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Integrated framework for compliance checking and performance evaluation in building design

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Abstract

Compliance checking and performance evaluation are crucial components of the iterative design and review process. However, traditional manual reviews and refined simulations are often subjective, time-consuming, and require a large number of input parameters. Therefore, automated rule checking (ARC) and performance simulation based on surrogate models have gained increasing attention. Despite this, most existing research focuses on one aspect or the other, without effectively integrating both, leading to gaps in reliability and efficiency when applied in practice. Therefore, this study proposes an integrated framework that combines automated compliance checking and efficient performance evaluation based on surrogate models, enabling rapid design review iterations. The framework comprises three interconnected modules: the NLP-AutoChecking module for rule checking based on IFC (Industry Foundation Classes) and semantic alignment; the DiffEvac module for evacuation performance simulation based on diffusion models; and a BIM design software module that connects both through a unified data interaction approach to modify design. Specifically, the BIM design can be converted into IFC format for rule checking to identify non-compliant elements and specify the violated regulations. Designers can then modify the design within the BIM software accordingly. It is important to note that multiple solutions may meet regulatory requirements, but not all are scientifically or practically optimal, as some may compromise safety or increase costs. Therefore, the modified BIM designs are exported as floor plans, cleaned and annotated, and then fed into the surrogate model for performance simulation, which evaluates and selects the optimal solution from the available options. This iterative cycle of compliance checking, simulation, and design modification continues until the design meets all regulatory standards and

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achieves optimal performance. Case studies demonstrate that this framework enables quick iterations and adjustments throughout both the design and review stages, significantly improving design quality and offering strong potential for widespread practical adoption.

1 Introduction

The design process is crucial for ensuring the quality, safety, and functionality of buildings, often requiring multiple iterations of review and modifications to achieve optimal building performance. During these reviews, compliance checking and performance evaluation are essential components. Compliance checking ensures the design meets regulatory requirements, while performance evaluation assesses the building's functionality under various scenarios, typically through simulation, to optimize the design. Traditional manual reviews, however, are often subjective, time-consuming, and costly, prompting extensive research into ARC and performance simulation based on surrogate models.

To enhance the automation of the review process, work on ARC can be traced back to the 1960s, when Fenves developed a tabular decision system for structural design review (Fenves, 1966). Building on this, Rasdorf and Lakmazaheri, employed predicate logic to formalize codes and regulations, enhancing the SASE (Standards Analysis, Synthesis, and Expression) system's ability to process standards (Rasdorf & Lakmazaheri, 1990). These early ARC studies primarily focused on 2D drawing reviews (Eastman et al., 2009). Since the 2000s, advancements in BIM models and IFC have significantly improved the capacity to describe design information, driving further ARC development (Ismail et al., 2017). For instance, Tan developed an automated code compliance checking system for building envelope design based on BIM and tabular decision systems (Tan et al., 2010). However, these studies often depend on manually created and maintained rule libraries, which pose challenges in flexibility and maintainability (Eastman et al., 2009; Nawari, 2019). Therefore, many scholars have proposed semiautomated and automated methods for interpreting the regulation text into a computer-processable format. One of the typical semi-automated rule interpretation methods is RASE (Requirement, Applicabilities, Selection, Exceptions) (Hjelseth & Nisbet, 2011), which helps experts analyze the semantic structure of regulatory requirements and uses document annotation techniques to mark different components of the regulations. Based on this, Beach developed a parser for the RASE method using ontology technology, reducing the manual effort required for semantic alignment and code generation in semiautomated methods (Beach et al., 2015). However, these methods still function at a coarse-grained level and rely heavily on manual input, leading to a relatively low level of automation. For this reason, natural language processing (NLP), widely used for analyzing and interpreting human language in text form (Fuchs, 2021), has been applied to automate rule interpretation from regulatory documents. Zhang and El-Gohary (Zhang & El-Gohary 2016) introduced a fully automated tagging and conversion method, developing a rule-based BIM extraction tool to align BIM objects with regulatory instances, enabling automated rule interpretation and checking. Zheng (Zheng et al., 2022) developed a large-scale domain corpus and pre-trained domain-specific language models for the AEC domain to assist in automated rule interpretation. Zhou (Zhou et al., 2022) introduced an innovative automatic rule extraction method using a deep learning model combined with context-free grammars (CFGs), which can interpret regulatory rules into pseudocode formats without manual intervention, increasing generality, accuracy, and interpretability. While these studies advanced automated rule interpretation, challenges remain: (1) High costs and low generalizability of regular expression-based methods (Tomassetti G, 2017); (2) Semantic misalignment between regulatory texts and BIM models due to differing terminologies (Zhou & El-Gohary, 2021); (3) Current methods rely on simple logic clauses, which are limited by missing implicit information (Zhang et al., 2018). To address these issues, we proposed NLP-AutoChecking in our previous research, a novel automated rule interpretation and design review method that automatically interprets the domain regulatory texts expressed in natural language into computer-processable code based on a pipeline of NLP techniques (Zheng et al., 2022; Zheng et al., 2023).

