2024 European Conference on Computing in Construction
Chania, Crete, Greece
July 15-17, 2024

FIRE SAFETY DESIGN OF BUILDINGS: A DECISION SUPPORT FRAMEWORK TO ASSESS THE SAFETY OF OCCUPANTS

Alessandro Carbonari, Massimo Lemma, Martina Tarsi
Polytechnic University of Marche, Department of Civil and Building Engineering and Architecture
60131, Ancona, Italy

Abstract

At the design phase, designers must investigate what design solution represents the best trade-off among a set of simulated fire scenarios. This choice requires a quantitative assessment, embracing the concept of performance-based design. This task can be facilitated using key performance indicators (KPIs). A KPI assessing life safety in the event of a fire is tested in this paper. Also, a framework to facilitate the mapping of KPI values through a graphical visualisation superimposed on the BIM model will be showcased. As a results, the life safety performance assessment is performed at any points of the building layout.

Introduction

The process of fire safety design of buildings entails the assessment of a variety of fire scenarios chosen among the most severe events that could reasonably occur. Out of all the solutions assessed in the various fire scenarios, that one which represents the best trade-off for the specific case will be selected. To this purpose, the adoption of quantitative assessment of the effects of fire on life safety related to the assumed design solutions would help make a grounded, non-personal decision. Quantitative assessment is permissible within the performance-based approach. This paper adopts this approach and tries to go even beyond the current concept of this method, which usually assumes that one scenario at a time is evaluated. Indeed, individual design solutions are evaluated in terms of whether or not they exceed performance thresholds, i.e., the quantitative translation of fire safety objectives. Whereas the approach proposed in this paper wishes to supply the designer with a quick and easy to handle method for choosing the best design solution for the specific case under scrutiny. The safety for occupants will be assessed at every point in the building. To this purpose, the building plan was discretized by creating a square mesh grid. This approach facilitates the comparison among alternative design solutions by making a spatial evaluation of life safety performances in case of fire. In order to make this process effective, one or more KPIs could be identified, not only to check whether a solution meets required design specifications, but also provides feedback about the tested design solution.

Therefore, the aim of this paper is to develop a framework, compatible with a BIM environment, capable of implementing performance-based procedures to assess the degree to which fire safety objectives are being met, in terms of life safety of occupants, through the use of a KPI. The KPI, in addition to assessing any design solutions, must supply a clear and immediate representation of safety conditions levels for occupants. Technically, a graphical display of the KPI has been worked out, taking advantage of the BIM-based design environment. Thanks to the approach proposed in this paper, not only do we display the results of simulations in the BIM environment, rather ASET and RSET values are combined and processed to check the positions where the KPI fails to be verified. It suggests what areas in a building are critical and what countermeasures can be adopted to improve life safety in the event of a fire. This approach enables a building-wide assessment and allows designers to compare an increasing number of design solutions until reaching a decision about the best one for the type of building under consideration. An analysis of the overall framework and workflow is performed to leverage the BIM environment as the preferred collaborative environment.

Literature review

Fire engineering has undergone significant innovations in the latest years, even introducing performance-based approaches. These approaches have proven particularly effective for those scenarios where traditional prescriptive design techniques are not sensibly applicable. Specifically in complex buildings and in buildings that combine different uses, fire safety engineering (FSE) may be the only practical way to achieve a satisfactory standard of fire safety (Fire Protection Association, 2008). Fire engineering has played a pivotal role in liberating building design, allowing for greater architectural flexibility while maintaining high levels of safety (Wilkinson et al., 2013). The safety of occupants in case of fire in buildings is one of the most crucial aspects of FSE (Kong et al., 2013). This is complex due to the high complexity of fire dynamics and the variability of human behaviour. As reported in the Italian fire regulation (D.M. 03/08/2015, 2015), the criteria underlying the performance-based approach for assessing life safety is ASET > RSET, that is occupants can feel safe if the time available to a safe escape (ASET) is greater than the time required to a safe escape (RSET). The difference between the two values is called ‘safety margin’. However, this concept has never evolved over time and has not adapted to developments in numerical evaluations (Schröder et al., 2020). Thus, mainly macroscopic assessments have been provided, evaluating only selected points in the building, and lacking a comprehensive view of the safety of occupants. Some methods for a more specific assessment have been proposed. For example, a system proposes expressing tenability conditions and egress accessibility of areas of the building (Poon, 2014). This introduces the concept of available safe utility time (ASUT) that must be longer than the required safe utility time (RSUT), where ASUT represents the time whereby an area is safe to use and RSUT indicates the time for the last person to safely use the area for egress. Another approach evaluates the safety level of egress routes and compartments (Mirahadi et al., 2019). It showed blocked routes, determined the safest egress route from each compartment, and identified critical fire initiation locations. In addition, for an even increasing number of details, a visual representation to depict safety conditions across the entire space was introduced (Schröder et al., 2020). Contrary to earlier evaluations focused on particular areas, this methodology measured safety thresholds comprehensively. Consequently, they produced maps concerning ASET and RSET, and the difference map was derived by subtracting RSET from ASET, effectively displaying the safety margin in the illustrative case of one room. The process of establishing ASET and RSET at each discrete point on the maps aim to move beyond macroscopic representation in favour of a dynamic approach supported by advanced simulation models.

