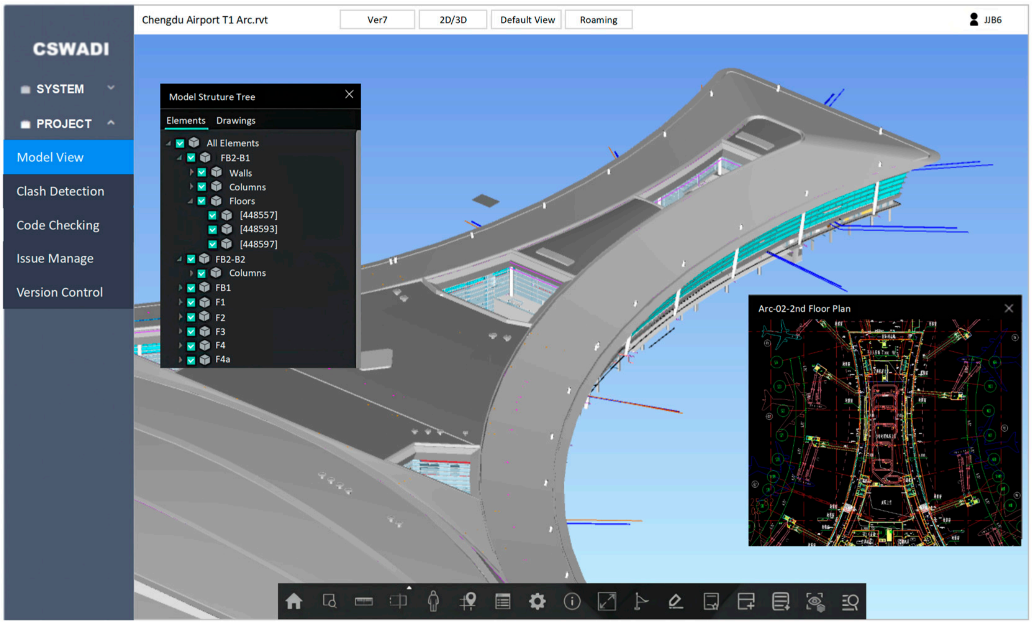

Figure 4. System prototype.

Beyond the visual aesthetics, the interface is also enriched with a series of interactive features. These include drag-and-drop functionalities for file uploads, a collaborative whiteboard for brainstorming sessions, and a dynamic 3D BIM viewer that allows users to manipulate and inspect design models in real time. To further simplify collaboration, integrated chat and comment systems have been introduced, allowing team members to communicate, share insights, and provide feedback within the platform itself.

Moreover, the prototype places a significant emphasis on customization. Recognizing that each project and stakeholder may have unique needs, the interface offers modular components. This means that users can tailor their workspace by adding, removing, or rearranging tools and functionalities according to their preferences and project requirements. As the platform moves from prototype to full-fledged application, continuous user feedback and iterative improvements will remain pivotal, ensuring that the OpenBIM-enabled design collaboration platform stays ahead of the curve and meets the ever-evolving needs of the industry.

5. Case Study

In an endeavor to quantify the tangible benefits of the OpenBIM-enabled collaborative design platform, a comparative case study was undertaken based on the Chengdu Tianfu International Airport project. This study aims to discern the contrasts between traditional and OpenBIM collaborative methods in terms of time efficiency, design quality, and user experience. The selection of this case project is underpinned by three reasons: (1) Opportunity for comparative analysis: The airport project includes different corridors (like the Terminal 1-B and 2-B corridors as shown in Figure 5) that are similar in scope and scale but distinct enough to allow for a comparative study. This similarity and distinction between the corridors provides a unique opportunity to directly compare the outcomes of different design methodologies within the same project context. (2) Complexity and scale: The Airport project, with its vast scope and complex design requirements, presents an ideal scenario for testing the effectiveness of the proposed method. The project encompasses various architectural and engineering challenges typical of large-scale infrastructure developments, making it a suitable case for a thorough and rigorous analysis of both traditional 2D CAD and advanced BIM methodologies. (3) Data availability and accessibility: The choice of the Airport project is further justified by the unique position of the paper's authors, who were directly involved in the project. This involvement granted them exclusive access to a wide range of project data, including detailed design documents, communication logs, and implementation records. Such direct access is crucial for conducting an in-depth and accurate analysis, as it ensures the availability of comprehensive and first-hand data, enhancing the validity and reliability of the research findings. This level of data access is rare in large-scale projects and provides a unique opportunity to closely examine and compare different design methodologies in a real-world setting.