Design regulations traditionally provide clear parameters and requirements to ensure building safety. However, due to variations in structure, space usage, and layout, designing strictly according to regulatory requirements may not always result in the most scientifically sound or cost-effective solutions, potentially leading to suboptimal safety levels or increased costs (Meacham & Custer, 1995). As a predictive and analytical tool, evacuation simulation facilitates the understanding of complex evacuation behaviors, enhances building design, and refines emergency plans. Consequently, it has garnered significant attention from both academic researchers and industry practitioners. Evacuation simulations can be broadly classified into macro-level and micro-level models, based on whether they emphasize overall crowd dynamics or individual interactions. Early models, such as fluid mechanics, Cellular Automata (CA), and social force models (Klote & Hadjisophocleous, 2008; Helbing et al., 2000; Fu et al., 2015; Gao et al., 2022), provided a basic framework for simulating macroscopic pedestrian movements. However, these models often rely on generalized crowd behaviors, leading to oversimplifications and a lack of accuracy in capturing the finer details of evacuation scenarios. Recent advances in computational capabilities and data accessibility have shifted the focus towards micro-level simulations, encouraging the development of more detailed and nuanced models, such as agent-based, virtual reality (VR), and multi-level simulations (Cotfas et al., 2022; Wang et al., 2023; Alac et al., 2023; Lim et al., 2023). These newer approaches simulate each evacuee as an independent agent, capturing individual behaviors and interactions (Senanayake et al., 2024). While these models offer higher precision in representing evacuation processes, they also require extensive input data and complex modeling, making them time-consuming and labor-intensive. As a result, researchers have turned to more efficient evacuation simulation methods, leveraging artificial intelligence (AI) technologies capable of learning from existing data and knowledge as the foundation for these advancements. For instance, Nourkojouri (Nourkojouri et al., 2023) explored the use of image generation algorithms for rapid evacuation simulations and evaluations, focusing primarily on Conditional GANs (Generative Adversarial Networks) in their initial experiments. However, Conditional GANs have limitations in generalization and image generation detail compared to more advanced models like diffusion models (Gu et al., 2024). Furthermore, their study showed poor performance on irregular floor plans, highlighting the need to investigate alternative image generation models that could provide better quality, stability, and support for faster evaluations of various building layouts. To address these issues, we proposed DiffEvac in our previous research, a novel method to learn building evacuation patterns based on diffusion model, for efficient evacuation simulation and enhanced safety design (Han et al., 2024).

Although significant progress has been made in ARC and performance simulation, existing research often focuses on one aspect without effectively integrating both. This leads to discrepancies in data interfaces and processing logic, requiring designers to spend considerable time on manual adjustments and re-entry, which severely impacts efficiency. Therefore, this study proposes an integrated framework that combines automated compliance checking and efficient evacuation performance simulation based on surrogate models, ensuring that the final design not only meets all regulatory requirements but also achieves optimal functionality and safety.