Another critical aspect in the application of FSE concerns the definition of fire scenarios and the choice of design fire scenarios for building structures (Del Prete et al., 2016). The number of possible fire scenarios is typically huge and can hardly be analysed singularly. Therefore, it becomes critical that those design fire scenarios that best represent the most severe cases for the structure are chosen. The US fire regulations NFPA 101 (National Fire Protection Association, 2017) provide us with eight predefined starting design fire scenarios on which to set specific scenarios for different activities. Scenarios selected as design fire scenarios should include but not be limited to those eight predefined. However, they are an excellent starting point on which to develop multiple scenarios for the specific activities.

The performance approach can be facilitated by BIM's ability to generate and return structured information. Fire safety engineers have been slower to adopt BIM as compared to other disciplines (Malagnino et al., 2022). Several research focus on the integration of BIM and fire prevention simulation tools (Wang et al., 2015; Sun and Turkan, 2020). The great limitation of one-way exchange between BIM and FSE tools was also identified. An example to overcome this limitation concerns the development of an open-source framework called 'Evac4BIM' to facilitate two-way data exchange, with a specific focus on fire evacuation (Yakhou et al., 2023). The authors yield the results of numerical evaluations available in the BIM environment which become accessible to all stakeholders but no graphical representation of the results covering every point of the building was provided in return.

Research questions

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

1. can a BIM-based framework assessing fire safety performances of buildings, in terms of life safety for occupants, be defined and implemented to support the designer during the design phase?
2. can a KPI be defined to assess the safety conditions of occupants and to gives back a clear and immediate visualization in a BIM environment?

Materials and methods

In order to answer the research questions formulated in the previous section, a framework to support the designer's choices during the assessments of life safety in case of fire emergencies was developed. This evaluation was meant to overcome the current approach based on calculating ASET and RSET only at a limited number of locations in a building and working out results that do not represent the consequences of the fire on occupants. Indeed, the current numerical evaluations can tell us whether occupants were able to exit the building or were entrapped, but it does not tell us where in the building they may have been hampered by the effects of fire. Thanks to the approach proposed in this paper, we want to assess the safety of the occupants at all points of the building, discretizing the entire area using a grid. In this way, it will be possible to visualise the points where the occupants may be subject to the effects of fire and the areas that are most dangerous for every different design scenario.

The project workflow for each design fire scenario

A representation of the processes that could be carried out to handle each design fire scenario is depicted in Figure 1.

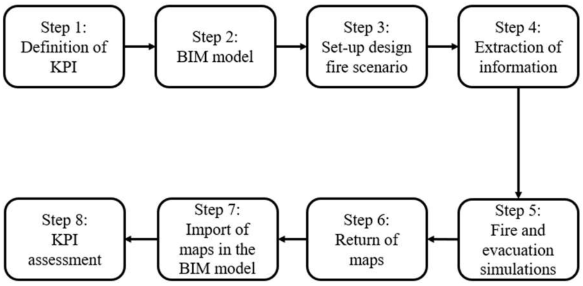

Figure 1 - Conceptual representation of the flow to handle design fire scenarios

By applying all the steps to the design fire scenarios identified, it will be possible to compare the different design solutions and decide which represent the best trade-off. According to the performance-based approach, KPI must be identified as a first step (step no. 1). Having set life safety as the aim of our work and taking the Italian fire regulations (D.M. 03/08/2015) as a reference, the safety margin (t_{safety}), i.e., the difference between ASET and RSET, was chosen as the KPI. As reported in paragraph M.3.2.2 of the reference regulation (D.M.

