



## INTEGRATING SIMULATION TOOLS FOR VALIDATING FIRE SAFETY DESIGN OF BUILDINGS

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### Abstract

Achieving high-level fire safety performances in building design requires addressing complex challenges to safeguard occupants. This paper presents a BIM-integrated framework for validating building fire safety designs, combining fire simulation tools to assess occupant safety, quantified through a KPI. The KPI facilitates results' visualization within the BIM environment, enabling even the identification of critical areas. The framework has been tested on a pilot case, to demonstrate its ability to assess compliance with fire safety objectives and to enhance design flexibility. This approach bridges simulation and design processes, providing stakeholders with actionable insights to validate and improve building fire safety strategies.

### Introduction

The performance-based approach to fire safety design offers a more flexible and tailored assessment of building safety, prioritising compliance with fire safety objectives over prescriptive solutions (Reichert, 2021). The process of fire safety design validation for buildings entails assessing various fire scenarios that represent the most severe yet reasonably plausible events. For each scenario, the performance of design solutions must be rigorously evaluated to ensure it meets fire safety objectives (National Fire Protection Association, 2024). In the context of project validation, adopting a quantitative framework to evaluate the effects of fire on occupant safety would enable an objective and transparent process, thus meeting the needs of authorities and other stakeholders.

Within the performance-based framework, this paper proposes a methodology to streamline the validation process for building fire safety design, by integrating advanced tools for assessing life safety in the event of a fire. The proposed methodology adopts a Key Performance Indicator (KPI) to quantify occupant safety and to assess the level of compliance against fire safety objectives. This KPI not only checks whether design solutions meet the required standards but also provides detailed feedback on critical areas in a building. The KPI is worked out by comparing the Available Safe Egress

Time (ASET) and the Required Safe Egress Time (RSET), using specialised simulation tools for fire dynamics and evacuation analyses. Furthermore, a graphical representation of the KPI is embedded in the BIM environment, enabling a spatial rendering of fire safety conditions.

Therefore, this paper focuses on developing a BIM-compatible framework to support the validation of fire safety designs by authorities and other stakeholders. This integration facilitates the efficient identification of areas where safety thresholds are not met and suggests measures to enhance occupant safety. The framework provides authorities with tools to validate design compliance objectively, while empowering clients to select optimal solutions tailored to their specific requirements.

The validity of the proposed framework was tested on a pilot building. One fire scenario was tested for this building. The entire methodology was applied to three validation scenarios, each representing a different situation that the authority responsible for project validation may encounter. The three validation scenarios are as follows:

- the first case, presented in the 'Validations of the building in its current design scenario' section, involves the assessment of a building originally designed with no concern for fire prevention measures,
- the second case, reported in the 'Validation of the code-compliant building design' section, concerns a building designed in compliance with prescriptive solutions outlined by the Italian fire safety regulation (D.M. 03/08/2015, 2015). In this case, the new methodology still provides an added value due to the quantification of the achieved safety level,
- the third case investigates the application of alternative solutions using a performance-based approach to compare them with the prescriptive solutions suggested by the previous validation scenario, and evaluates which fire safety prescriptions could be omitted, if any. This third case is in the subject of 'Validation of the building design with a performance-based approach' section.

Overall, the suggested methodology serves primarily as a tool for authorities to validate fire safety designs projects. However, in case it is adopted at the design phase, it can provide greater flexibility in design choices, too.

## Literature review

BIM has deeply influenced the Architectural Engineering and Construction (AEC) industry by enhancing 3D visualization and facilitating efficient data and information structuring and management across the planning, construction, and operation phases of building projects (Sacks et al., 2018). However, fire engineers have been slower to adopt BIM compared to other disciplines (Malagnino et al., 2022), largely due to interoperability limitations between BIM platforms and Fire Safety Engineering (FSE) simulation tools (Siddiqui et al., 2021). Nevertheless, several studies focus on the integration of BIM and fire prevention simulation tools (Dimyadi et al., 2018; Sun and Turkan, 2020; Wang et al., 2015; Yakhou et al., 2023).