2 Framework

The proposed framework comprises three interconnected modules: the NLP-AutoChecking module for rule checking based on IFC and semantic alignment (Section 2.1); the DiffEvac module for evacuation performance simulation based on diffusion models (Section 2.2); and a BIM design software module that connects both to modify design (Section 2.3). Specifically, we propose a unified data interaction approach that makes various design software compatible with the NLP-AutoChecking and DiffEvac modules, allowing for rapid export of IFC formats for automated rule checking, as well as quick export, cleaning, annotation, and feature decoupling of floor plans for evacuation simulation. The relationship between the three modules is shown in Figure 1.

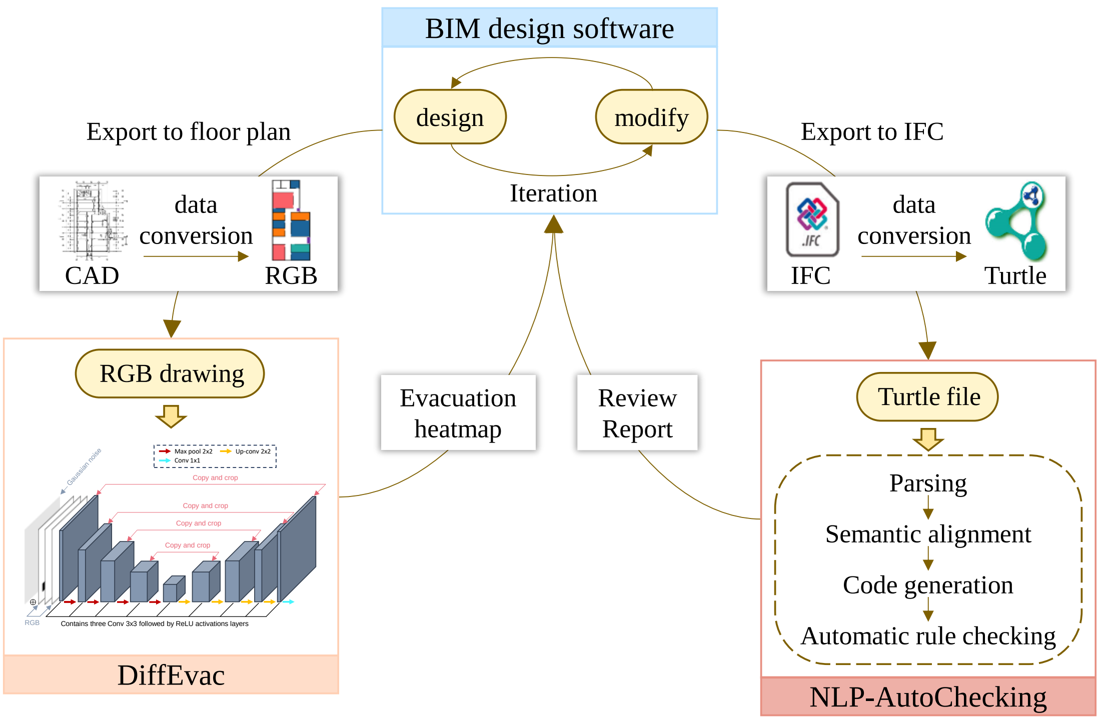


Figure 1 The relationship between the three modules

2.1 Styles for the Article Body

This module is based on our previously proposed NLP-AutoChecking, a novel automated rule interpretation and design review method that automatically interprets the domain regulatory texts expressed in natural language into computer-processable code based on a pipeline of NLP techniques (Zheng et al., 2022; Zheng et al., 2023). To enhance the scalability of this module and enable rapid automated rule checking across various types of BIM software, we proposes a unified data conversion method.

The IFC format is widely used for collaboration and model storage in BIM projects, with many BIM software programs supporting it (IFCwiki, 2018). However, since IFC uses the EXPRESS schema, it cannot be directly processed by the ontology-based reasoning engine in NLP-AutoChecking, requiring additional conversion. To address this, we developed a custom IFC-to-ontology mapping method to automatically convert BIM data stored in IFC format into Turtle (Terse RDF Triple Language) format. This process involves three key steps: concept mapping, IFC parsing, and generating the Turtle file.