03/08/2015), this safety margin can either be set as a percentage value, e.g., RSET must double ASET, or as a predefined time limit. The minimum required threshold in the fire regulation is 30 seconds (Eq. 1), which is the threshold set in the test case reported in this paper. Hence, the KPI was set as:

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

The BIM model of the building must be available (step no. 2). In the application proposed in this paper it was created within the authoring software Revit^{TM}. Once the design solution has been assumed for the design fire scenario under consideration (step no. 3) the required information is extracted from the BIM model (step no. 4). The latter will be needed as input to simulation tools (step no. 5). Two different simulation software tools were used for this step. The execution of fire simulations was entrusted to the software FDS (fire dynamics simulator). It is a field model, i.e., it divides the environment into elementary volumes, calculating and outputting data for interested variables in each volume. In the input list for FDS, in addition to geometry and fireplace, even the positions and quantities of the slices are specified as output, because they are necessary for the graphical visualisation of results. The use of this software becomes relevant to our method, as long as the building's space must be discretized to assess the safety of the occupants at every location. Then, the Jülich Pedestrian Simulator (JuPedSim) was used to conduct evacuation simulations. It represents an extensible framework designed for the simulation and analysis of pedestrian movement at the microscopic level (Kemloh Wagoum et al., 2015). Again, the simulation environment was discretized to assess the passage of occupants across every cell of the grid. In order to read the results of the simulations clearly and immediately, three Python scripts have been implemented to obtain a visual representation of them (step no. 6). In practice, maps will be produced containing the ASET and RSET evaluated at each point of the building and, as a result, the safety margin map, i.e., the aforementioned KPI, can be obtained. The maps created are imported into the BIM model of the building to visualise directly within it (step no. 7). At this point, the KPI must be evaluated by the designer (step no. 8). If the KPI is verified and, therefore, the threshold is not exceeded, the proposed solution can be considered and compared with other ones. Otherwise, the designer is required to investigate other solutions on the considered design fire scenario. In this way, the designer can assess the effect of different design solutions on a design fire scenario quantitatively and efficiently.

Extraction of information

Structured information needed to carry out evaluations can be extracted from the BIM model of the building. In particular, it is possible to automatically create the input list for the simulation software tools. Having implemented the building model in Revit^{TM}, Dynamo^{TM} was chosen as the tool for data export. In addition, Dynamo^{TM} was used to read the geometry of a building, to create a mesh of the building area composed of quadrilateral finite elements characterized by a predefined parametric value, and to export the list of mesh points along with their coordinates automatically. In the case study reported in this paper, a mesh element size, to create the maps, as big as 0.50 x 0.50 m was used. This size of the mesh was considered accurate enough to represent the path followed by people and the spread of fire. The authors' opinion is that a smaller mesh size would not add relevant information about hazardous areas in the building.

Return of maps

In order to provide a clear and immediate visualisation of the results of the occupants' life safety assessment, maps have been implemented. For this, we have taken into consideration what was proposed by Schröder et al., 2020. The authors proposed using the Python programming language to create ASET, RSET and difference maps by importing the results of fire and evacuation simulations into scripts. The Python scripts implemented in our paper are an adaptation of those ones made available by Schröder et al., 2020.

ASET maps were worked out for two environmental parameters: the temperature room and the light extinction coefficient. The thresholds for these parameters are 45°C for the temperature field and 0.23 m^{-1} for the light extinction coefficient field, assessed at the height of 2 metres above the floor level (Zehfuβ, 2020). The script to obtain the ASET map converts the slices given as output by the FDS simulation as an ASCII file. The geometry of a building, the mesh size, and the colour scale of the maps are the other input data needed. The resulting ASET map is produced in both 'png' and 'txt' formats. RSET maps were worked out according to the trajectories of the occupants. In our case, ten different trajectories for each hypothesised design solution were assumed for the occupants, arranging them randomly. The script to realise the RSET map is divided into two parts. The first part processes the results of the imported occupant trajectories. These are contained within an 'xml' format file processed from the 'txt' format file provided by the evacuation simulator. The second part of the script creates the global RSET map, interpolating the worst cases from all the earlier ones. The input set consists of the building geometry, the mesh size, and the map colour scale. The output is the RSET map in 'png' and 'txt' formats. Once the final ASET and RSET maps were created, the difference map was completed. The script creates the difference map, which is the map including safety margin values, by subtracting the RSET map from the ASET map. It accepts ASET and RSET maps in 'txt' format as inputs, as well as building geometry, mesh size, colour scale of the map and produces the difference map in 'png' and 'txt' formats.