Other research explores the use of BIM for the automated verification of safety conditions in the event of a fire. For instance, Porto et al., 2018 present a methodology for automating fire compliance verification through a BIM-compatible plugin called 'BIMSCIP'. This approach automates the code-checking process, reducing errors and improving efficiency, enabling detailed analyses of fire resistance requirements. While this work represents a novel contribution to the field, it relies on prescriptive norms, limiting its flexibility. Another research develops a BIM-based automated code-checking framework, focusing on compliance with passive fire protection regulations in the Canadian context (Kincelova et al., 2020). Even this paper focuses on prescriptive standards, using explicit criteria to verify compliance with passive fire protection rules. Despite challenges like incomplete BIM data and supplementary manual inputs, another study demonstrates BIM's potential in performance-based design and compliance verification (Dimyadi et al., 2016). In this case, the authors focus on the development of a framework that combines BIM data with advanced computational models, enabling the calculation of RSET and its comparison with the ASET to ensure compliance with performance-based safety standards. Overall, the paper highlights the potential of BIM integration to advance performance-based design and compliance verification while calling for further standardization to enable broader applications in fire safety simulations.

Occupant safety in the event of a fire is one of the most critical aspects of FSE (Kong et al., 2013). Current fire prevention practices, often implemented by means of commercial software tools, assess life safety by comparing two-time values: ASET and RSET, evaluated at a limited number of specific locations within a building. The quantitative assessment of performances can be facilitated by the definition of KPIs, allowing a quick and comprehensive evaluation and quantification of safety levels. KPIs have become an essential element in assessing performance against various objectives in some

engineering areas (Sharp et al., 2008). Several studies have proposed alternative indicators to ASET/RSET to improve the assessment of occupant safety in fire scenarios. These include ASUT/RSUT (Poon, 2014) which consider the available and required time for the safe use of egress areas, the risk indices RRI and CRI (Mirahadi et al., 2019) for evaluating the safety of exit routes and compartments, and a safety margin indicator (Schröder et al., 2020) for a detailed building-wide safety analysis.

In the latter case, the authors proposed discretizing the entire building into a grid, to evaluate safety levels at every node. The results were visualized using maps that display ASET, RSET, and their differences. The process of determining ASET and RSET at each separate point favours a dynamic approach supported by advanced simulation models.

## Materials and methods

### Research questions

This paper suggests a methodology and tries to develop tools to answer the following research questions (RQs):

1. Can a BIM-based framework be defined and implemented to support the validation of building fire safety design projects, ensuring compliance with established fire safety objectives?
2. Can the framework effectively identify critical areas in fire safety design and facilitate targeted revisions by designers to meet fire safety objectives?

This research proposes a BIM-based framework to address the above-mentioned research questions by integrating fire safety analysis tools with a specific focus on occupant life safety. The framework leverages BIM to centralise and visualise fire safety performance values, namely evacuation safety evaluations based on the ASET/RSET concept. These time values were estimated through fire dynamics and evacuation simulation tools, and their results were displayed back within the same BIM model to offer a spatial assessment of occupant safety levels. Custom Python scripts were executed to process and visualize data needed to calculate a predefined KPI. The KPI, visualised directly in the BIM environment, enabled quick and intuitive design validations, the identification of critical areas, and the implementation of targeted design revisions to meet unattended fire safety objectives.

### Definition of the Key Performance Indicator (KPI)

For illustrative purpose, in this paper a single KPI was identified but the entire methodology can be applied by setting additional KPIs. The name of the KPI is 'safety margin ( $t_{\text{safety}}$ )', which is the difference between ASET and RSET as defined by the Italian fire regulation Ministerial Decree 3rd August 2015 in paragraph M.3.2.2. The minimum required threshold set by the Italian fire regulation is equal to 30 s, which was adopted as the threshold in this paper, too. Hence, the KPI threshold was set as:

$$t_{safety} > 30 \text{ seconds} \quad (1)$$

### Proposed framework for fire assessment

A representation of the processes that could be carried out to meet the aforementioned objectives is depicted in Figure 1.