Concept mapping aims to align IFC concepts and attributes with fire protection of building ontology (FPBO) classes, object properties, and data properties through the mapping table established in this study, as shown in Table 1. IFC object concepts are mapped to corresponding FPBO classes; for example, "IfcBuildingStory" maps to "BuildingStory." Similarly, IFC attributes are linked to FPBO data properties, such as "fire_resistance_rating" being mapped to "hasFireResistanceLimits_hour." The relationships between instances in FPBO are determined by three key IFC relationships: decomposition, contains, and BoundedBy. First, the domain and range objects of these relationships are identified by parsing the IFC file, then their corresponding FPBO classes are determined. A HashMap is used to define the object properties between two objects, using two keys: one for the domain object's class and the other for the range object's class.

Table 1 Part of the ontology mapping dictionary

IFC Schema	FPBO concepts
IfcBuildingStorey	BuildingStorey
IfcBuilding	BuildingRegion
IfcSpace	BuildingSpace
IfcColumn	Column
IfcBeam	Beam
IfcSlab	Floor
IfcWallStandardCase	Wall
IfcWall	Wall
IfcWindow	Window
IfcDoor	Doors
IfcStair	Stairs
GlobalId	hasGlobalId
fire_resistance_rating (user defined attribute)	hasFireResistanceLimits_hour

Several tools are available for parsing IFC formats, including IfcOpenShell (Python), IfcPlusPlus (C++), and the xBIM toolkit (.NET). Among these, IfcOpenShell, which is based on OpenCascade technology and operates in Python, is the most suitable for this study. Therefore, IfcOpenShell was selected to parse the IFC files (IfcOpenShell, 2023). During the parsing process, relevant objects and attributes are stored in memory and subsequently mapped to FPBO concepts using the concept mapping method described earlier.

Finally, in the Turtle file generation step, the mapped data stored in memory are formatted according to the Turtle syntax, a widely used format for ontology data exchange, and then outputted as a Turtle file.

With this approach, architects can efficiently export BIM models into a format compatible with the semantic parsing, semantic alignment, conflict resolution, and code generation processes in NLP-AutoChecking for automated rule checking. Specifically, a Turtle file is used as the input, and a file that documents non-compliant elements and specifies violated regulations is produced as the output, supporting design modifications. Additionally, the generated .ttl file allows for easy editing and further adjustments.

2.2 DiffEvac module for efficient evacuation performance simulation

This module is based on our previously proposed DiffEvac, a novel method to learn building evacuation patterns based on diffusion model, for efficient evacuation simulation and enhanced safety design (Han et al., 2024).

To ensure designs from various BIM software can be efficiently exported into a format suitable for evacuation performance simulation, this study introduces a unified data conversion method that includes four key steps: floor plan export, data cleaning, data annotation, and feature decoupling.

For floor plan export, each floor of the BIM model is individually exported as a floor plan in an editable CAD format. This process extracts the 2D layout of each level from the 3D BIM model, ensuring that the necessary spatial details are preserved for evacuation performance simulation.

Subsequently, irrelevant elements such as annotations, symbols, text, and redundant lines are removed, leaving only the essential structural features like walls, windows, and door openings (without indicating door swing directions). The drawings are then converted into RGB images, with each image adjusted to maximize the use of available space.

In addition to area capacity and exit locations, which can be reflected through pixel positions in building floor plans, crowd density is also a crucial parameter in evacuation simulations, requiring manual annotation. Therefore, based on the “Standard for Design of Office Building (JGJ/T67-2019)” (The Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2019) and the “Code for Design of Library Buildings (JGJ 38-2015)” (The Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2015), occupant densities for rooms of different functions were determined, as detailed in Table 2. To differentiate room occupancy density and function, we applied distinct colors, embedding crowd density information directly into the floor plans to ensure the model captures all key parameters. Afterward, the floor plans were annotated according to the color schemes outlined in Table 2, producing the functional layout drawings for each room.

Table 2 Occupant densities for rooms of different functions

Function of room	Density (m2/person)	Color
Ordinary office	6	(dark blue)
Meeting room (with table)	2	(orange)
Meeting room (no table)	1	(pink-red)
Exhibition Hall	1.43	(teal)
Other region	9	(green)
Corridor & Restroom	0	(white)
Exit (stairs)	0	(light blue)
Exit (door)	0	(purple)

This method allows us to export various BIM models into a format compatible with the DiffEvac approach, using an RGB drawing as input. The surrogate models in DiffEvac can then be applied for rapid evacuation performance simulation, generating evacuation heatmaps to effectively guide design modifications.