Import of maps into the BIM environment

Once the maps have been created via Python, these were imported into the BIM environment to be assessed by the designer. To conduct this step, a flow was created in Dynamo^{TM} that imports the text file produced by Python, containing the KPI values. In the BIM model, the discretization mesh was already created, as shown in the section 'Extraction of information'. A geometric element was placed in the centre of each mesh element. Then, a new design parameter was created, named 'T_{safety}' and associated with the above element. The text file created by Python was converted into Excel and imported into the Dynamo^{TM} flow. Next, Dynamo^{TM} nodes were used to transform the excel matrix into a list, so that it could be imported as a list node. The values contained within it were assigned to the 'T_{safety}' parameter according to the order of the list of elements. At this point, each element was assigned a different colour according to the value of the parameter. Values below 30 seconds, i.e., the KPI threshold (Eq. 1), were coloured red, the others green. Some points are left without a numeric value. These have been colored white and they indicate that no occupant has ever walked through that point.

Application on a case study

The feasibility of the proposed framework was assessed through the case of a pilot building. It is a building located in the campus of the Polytechnic University of Marche (Ancona, Italy), which hosts the school of Medicine (Figure 2). It is an 8-floor level building, 7 floors above ground and 1 basement. The building is used for teaching, research, a library, and other services. For the purposes of this paper, only the ground floor of the building has been considered.

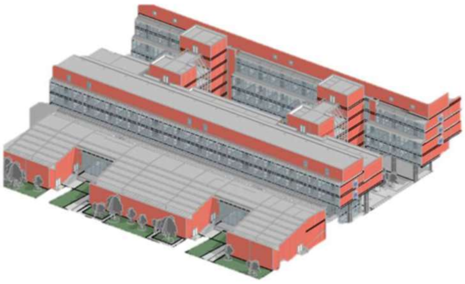

Figure 2 - 3D model of the pilot building

Fire and evacuation scenarios

Fire scenarios represent the most severe but realistic events that can occur while performing activities allowed in the building. These can be very numerous, especially in complex buildings. For the purpose of this paper, the default scenarios contained in the US fire regulations were considered. In fact, NFPA 101 covers a wide range of situations and defines fire scenario in Chapter 5.5.3. The latter provides us with eight starting scenarios on which to develop the most appropriate scenarios based on the specific case. In particular, two out of the eight predefined scenarios listed in NFPA 101 were analysed, namely:

- scenario no. 2, which describes a fire that develops through the burning of a material having an ultrafast growth curve, located along any major egress route. The interior doors at the beginning of the fire are supposed to be open. This scenario must address the simulation of the fire paying particular concern to people's egress problems. In fact, due to the hypothetical fire having a rapid spread, special attention should be paid to reducing the number of available egress routes, evaluating the availability and effectiveness of alternative egress systems and the consequences of the fire on the assets;
- scenario no. 6, involves an intense fire as a consequence of the highest possible fire load in normal operations in the building. It refers to the rapid growth in the presence of people.

In fact, designers are expected to test and compare several fire scenarios. They usually assume a first design solution and investigate the obtained performances. Then, changes could be made to the first solution to improve it and new investigations are performed until the verification process is concluded. In this paper, two scenarios have been assumed as relevant, each split into three subsets.

Referring to the scenario no. 2 of the NFPA 101 described above, the fire hearth was positioned along the corridor as this is the main escape route. The corridor serves offices, the library, the cafeteria and seven classrooms for a total capacity of 1040 occupants. The occupants inside the seven classrooms have also emergency exits directly into the classrooms. This set of scenarios is called 'scenario LS1'. Taking into consideration the scenario no. 3 of the NFPA 101, the fireplace was positioned inside the library. This set of scenarios is called 'scenario LS2'. In Figure 3 the fire compartment and the library are marked in green and blue, respectively. Each fire scenario was combined with ten different occupant evacuation trajectories.