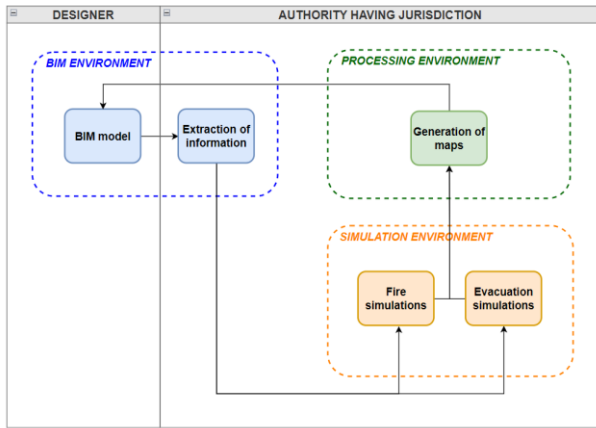


Figure 1: Conceptual representation of the work developed in this paper

In a digitalised world, the traditional use of 2D drawings or graphic plans has been replaced by the adoption of BIM models. Out of these BIM models, developed by the designer, an authority can extract relevant information and perform simulations to verify a design's compliance and effectiveness.

The entire framework is organised into three main areas: the BIM environment, the simulation environment, and the processing environment. In the BIM environment, the BIM model of the building was developed using the authoring tool Revit<sup>TM</sup>. Relevant information needed for the fire safety assessment was extracted from the BIM model to serve as an input for the simulation tools. In the simulation tools area, two specialised software applications were employed. Fire simulations were performed using FDS (Fire Dynamics Simulator), which discretizes the building into elemental volumes to calculate fire-related variables, such as temperature and smoke density. These simulation tools also produce slices for graphical visualisation of the results. Evacuation analysis was carried out using JuPedSim (Julich Pedestrian Simulator), an extensible framework for microscopic pedestrian dynamics simulations. JuPedSim tracks individual movements across a grid representing the environment, enabling detailed analysis of occupant trajectories and passage timestamps at each cell within the environment. Subsequently, the data outputs from the simulation results were processed using Python. Custom Python scripts were implemented to generate visual maps representing ASET, RSET, and the resulting safety margin. As a result, these maps provide a detailed spatial representation of safety conditions throughout the building. Finally, these maps were re-imported into the BIM model, closing the loop of the framework. This seamless reintegration ensures that authorities and

stakeholders can evaluate and refine fire safety strategies efficiently and effectively cooperating within the same BIM environment.

### Extraction of information

The structured information required for fire safety evaluations was extracted directly from the BIM model of the building. More specifically, this process allowed the automated generation of input data for simulation software tools. Within the proposed framework, the building model was developed in Revit<sup>TM</sup>, and Dynamo<sup>TM</sup> acted as the export tool. Dynamo<sup>TM</sup> facilitated reading building's geometry, generating a quadrilateral finite element mesh of the building area with predefined parametric dimensions, and exporting the points of the mesh along with their coordinates. For the case study discussed in this paper, a mesh element size of 0.50 x 0.50 m was used to create the visual maps. This mesh resolution was considered sufficiently accurate to represent both occupant movement paths and fire propagation.

### Generation of maps

To provide an intuitive and detailed visualisation of the occupant life safety assessment, a series of maps were developed using Python-based scripts, adapted from the methodology proposed by Schröder et al., 2020. These scripts facilitated the generation of ASET, RSET, and difference maps by post-processing the results from fire and evacuation simulations. The ASET maps were derived from the FDS simulation outputs, specifically focusing on environmental parameters such as temperature and light extinction coefficient. First, the script processes ASCII file outputs from FDS to create the ASET maps, which were exported in both 'png' and 'txt' formats. Then, RSET maps were processed from occupant trajectory data obtained from evacuation simulations. Every simulation incorporated multiple potential trajectories, defined during the design phase. The script processes these trajectories, provided in 'xml' format, and then interpolates the worst-case scenarios to produce a global RSET map. The resulting maps, representing the longest evacuation times, were saved as 'png' and 'txt' files. Finally, the difference map, representing the safety margin, was generated by subtracting the values in RSET maps from the corresponding values in ASET maps. This step integrates both the fire and evacuation data to provide a comprehensive visualisation of safety conditions across the building. Similarly, the difference map outputs were saved in 'png' and 'txt' formats, allowing seamless integration back into the BIM model.