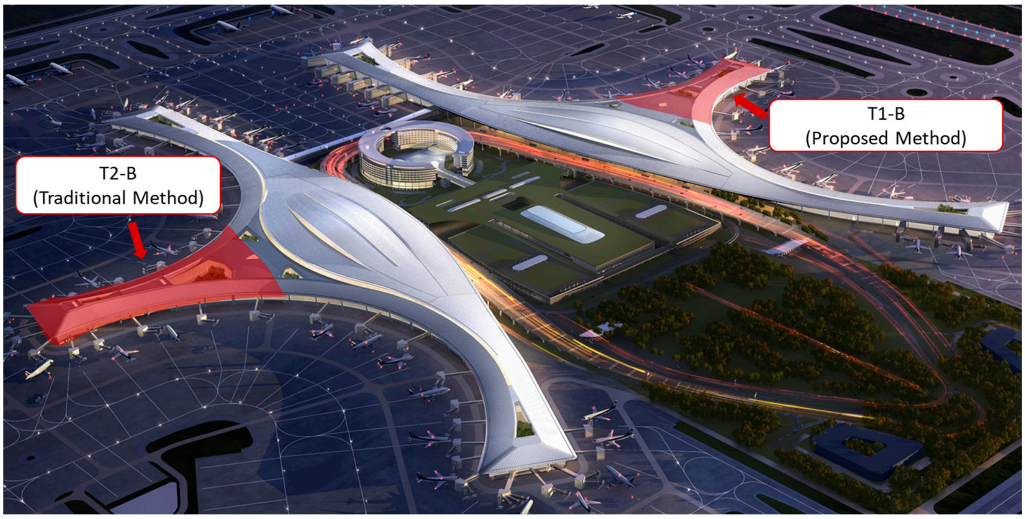

Figure 5. Terminal 1-B and 2-B corridors of the Chengdu Tianfu International Airport project.

5.1. Case Overview

In this study, a segment of the Chengdu Tianfu International Airport project, specifically the Terminal 1-B corridor located in Chengdu, China, was chosen as the pilot area. For comparative purposes, the Terminal 2-B corridor, which has a similar scope and scale, was also chosen (as shown in Figure 5). The Terminal 1-B corridor spans a construction space of 70,000 square meters, comprising one underground level and four above-ground levels. These areas host a range of functionalities, including a baggage room, international arrival and departure levels, as well as a domestic mixed departure and arrival level. This targeted selection ensured that the inherent complexities of larger undertakings did not eclipse the focal design methodologies under evaluation.

The primary objective of this study is three-fold:

1. Time efficiency: Measure the time taken by both teams from project initiation to completion. The assumption being that the collaborative nature of BIM would lead to faster decision making, reduced rework, and a more streamlined design process.
2. Design quality: Post-design, an independent review was conducted to identify any clashes or discrepancies in the designs submitted by the two teams. This assessment aimed to gauge the precision and accuracy of the design outputs, hypothesizing that

the BIM platform's in-built clash detection capabilities would lead to fewer errors as compared to the conventional 2D CAD method.

3. User experience: Both teams were surveyed post-project to evaluate their experience using the respective design methods. This subjective assessment aimed to understand the ease of use, perceived efficiency, and overall satisfaction of the designers with the tools at their disposal.

5.2. Comparative Method

5.2.1. Team Selection

Two distinct teams, each with comparable experience and expertise, were recruited for the study. Team A, responsible for the design of the T2-B corridor, employed traditional 2D CAD methods for both individual discipline design and cross-discipline coordination. This approach reflects long-standing practices that have been prevalent in the industry for decades. On the other hand, Team B, tasked with the design of the T1-B corridor, utilized the innovative OpenBIM-enabled collaborative design platform, embodying the latest advancements in design collaboration technology.