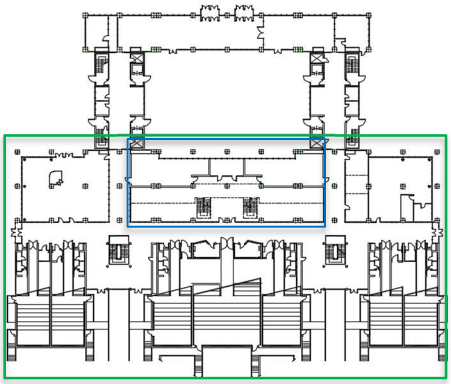

Figure 3 - Ground floor of the pilot building

Scenario LS1

For this first scenario, three alternatives were analysed. In the first case, called 'LS1_1 scenario', two emergency exits were placed along the corridor for the safe exit of the occupants. From the fire simulation, the values of the environmental parameters specified in the input list are obtained. In addition, it is possible to display them graphically with the set slices. An example is provided in Figure 4, displaying a slice taken from the FDS tool called

‘Smokeview’, concerning the light extinction coefficient reached at the end of the simulation (300 seconds) for the ‘LS1_1 scenario’.

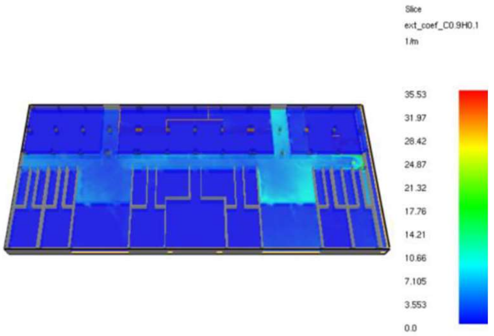

Figure 4 - Slices generated by FDS about light extinction coefficient for the ‘LS1_1 scenario’

Regarding the evacuation simulation, the times required by the occupants are shown in Table 1 for the ten different trajectories (denoted by the term ‘Seed_ID’ from the number 1254 to 1263). In the second alternative (‘LS1_2 scenario’), two emergency exits were added along the corridor. The effects of the fire remain the same as in the ‘LS1_1 scenario’, while the times required by the occupants change and are shown in Table 1. In the last alternative ‘LS1_3 scenario’, two more doors were added along the corridor for a total of six emergency exits. Again, only the RSET values change (Table 1).

Table 1 - Required safe escape time as a result of the JuPedSim simulation

	Required safe escape time [s]					
Seed_ID	LS1_1	LS1_2	LS1_3	LS2_1	LS2_2	LS2_3
1254	67.88	67.13	67.13	67.13	65.50	65.50
1255	67.63	66.50	66.50	66.50	66.62	66.62
1256	69.25	67.38	67.38	67.38	67.38	67.38
1257	68.50	68.50	68.54	68.54	68.54	68.54
1258	70.50	68.75	68.80	68.80	68.75	68.75
1259	67.38	69.00	69.00	69.00	69.00	69.00
1260	69.38	66.88	66.91	66.91	66.90	66.90
1261	68.50	68.75	68.87	68.87	68.87	68.87
1262	68.25	68.25	68.30	68.30	68.30	68.30
1263	64.63	65.63	65.72	65.72	65.73	65.73

Scenario LS2

In the ‘LS2 scenario’, the fire was placed inside the library, where the greatest fire load is expected. A first analysis assumed 38 occupants inside the library, which is divided into a reading room and the book depository (‘LS2_1 scenario’). Also in this case, ten different simulations were conducted for the trajectories of the occupants and the times are shown in Table 1. Subsequently, an increase in the number of occupants, from 38 to 88, within the library and the elimination of subdivisions was assumed. This scenario was called ‘LS2_2’. In this case, the fire simulation was run again because the building layout was changed and, as a result, the fire will spread differently. The third alternative (‘LS2_3 scenario’) differs from ‘scenario LS2_2’ only in that a library wall is replaced by a glass wall. The RSET values are contained in Table 1, but they are the same as in the ‘LS2_2 scenario’, while the fire simulation is re-run.

Maps generation

Once the simulations for the fire and evacuation have been carried out, the results are imported into the scripts developed with Python. The latter gives as output the graphical representations of the results in the form of a map. In particular, the values of ASET, RSET and the differences between the two are calculated. In this way, we can get a graphical representation of the safety margin, i.e., our KPI.