### Import of maps into the BIM environment

A customised visual flow was developed in Dynamo<sup>TM</sup> to process the text file generated by Python, which contains KPI values. In the BIM model, the mesh grid had already been created, as detailed in the 'Extraction of information' section. Geometric points were associated with the central point of each mesh element, and a new design parameter,

' $T_{\text{safety}}$ ', was assigned to these points. To facilitate the import process, the text file was first converted into an Excel spreadsheet, which was then processed in Dynamo™. The Excel matrix was transformed into a list using dedicated Dynamo™ nodes, and the KPI values were mapped to the corresponding ' $T_{\text{safety}}$ ' parameters in the BIM model. Every mesh point was then assigned a colour based on a ranking of its ' $T_{\text{safety}}$ ' value: red if it falls below the threshold of 30 seconds (Eq. 1); green if it meets or exceeds the threshold; white if no occupant path was recorded. This integration enables a visualisation of safety-critical areas within the BIM model. By leveraging this method, the visual representation ensures a clear understanding of fire safety conditions directly within the digital model, enhancing decision-making and enabling targeted design improvements.

### Application on a case study

The feasibility of the proposed framework was evaluated through a pilot case. The building is a five-storey structure designed to accommodate offices (inspired by the project available at: <https://openifmodel.cs.auckland.ac.nz/>). Figure 2 illustrates the 3D view of the building model.

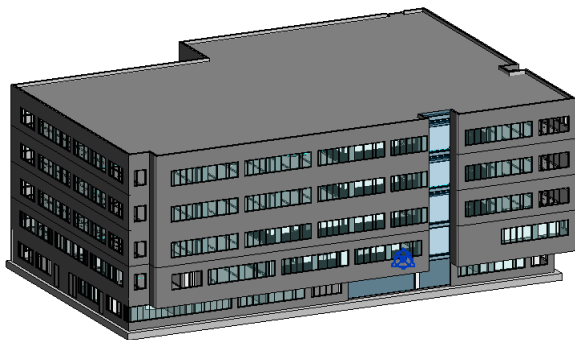


Figure 2: 3D view of the building model

For illustrative purposes, the analysis was not conducted on the entire building but only on the ground floor and the third floor considering fire compartments on separate floors. We are aware that a complete assessment of the method asks for further developments including evaluations on entire buildings and even on fire compartments spreading across different floors. So far, the methodology was tested first for the original design lacking fire prevention measures; secondly, for a project following the compliant solutions of the Italian fire regulations; finally, for a project adopting alternative solutions resulting from the application of a performance-based approach.

### Fire scenarios

The application of the performance-based approach involves the selection of a representative set of design fire scenarios and the evaluation of proposed design solutions subject to these conditions (D.M. 03/08/2015, 2015). This process ensures that the design meets the safety objectives for a range of realistic fire events. For the illustrative purpose of this study, a comprehensive risk assessment of

all possible fire scenarios was not conducted. Rather, the predefined design fire scenarios provided by the American NFPA 101 (National Fire Protection Association, 2024) fire code were considered. Specifically, Chapter 5.5.3 of the code outlines eight predefined design fire scenarios. At the initial analysis, the following predefined design fire scenario was selected:

- Scenario no. 2 of NFPA 101: it is an ultrafast developing fire, in the primary means of egress, with interior doors open at the start of the fire. It addresses the concern regarding a reduction in the number of available means of egress.

### Validations of the building in its current design scenario

The selected fire scenario was simulated for the building in its first design scenario, hence designed with no concern for fire prevention aspects. The fire hearth was placed along the main corridor on the ground floor, which is the main egress route. This fire simulation generated the initial environmental parameters, as previously outlined in the 'Generation of maps' section. Additionally, the evacuation simulation provided the trajectories of the occupants in the building, in the case of maximum occupancy. Similarly, the same fire scenario was assumed on the third floor. Here, the fire hearth was placed near one of the two staircases, which serve as the main egress route.

The results of the fire and evacuation simulations obtained were post-processed using Python. Through the scripts previously described in the 'Generation of maps' section, maps of ASET, RSET, and their differences were generated. The KPI values are shown in the difference map. When the value falls below the threshold of 30 seconds (Eq. 1), it means that such points are unsafe for occupants. The maps of ASET (Figure 3-a), RSET (Figure 3-b), differences (Figure 3-c) for the ground floor are depicted below, along with the maps of ASET (Figure 4-a), RSET (Figure 4-b) and differences (Figure 4-c) for the third floor.