In Team B's workflow, BIM was the primary tool for designing architectural and structural models at the single discipline level. Meanwhile, 2D CAD was utilized for designing other disciplines. For cross-discipline design collaboration, BIM played a pivotal role in streamlining the coordination process. Whenever a discipline initially used 2D CAD for their design, those drawings were converted into BIM models to facilitate more integrated coordination. Additionally, 2D CAD drawings were also extracted from the architectural and structural BIM models to serve as references for other disciplines during their individual design phases. This hybrid approach leveraged the strengths of both BIM and CAD, ensuring a comprehensive and cohesive design process.

Team A and Team B from the same design group company, but operating in distinct studios, present a well-matched pair for the study. Their equivalent composition (as shown in Table 1) in terms of design skills, experience, and team structure offers a unique opportunity to conduct a comparative analysis with high reliability and relevance. Their similar yet diverse backgrounds provide a solid foundation for evaluating and understanding the effectiveness of different design methodologies in a controlled and comparative environment.

Table 1. Profiles of Team A and Team B.

	Team A	**Team B**
Team Size	15 key professionals	15 key professionals
Experience	10 years (average per member)	9 years (average per member)
Specializations	4 architects (commercial, residential), 3 structural engineers (high-rise, complex structures), 3 MEP engineers (sustainable, energy-efficient designs), 2 interior designers (ergonomic, aesthetic spaces), 3 design managers (coordination, client relations)	5 architects (commercial, residential), 2 structural engineers (complex structures), 4 MEP engineers (HVAC, electrical systems), 2 interior designers (commercial, green space design), 2 design managers (coordination, timeline adherence)
Notable Projects	Over 30 major projects (including 3 airports, 10 high-rise buildings)	25 major projects (including 4 airports, 3 large-scale shopping centers)

5.2.2. Data Collection and Analysis

A structured approach to data collection and analysis was conducted. The data collection phase focused on gathering extensive records of each team's design process, including documentation of design drafts, revision histories, and final outputs. This provided a comprehensive view into the evolution of the design, the decision-making processes, and the efficiency of each methodology. Additionally, the amount of time spent by each team on various stages of the design process, such as initial designs, revisions, coordination meetings, and finalizing designs, was monitored and recorded to assess productivity and efficiency.

The quality assessment of the designs produced by each team was a critical component of the data collection. This evaluation included factors like accuracy, adherence to project specifications, innovation, and the level of detail in the designs. Feedback from team members was also gathered, offering insights into their experiences with the tools (traditional method or proposed method), including their perceptions of efficiency, ease of use, collaboration, and any challenges faced.

In the analysis phase, the collected data were compared to identify differences and similarities in the design processes of both teams. This comparative analysis involved looking at the time spent on various tasks, the nature and number of design revisions and clashes, and overall project timelines. The quality of the designs from both teams was evaluated against established criteria, involving expert reviews and specific quality metrics like compliance with design standards, functionality, and aesthetic appeal.

5.3. Results and Discussions

5.3.1. Time Efficiency

The overall duration taken by Team A, utilizing the 2D CAD approach, spanned 240 h. This prolonged period is reflective of the traditional challenges posed by the 2D CAD design process. The initial stages of conceptualization and drafting consumed a sizable 70 h, largely due to the manual nature of the 2D CAD system. As the design progressed to the detailed stages, further complications arose, resulting in an additional 170 h. One significant factor contributing to this extended duration was the iterative nature of their work; the team frequently found themselves revisiting earlier stages to accommodate fresh feedback or to rectify overlooked issues. In total, they reverted to prior design stages 12 times, with each iteration adding roughly 6 h to their workload. Additionally, the team grappled with delays stemming from the need to continuously cross-check, coordinate, and verify design elements among team members. This alone amounted to approximately 40 h, emblematic of the segmented and siloed workflow intrinsic to their chosen method.

Contrastingly, Team B's experience with the BIM-based collaborative design platform was markedly different. They completed their design in a condensed timeframe of 175 h. Their early stages of conceptualization took up 60 h, slightly shorter than Team A's. However, the subsequent stages, where detailed design elements were integrated, alterations made, and final touches added, were streamlined into 115 h. The significant time reduction can be largely attributed to the platform's real-time collaboration capabilities. Instead of laborious manual iterations, the team received and acted upon immediate feedback. They underwent only five minor iterations throughout the process, with each adding an average of just 2 h. Moreover, the BIM platform's capability to support multiple team members working concurrently on varied design aspects meant that processes that traditionally followed a sequence could now be executed in parallel, leading to further efficiencies.