Scenario LS1

The ASET maps obtained for temperature and light extinction coefficient are shown in Figure 5-a and Figure 5-b, respectively. Two maps are shown because there are two environmental parameters to be assessed. The final ASET map is the one with the highest risk, i.e., with the least available time. The RSET map, on the other hand, can be seen in Figure 5-c. Finally, Figure 5-d shows the difference map obtained by subtracting RSET values from ASET values. In this map, therefore, the KPI is shown. When the value falls below the threshold of 30 seconds (Eq. 1) indicates that the point is not safe for the occupants. For the second and the third alternative of the ‘LS1 scenario’, since the position of the fire hearth and the layout of the building remain unchanged, the maps of ASET will be the same as those already shown in Figure 5-a and Figure 5-b. The new RSET maps have been produced and, as a result, difference maps were shown in Figure 6-a for the ‘LS1_2 scenario’ and Figure 6-b for the ‘LS1_3 scenario’.

Scenario LS2

For the ‘LS2 scenario’, the difference maps are shown directly in Figure 7-a (scenario LS2_1), Figure 7-b (scenario LS2_2) and Figure 7-c (scenario LS2_3).

Visualization of maps in a BIM environment

Once the maps have been created via Python, these were imported into the BIM environment for a seamless evaluation by designers. To conduct this process, the Dynamo^{TM} script created as described in ‘Import of maps into the BIM environment’ section was used. In this way, the designer can visualise the results directly within the BIM model and all stakeholders can collaborate in one environment. Even those who are not familiar with fire simulation tools can visualise simulation results in the BIM environment. For the sake of clarity, the Revit^{TM} screenshots including the imported difference maps were shown in the following. For representative purposes, only the maps imported into Revit^{TM} relating to the ‘LS1_1 scenario’ in Figure 8-a, ‘LS1_2 scenario’ in Figure 8-b and ‘LS1_3 scenario’ in Figure 8-c have been shown.

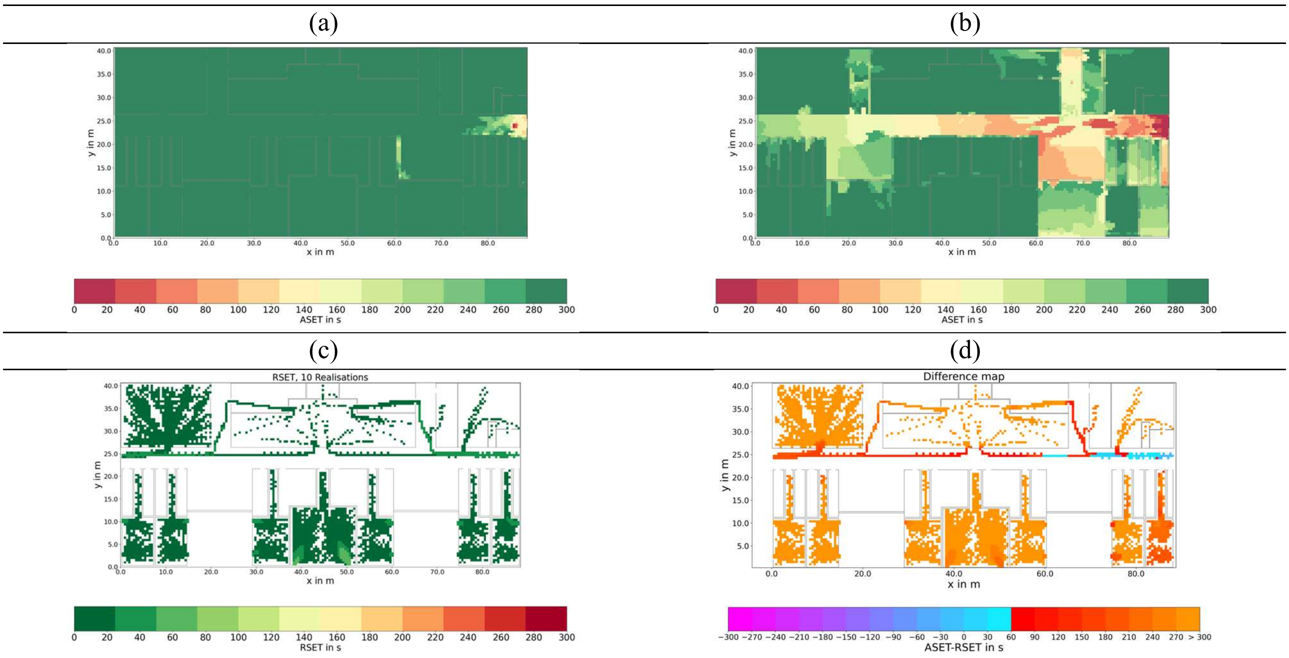

Figure 5 - ASET, RSET and difference maps for the 'LS1_1 scenario' (output of Python)