The difference map, representing the KPI values, was subsequently imported into the BIM model, as described in the 'Import of maps into the BIM environment' section. This integration allows a clear and immediate visualisation of whether the design meets fire prevention requirements or there are critical areas for occupants within the building. For instance, Figure 3-d contains several points on the ground floor where the KPI does not meet the threshold. More specifically, fifty-six critical points were identified along the main corridor, which are those in red in Figure 3-d. These conditions result in a decrease in the time available and an increase in the time required for escaping, in fact creating a critical area. These fifty-six points are defined as critical because they do not

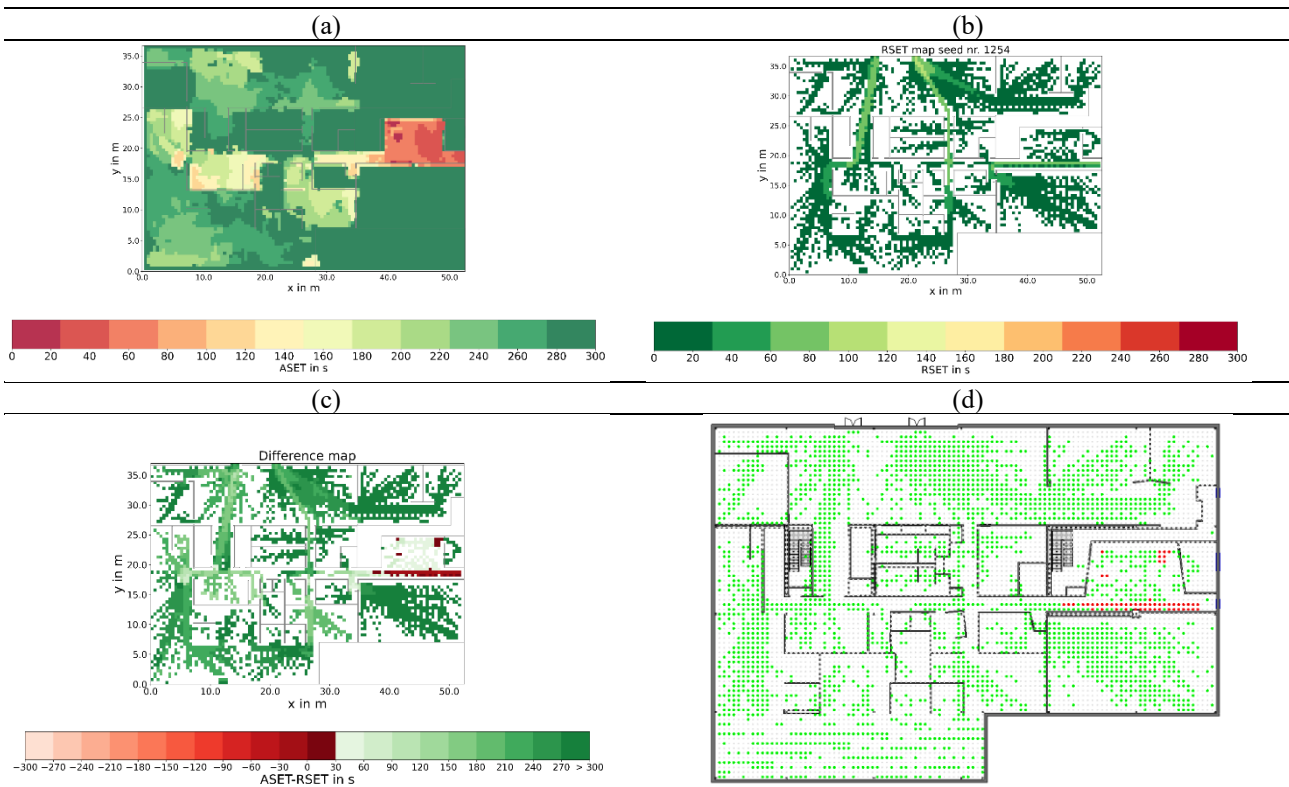


Figure 3: ASET (a), RSET (b), difference maps (c) (output of Python), and their visualization when imported into the Revit<sup>TM</sup> model (d) of the ground floor in the first scenario