In summarizing the findings on time efficiency, it becomes abundantly clear that the methodological choice in design can have profound implications on the duration and seamlessness of a project. The BIM-based collaborative design platform, with its synchronized and integrated approach, demonstrates a marked advantage over traditional 2D CAD methods in this domain.

5.3.2. Design Quality

Quality, as a measure in the design realm, is multifaceted, encompassing the accuracy, comprehensiveness, and the practicality of the design. For Team A, employing the traditional 2D CAD system, the post-design review by an independent panel brought to light several discrepancies. Upon evaluating the design, we identified a sum of 427 design errors, illustrating a diverse array of issues. These ranged from minor inconsistencies, such as overlapping ductwork, to pressing conflicts, like significant structural incompatibilities with utility systems.

When classified into distinct categories (as shown in Table 2), there are 25 category A issues, 134 category B issues, 111 category C issues, and 157 category D issues (as shown in Figure 6). A closer examination of these figures suggests that the majority of the issues lies in categories B and D, pointing towards challenges in the spatial planning for MEP systems and inconsistencies in coordinated designs. Such a trend indicates a need for enhanced communication and better-integrated planning between the architectural, structural, and MEP design teams. Addressing these issues early can potentially reduce the iterative design modifications later, saving both time and resources.

Table 2. Design error classification.

Design Issues	Description
Category A	Violations of clear height requirements
Category B	Limited space obstructing MEP system installation
Category C	Interferences among the architectural, structural, and MEP layouts
Category D	Design mismatches across architecture, structure, and MEP systems

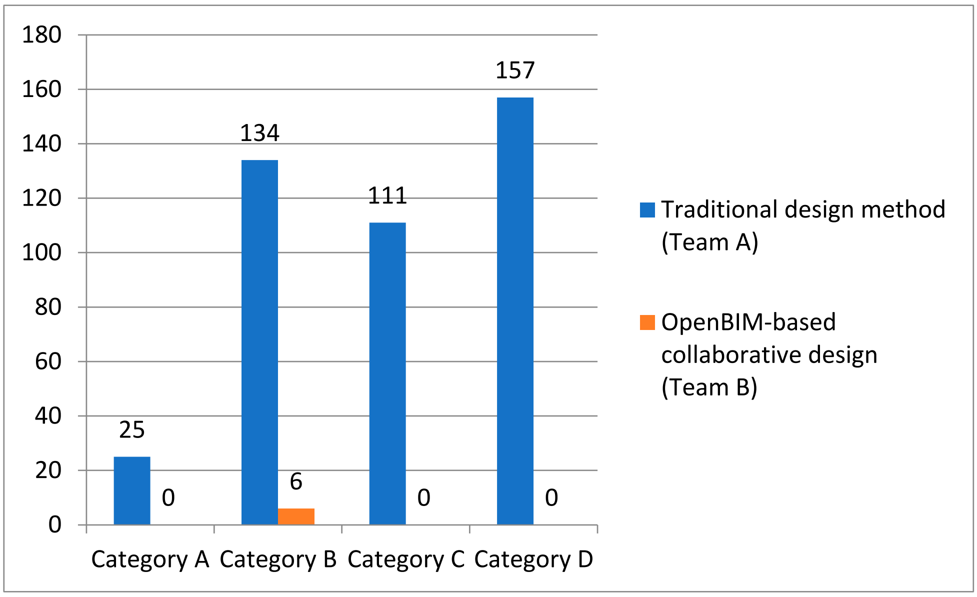

Figure 6. The number of different types of design issues in two design ways.

These findings underscored the challenges inherent in the 2D CAD process. The lack of real-time integration between different design elements meant that inconsistencies often went unnoticed until the later stages, necessitating backtracking and revisions. Such iterative fixes, while sometimes seen as part and parcel of the design process, underscore a certain lack of fluidity and cohesion in the design's final rendition.