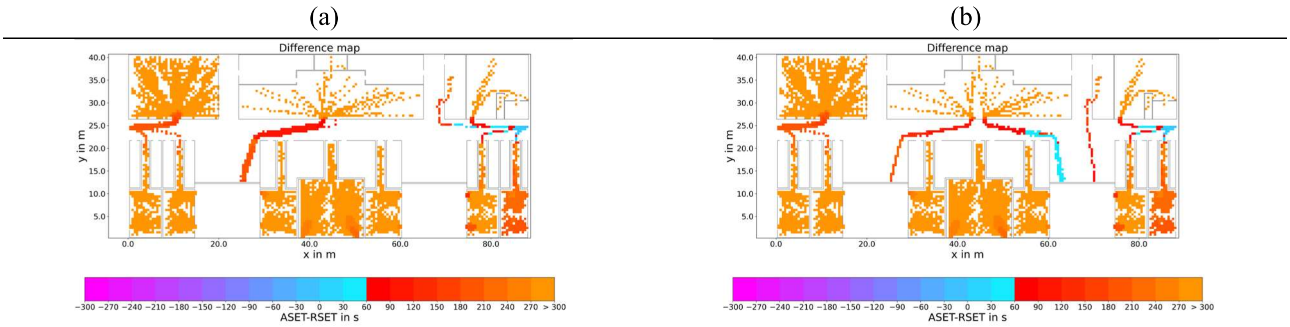

Figure 6 - Difference maps for the 'LS1_2 scenario' and 'LS1_3 scenario' (output of Python)

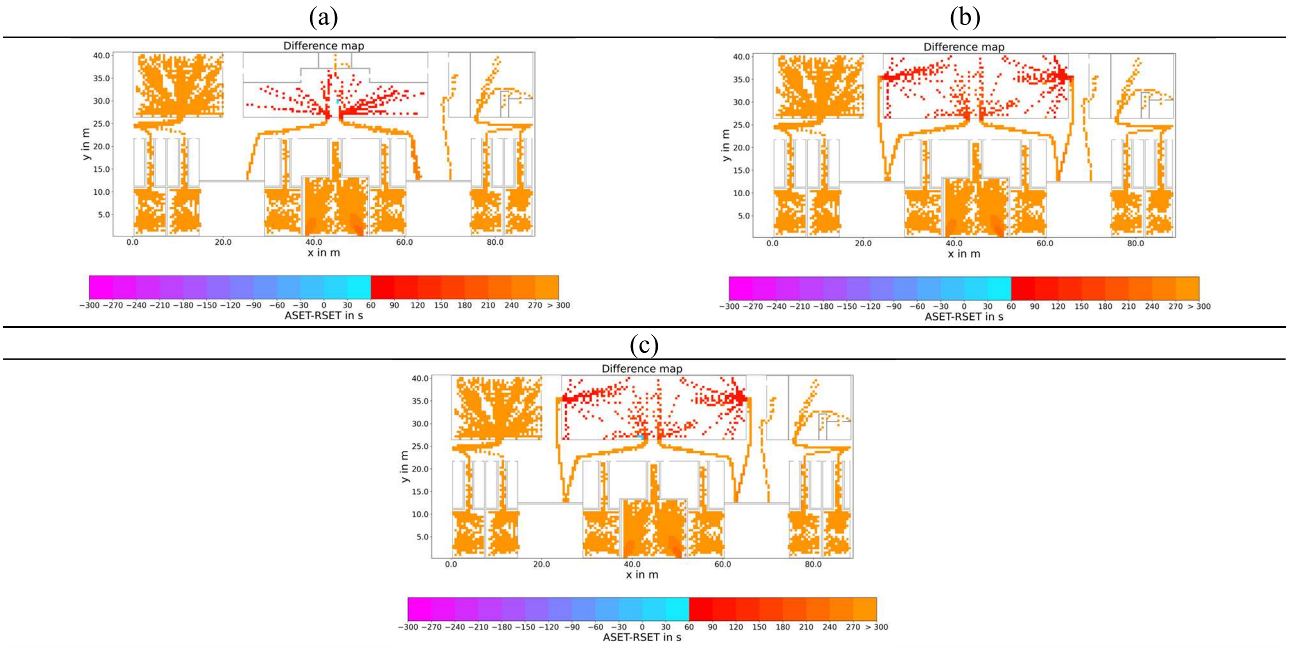

Figure 7 - Difference maps for the 'LS2 scenario' (output of Python)