2.3 BIM design software module for design modification

Using the unified data conversion method described in Sections 2.1 and 2.2, we can achieve rapid automated rule checking and evacuation performance simulation during the design and review process for various BIM models.

The process begins by converting the initial BIM design into IFC (Industry Foundation Classes) format, which is then input into the rule checking module to identify non-compliant elements and specify the violated regulations. Designers can use this information to modify the design within the BIM model. It is important to note that multiple modification solutions may meet regulatory requirements. However, due to differences in building structure, space usage, and other factors, designing strictly according to standardized code parameters may not always result in the most scientifically sound or cost-effective solution, potentially leading to suboptimal safety levels or increased costs. Therefore, we enable the modified BIM designs to be quickly exported as floor plans, cleaned, annotated, and then fed into the surrogate model for performance simulation. This step evaluates and selects the optimal solution from among the available options. This iterative cycle of compliance checking, simulation, and design modification continues until the design meets all regulatory standards and achieves optimal performance, as described in Figure 1.

3 Case study

This section demonstrates the practical application of the proposed integrated framework in the design and review process, using a case study of fire protection checking for a three-story office building. The workflow for optimizing design plans during the design and review process using the proposed framework is shown in Figure 2.

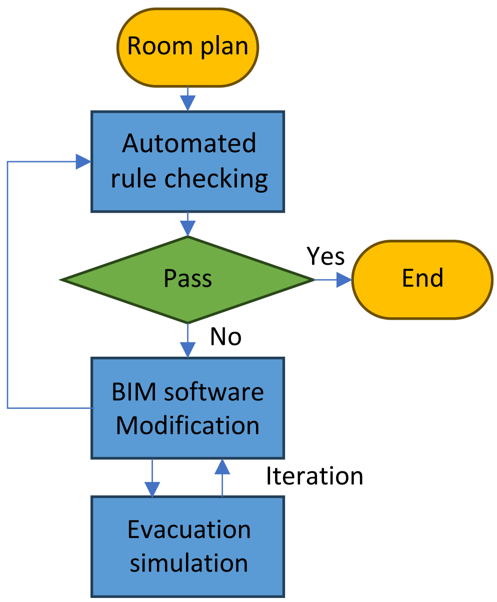


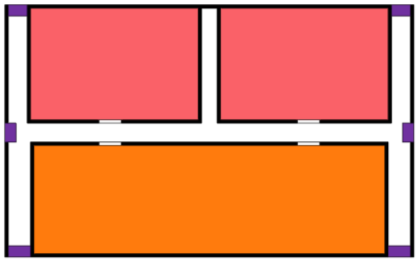
Figure 2 The workflow for optimizing design plans using the proposed framework

This building has a first-level fire resistance rating, spanning approximately 2500 m², and features a high-occupancy conference hall. In this case, Revit is used as the BIM software, and the regulation checked by the NLP-AutoChecking module is: "For crowded places such as conference halls and multi-purpose halls in buildings, there should be no less than two evacuation doors in a hall or room, and the building area should not exceed 400m2." (GB 50016-2014). The corresponding model is shown in Figure 3.

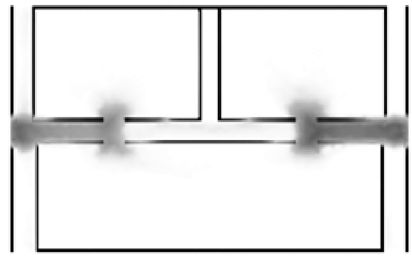
Figure 3 Three-dimensional model of the three-story office building

After the architect completes the preliminary design, the BIM model can be exported as a Turtle file following the process described in Section 2.1, and then input into the previously developed NLP-AutoChecking method for rapid automatic rule checking. This process identify that the number of evacuation doors in two rooms was less than the required minimum of two, as stipulated by the code. Since the model did not pass the review, adjustments are needed for the non-compliant rooms. The original layout is shown in Figure 4(a), where the two red areas each have only one emergency exit, failing to meet the code requirements. Therefore, the number of emergency exits in these areas must be increased. However, further research is needed to determine where in the room to add a new emergency exit to enhance the evacuation performance. Figure 4 presents three modified room layouts. Option 1, shown in Figure 4(c), adds both evacuation exits to the front. Option 2, shown in Figure 4(e), places one evacuation exit at the front and the other at the side. Option 3, shown in Figure 4(g), places both evacuation exits at the side.