Conversely, Team B's output (as shown in Figure 7), crafted on the OpenBIM-enabled collaborative design platform, demonstrated a marked improvement in design quality. Only six clashes were identified by the review panel, and they are all Category B clashes. The platform's inherent clash detection feature proved invaluable in this regard. As team members worked, potential issues were flagged almost instantaneously, allowing for on-the-spot corrections. This preemptive approach significantly reduced the chances of oversight and ensured a tighter, more harmonized design. Additionally, having all design elements integrated within a singular platform ensured that changes made in one section were seamlessly reflected across all related segments, resulting in a consistent and unified design output.

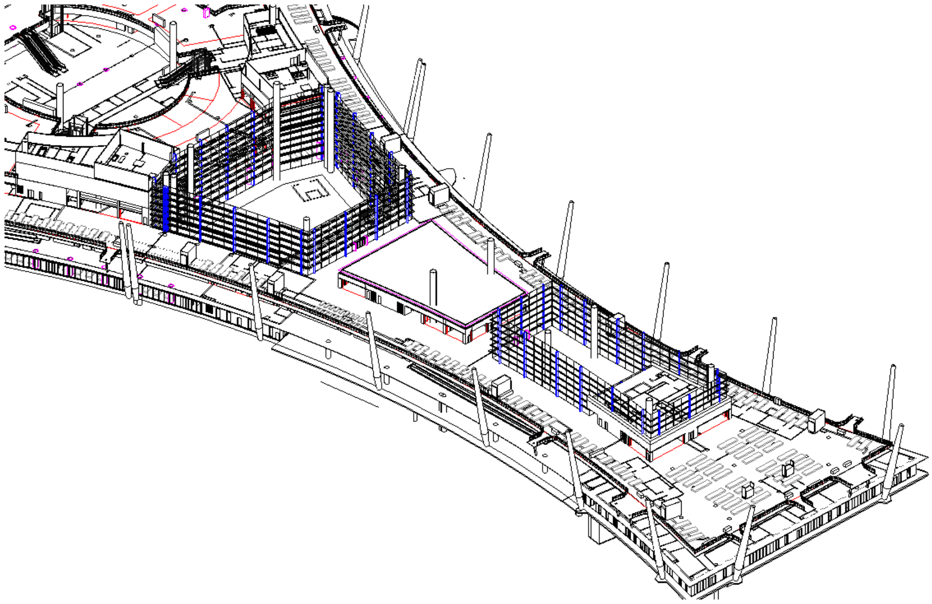

Figure 7. BIM models designed by Team B.

Drawing from the comparative results on design quality, it is evident that the technological underpinnings of the design tool play a pivotal role in determining the accuracy and coherence of the final output. The OpenBIM-enabled collaborative design platform's ability to detect and address discrepancies in real time offers a profound advantage in ensuring superior design quality, marking a considerable leap from the challenges presented by traditional 2D CAD methods.

5.3.3. User Experience

The design process, while primarily being about tangible outcomes, is also deeply influenced by the designers' subjective experiences, which can shape the quality and efficiency of work. When gauging the experiences of Team A, who employed the 2D CAD system, a mixed picture emerged. The familiarity and comfort with the tools they had been using for years were evident in their work. However, this was juxtaposed with palpable frustrations. The segmented workflow inherent to the 2D CAD approach meant they often felt disconnected from other team members. They articulated a recurring need to consistently cross-check and align with colleagues, resulting in a perception of interrupted flow. Such frequent breaks in concentration can inadvertently lead to oversights, reducing confidence in the final design. Quantitatively, when asked to rate their user experience on a scale from 1 to 10, the average score given by Team A was 6.2, reflecting these nuanced challenges.

On the other side of the spectrum was Team B, who had the opportunity to use the OpenBIM-enabled collaborative design platform. Their feedback painted a distinctly positive picture. The team unanimously appreciated the platform's real-time collaborative features, which they felt not only saved time but also ensured better integration of design elements. The interactive nature of the platform meant immediate feedback could be incorporated, fostering a more iterative and dynamic design approach. There was, however, a mention of an initial learning curve associated with familiarizing themselves with the new tools. But as the project progressed, the initial hesitancy gave way to confidence and appreciation for the platform's capabilities. Reflecting this sentiment, Team B's average user experience score stood at a commendable 8.7.