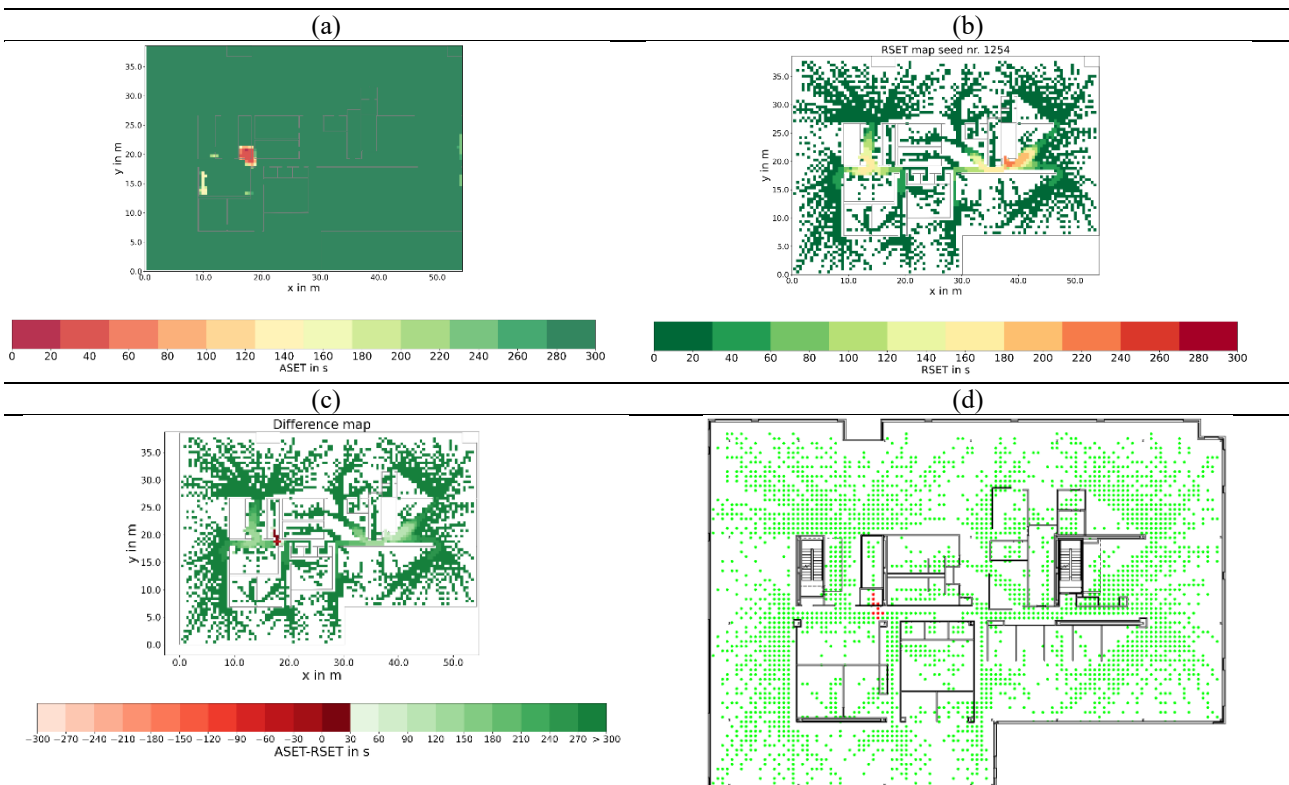


Figure 4: ASET (a), RSET (b), difference maps (c) (output of Python), and their visualization when imported into the Revit<sup>TM</sup> model (d) of the third floor in the first scenario