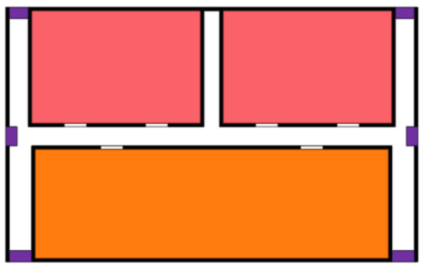
It can be seen that all three proposed modifications meet the regulatory requirements. To select the option with the best evacuation performance, we used the data processing method described in Section 2.2 to convert these BIM models into three-channel input with decoupled features. These were then fed into the DiffEvac method proposed in our previous research, generating corresponding evacuation heatmaps to evaluate the performance of each plan, as shown in Figures 4(b), 4(d), 4(f), and 4(h). Figure 4(b) illustrates that the original room layout leads to inadequate use of exits located at the top and bottom of the building, leading to severe congestion in the central corridor, which significantly impairs evacuation efficiency. Figure 4(d) shows that the design option with additional evacuation exits at the front of the two rooms (Figure 4(c)) also fails to fully utilize the exits at the top and bottom of the building, similarly causing large-scale congestion in the central corridor. Even though this design meets code requirements, the additional exits do not substantially enhance evacuation efficiency. When an evacuation exit is added to the side of the room, as shown in Figure 4(f), some people evacuate through the upper exit, significantly alleviating the crowding in the central corridor. When both evacuation passages in the rooms with red backgrounds are located at the side (Figure 4(g)), Figure 4(h) shows that the level of crowding is lower compared to the results in Figure 4(f), indicating that this layout is more effective for facilitating evacuation.



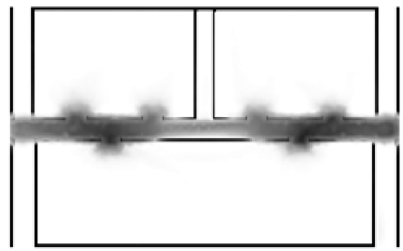
(a) Original room layout



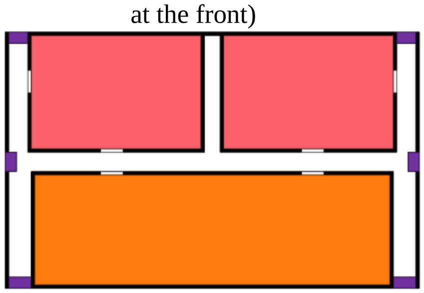
(b) Evacuation heatmaps corresponding to the left layout



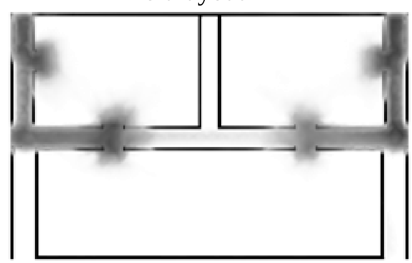
(c) Option 1 (both evacuation exits are placed at the front)



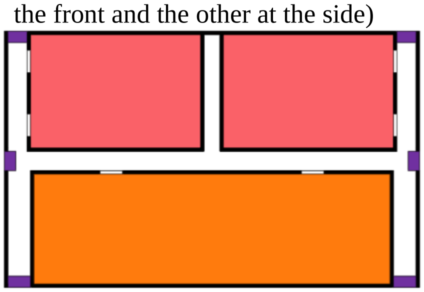
(d) Evacuation heatmaps corresponding to the left layout