In essence, the user experience is a critical facet of the design process, influencing both efficiency and end results. From the feedback of both teams, it is evident that the integrated and real-time nature of the OpenBIM-enabled collaborative design platform offers a superior, more streamlined experience compared to traditional 2D CAD methods, indicating a promising direction for the future of design collaboration.

5.4. Limitations

The comparative study, while providing valuable insights, also had several limitations that should be acknowledged:

(1) Sample size and scope: The study was limited to two design teams working on specific segments of the Airport project. This relatively small sample size and the specificity of the project scope may not fully represent the diverse range of projects and teams in the architecture, engineering, and construction industry. Therefore, the findings might not be entirely generalizable to all types of projects or teams.
(2) Experience with tools: Both teams had varying degrees of familiarity with their respective tools. Team B's proficiency with the BIM and Team A's experience with traditional 2D CAD could have influenced the outcomes. The learning curve associated with the OpenBIM-based design data exchange could affect time efficiency and user experience, which might not have been fully captured in the study.
(3) Technological advancements: The study was conducted at a specific point in time, and technology in the field of design and construction is rapidly evolving. The capabilities and limitations of the software used in the study might change, affecting the relevance of the findings over time.
(4) Cost analysis: The study focused primarily on time efficiency, design quality, and user experience, without a detailed analysis of the cost implications of using OpenBIM versus traditional 2D CAD. Cost is a crucial factor in project design management and could provide a more comprehensive understanding of the practicality of adopting new technologies.
(5) Validation of the OpenBIM-based design data exchange workflow: The study did not validate the workflow for design data exchange using the OpenBIM platform. In a collaborative design environment, the efficiency and effectiveness of the data exchange between various stakeholders are crucial. While OpenBIM promises improved interoperability and data-sharing capabilities, the study did not empirically test these aspects in a real-world scenario. This gap means that the potential benefits or challenges of OpenBIM's data exchange workflow remain unexplored in this study. Future research could focus on this area, evaluating how well OpenBIM facilitates the transfer and integration of design data across different software platforms and among various project stakeholders. Such research would provide a more comprehensive understanding of the platform's capabilities and limitations in a collaborative design setting.

6. Conclusions

This research paper presents the development of a dual-level OpenBIM-enabled collaborative design framework, which has significantly enhanced design efficiency in a mixed environment utilizing both 2D CAD and 3D BIM. The core originality of this research lies in the development of a novel framework that seamlessly integrates 2D CAD and 3D BIM design technologies. While most existing studies focus on either 2D CAD or 3D BIM design in isolation, our framework uniquely bridges these two, offering a comprehensive solution that leverages the strengths of both. This integration represents a significant leap in collaborative design methodologies, addressing a gap in current research and practice. The results of the comparative case study emphatically underscore the advantages of this collaborative approach. Using the proposed method, Team B was able to complete their design task in just 175 h, marking a substantial reduction from the 240 h taken by Team A, which relied on traditional 2D CAD techniques. This reduction, amounting to 27%, is a testament to the efficiency of the new approach. In the realm of design quality, the contrast is even more striking: Team A faced 427 design errors, in stark contrast to the mere six clashes encountered by Team B, translating to a remarkable 98% decrease in errors. Moreover, this method's benefits are mirrored in user experience ratings, with Team B achieving an impressive average score of 8.7 out of 10, significantly surpassing Team A's average of 6.2.

Future research, addressing the limitations identified in the comparative case study, should aim to broaden the scope by including a larger and more diverse range of projects and teams to enhance generalizability. It is essential to conduct longitudinal studies to better understand the learning curve and long-term efficiency gains with the proposed method, alongside implementing more objective measures for assessing design quality and user experience. Keeping pace with technological advancements and including a comprehensive cost–benefit analysis will provide a more holistic understanding of the proposed method. Additionally, empirical validation of the OpenBIM-based data exchange workflow will be crucial in assessing its interoperability and effectiveness in diverse project settings.

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Abbreviations

AEC	Architecture, engineering, and construction
BCF	BIM Collaboration Format
BIM	Building Information Modeling
bsDD	Building Smart Data Dictionary
CAD	Computer-aided Design
HVAC	Heating, Ventilation, and Air Conditioning
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
MEP	Mechanical, electrical, and plumbing
MVD	Model View Definition

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