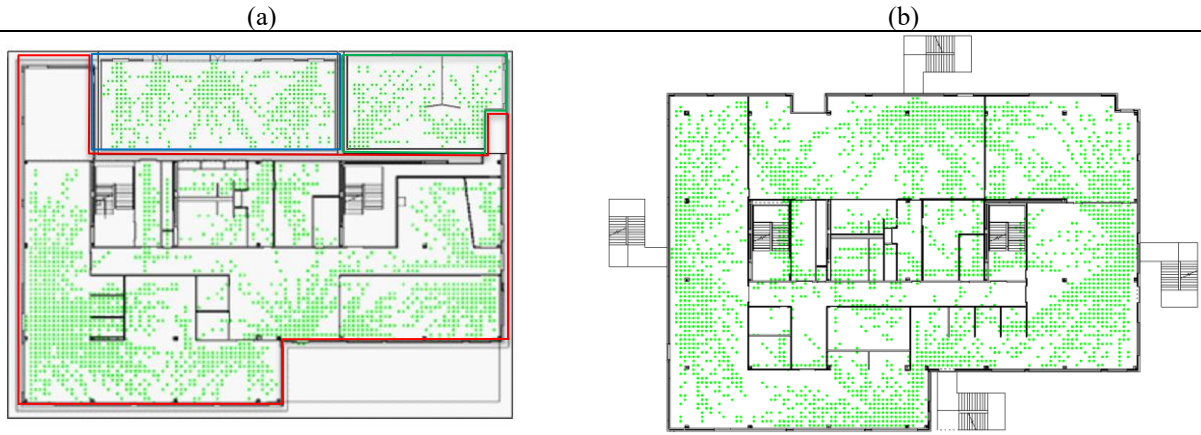


Figure 5: Difference maps once displayed in Revit<sup>TM</sup> for the code-compliant design regarding the ground (a) and third floors (b)

Table 1: KPI values obtained for the three validation scenarios

Validation scenario	Interval number	KPI interval	No. of cells in the interval
Ground floor in the current design scenario	1	< 30 seconds	56
	2	From 30 to 60 seconds	95
	3	> 60 seconds	2749
Third floor in the current design scenario	1	< 30 seconds	9
	2	From 30 to 60 seconds	4
	3	> 60 seconds	2993
Ground floor in the code-compliant design	1	< 30 seconds	0
	2	From 30 to 60 seconds	1
	3	> 60 seconds	2899
Third floor in the code-compliant design	1	< 30 seconds	0
	2	From 30 to 60 seconds	2
	3	> 60 seconds	3004
Ground floor in the performance-based design	1	< 30 seconds	0
	2	From 30 to 60 seconds	1
	3	> 60 seconds	2899
Third floor in the performance-based design	1	< 30 seconds	0
	2	From 30 to 60 seconds	2
	3	> 60 seconds	3004

meet the threshold of the KPI initially set and fall in the first interval of Table 1. Similarly, in Figure 4-d, the third-floor difference map, once imported into Revit<sup>TM</sup>, unveils nine unsafe points (shown in red in Figure 4-d and listed in Table 1) that fail to meet the KPI threshold. These points are located near the fire hearth, where combustion products rapidly reach the main corridor, generating a critical area. This area is particularly vulnerable as many occupants must walk through it to reach one of the two staircases, which constitute the vertical escape routes.

On both floors, KPI values fall within interval no. 1 of Table 1, indicating that, in this state, the building does not meet fire safety objectives, because the KPI threshold is not met at fifty-six cells on the ground floor and nine cells on the third floor. Additionally, some points fall within interval no. 2 of Table 1, which means that, although those areas are considered safe for occupants, the safety margin is limited, and there is room for improvement. These results provide a basic validation of the current design,

highlighting specific areas where the building fails to meet fire safety standards.

#### Validation of the code-compliant building design

Based on the results obtained for the building in its first scenario, changes were made to ensure compliance with fire safety regulations. Specifically, fire prevention measures outlined in the Italian fire safety code were implemented, and code-compliant solutions were applied. These solutions included a combination of active, passive, and organisational measures designed to address the deficiencies identified in the original design. Following the implementation of code-compliant solutions, the ground floor was subdivided into three fire compartments. These compartments are shown in Figure 5-a, where fire compartment 1 is marked in red, fire compartment 2 in blue, and fire compartment 3 in green. Additionally, the internal layout of the offices was modified to increase the corridor's width serving the main egress route. Four emergency exits were added, too. On the third floor, four

external emergency staircases were introduced, and the internal office layout was adjusted to extend the corridor corresponding to the main escape route and to widen the two existing internal staircases.

The updated design (i.e., second validation scenario) was validated using the same methodology described for the first scenario. Difference maps imported into Revit™ are depicted in Figure 5-a, which represents the difference map displayed in the Revit™ interface for the ground floor. Similarly, the difference map imported into Revit™ for the third floor is shown in Figure 5-b, which was treated as a single fire compartment. The results showed a marked improvement in terms of KPI values, since all cells in the building are green and meet the KPI threshold. The results are also shown in Table 1, where it can be seen that all cells have a wide safety margin (interval no. 3), except for one on the ground floor and two on the third floor that fall within the interval no. 2.