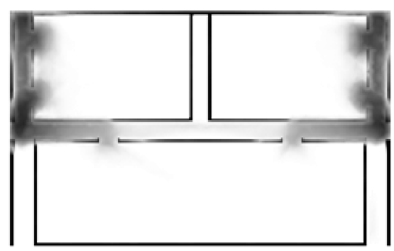
(e) Option 2 (one evacuation exit is placed at the front and the other at the side)



(f) Evacuation heatmaps corresponding to the left layout



(g) Option 3 (both evacuation exits are placed at the side)



(h) Evacuation heatmaps corresponding to the left layout

Figure 4 Room layouts and their corresponding evacuation heatmaps

To further analyze the evacuation effectiveness of different design options, this section utilized Pathfinder to develop the refined models and perform simulation analyses, with the evacuation times recorded in Figure 5. It is observed that while placing both evacuation exits at the front meets regulatory requirements, it does not result in a substantial reduction in evacuation time. In contrast, relocating the evacuation exits to the sides of the rooms alleviates crowd congestion and results in a considerable decrease in evacuation time.

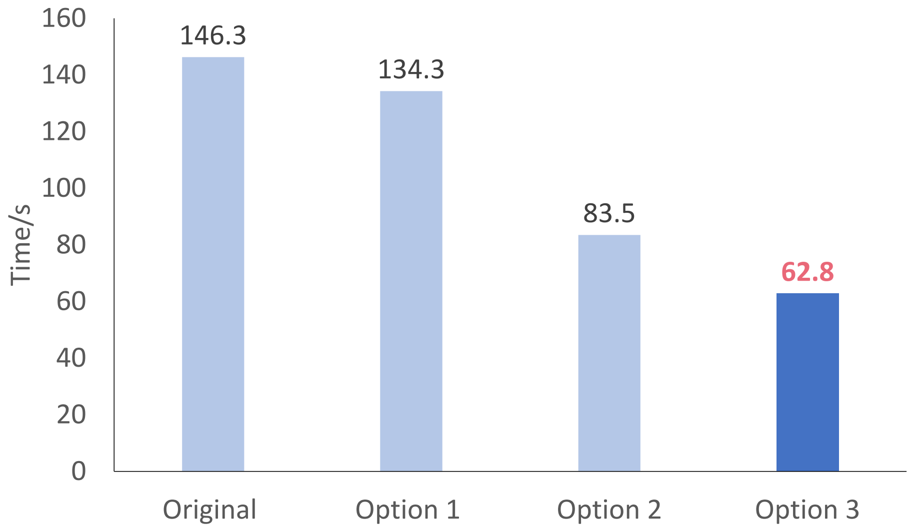


Figure 5 Evacuation time required for different layout plans

This case study highlights the practical value of the proposed integrated framework, for revising design plans following automatic rule checking and efficient evacuation performance simulation, demonstrating its effectiveness in aiding users with design optimization and validation. While this example focuses on a single regulation, real-world applications often involve multiple violations, and modifications may conflict with other regulations. Therefore, the process should be iterative to ensure the design complies with all regulatory standards and achieves optimal performance.

4 Conclusion

This study proposes an integrated framework that combines automated compliance checking and efficient performance evaluation based on surrogate models, enabling rapid design review iterations. Specifically, we propose a unified data interaction approach that makes various design software compatible with the NLP-AutoChecking and DiffEvac modules, allowing for rapid export of IFC formats for automated rule checking, as well as quick export, cleaning, annotation, and feature decoupling of floor plans for evacuation simulation.

Case study demonstrate that this framework enables quick iterations and adjustments throughout both the design and review stages, significantly improving design quality and offering strong potential for widespread practical adoption.

It is important to note that the data processing framework proposed in this study is not limited to evacuation performance evaluation but can be extended to a wider range of applications. For example, by modifying the surrogate models, this framework can be expanded to assess other building performance criteria. Moreover, the data processing flow can also be adapted to support text-guided design modifications. Specifically, engineers' textual design requirements would be processed into a language understandable by computers, while existing design drawings would be transformed into feature tensors through image processing. To enable this, adjustments would need to be made to the deep learning models within the framework, ensuring that they are capable of effectively handling both textual input and image-based design features, thus facilitating automatic design modifications driven by textual descriptions.

Acknowledgments

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