### **Validation of the building design with a performance-based approach**

Finally, the methodology proposed in this paper was applied to validate design scenarios developed with alternative solutions, thus following a performance-based approach. Based on the results obtained following the implementation of code-compliant solutions, as reported in the ‘Validation of the code-compliant building design’ section, KPI values in the interval no. 3 at most points in the building was achieved. This suggests that some modifications made to the building may be oversized.

For this reason, on the ground floor two emergency exits only were added, without changing the internal layout or organizing that floor into three fire compartments, as initially suggested by the code-compliant solutions. The application of the proposed methodology showed that the revised design complies with fire safety objectives.

Similarly, the code-compliant solutions proposed for the third floor added four external emergency staircases, modified the internal office layout to extend the main escape route corridor, and enlarged the two existing internal stairwells. However, the application of the performance-based design demonstrated that the addition of just two external emergency staircases was sufficient to meet fire safety requirements. These were located so as to ensure efficient evacuation, avoiding the need for internal layout modifications.

In this case, the building maps related to this scenario are not included; however, Table 1 shows that the KPI value is met at all evaluated points. In addition, it can be seen from Table 1 that, although minor modifications were made to the building, resulting in reduced times and costs, a wide safety margin (interval no. 3) has been achieved in almost all cells, except for one on the ground floor and two on the third floor, which fall within interval no. 2, likewise for the second validation scenario. These cells, however, still meet the fire safety objectives set.

### **Discussion**

The results presented in the previous sections showcased the effectiveness of the proposed methodology in assessing whether a building meets fire safety objectives

in terms of occupant safety. If the KPI threshold is not met at certain points in the building, these are identified as critical, i.e., unsafe for occupants, enabling designers to implement targeted and considerate changes. Concerning the current state of the building (first validation scenario), where fire prevention measures had not been implemented, the methodology determined that both the ground floor and the third floor failed to comply with fire safety requirements because, as shown in Table 1, there are some cells that fall in interval no. 1 of KPI categories. Then, compliant solutions provided by the Italian fire safety regulations were applied in the next scenario. These solutions entailed a number of changes on both the ground and third floors. The methodology confirmed the compliance of both floors, assessing a significant safety margin for occupants, too, as reflected in the improvement of KPI values, moving from interval no. 1 to interval no. 3. Finally, once critical zones had been identified, targeted changes were made to both the ground and third floors with respect to the first scenario, involving alternative design solutions. In this case as well, all cells meet the KPI threshold because they fall within interval no. 2 and no. 3 of Table 1. The application of the methodology to the case study demonstrated its effectiveness in validating fire safety designs and also highlighted the advantages of the performance approach over the prescriptive approach in providing targeted and customised solutions.

### **Conclusions**

This research investigates the technical feasibility of a BIM-based framework that integrates fire dynamics and evacuation simulations to validate building fire safety design. By leveraging visual tools and a quantitative KPI (safety margin), the framework provides a transparent and immediate assessment of occupant safety, enabling authorities and stakeholders to make informed decisions. Unlike traditional approaches that primarily provide a global evaluation of evacuation routes, the proposed method identifies specific areas where critical conditions apply, such as areas where the KPI threshold is not met, enabling targeted design adjustments. This approach ensures that safety objectives are met while fostering collaboration in a unified BIM environment. The application of the methodology to a pilot case study demonstrated its ability to identify design shortcomings and optimise safety strategies, ultimately ensuring compliance with fire safety objectives. This approach not only enhances the reliability of fire safety designs but also supports a performance-based approach that prioritises tailored solutions over prescriptive measures. Additionally, integrating simulation results into the BIM environment fosters a more transparent and collaborative decision-making process.

The case study demonstrates the applicability of the method but also presents some limitations, including:

- the methodology has been tested on a single case study only,
- the methodology has been applied to fire compartment on a single floor, without considering interactions with stairwells,

- the loop was developed around one specific type of BIM authoring tool,
- the entire process is not fully automated; only individual steps are automated, while data transfer between steps remains manual.

Based on these limitations, possible future developments include:

- application to multiple case studies: involving additional case studies and expert evaluations to assess its robustness and generalizability,
- integration of vertical interactions: extending the analysis to consider fire compartmentation across multiple floors, including stairwells and vertical circulation areas,
- development of an openBIM framework,
- full automation of the process: developing automated workflows to streamline data transfer between different steps, reducing manual intervention and improving efficiency,
- integration of additional KPIs.

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