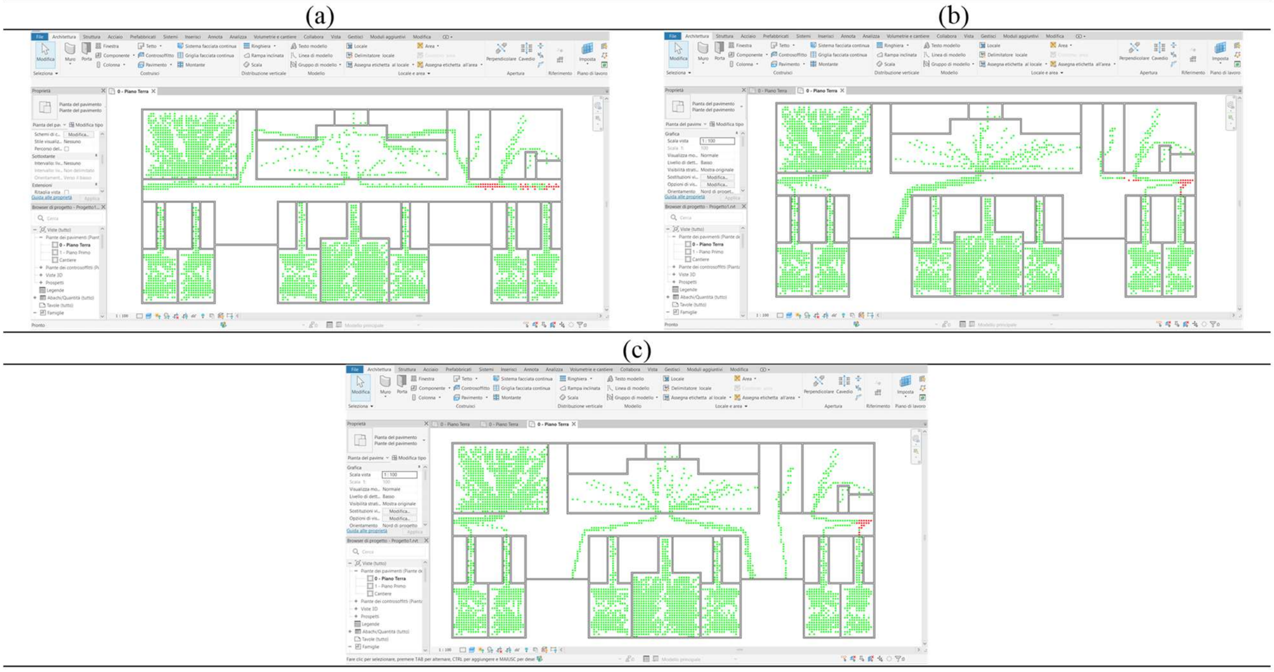
(a) (b) (c)

Figure 8 - Difference map for the fire compartment for the 'LS1_scenario' once it has been imported into Revit^{TM}

The pictures show the geometric elements inserted in the centre of each grid mesh. These take on a green colour when the value of the imported KPI associated with the 'T_{safety}' parameter is greater than 30 seconds. The red colour corresponds to a KPI of less than 30 seconds. When no value is associated with the parameter, it means that no occupant has passed through that grid mesh, so there is no RSET value and, so, no safety margin can be calculated. For this reason, these points have been left white.

As a result, Revit^{TM} was able to integrate the KPI information and display the points where safety conditions could not be verified.

Discussion

Thanks to the results reported in the earlier section, it can be seen that the methodology introduced gives us a clear and immediate view of the KPI values and, therefore, of the level of safety of the occupants inside the building in case of fire. Concerning the 'LS1 scenario', two emergency exits are not sufficient for a safe escape of the occupants. Indeed, in Figure 8-a includes forty-six points are coloured in red along the corridor. This means that the KPI threshold has been exceeded at those points and the occupants passing through that area are not safe. Consequently, the designer could think of adding two emergency exits along that corridor. The result is depicted in Figure 8-b and shows that conditions have been improved, despite twenty-three points close to the fire hearth still remained below the required safety level. To overcome this problem, the designer could choose to add two additional emergency exits, for a total of six. Figure 8-c shows that the life safety level has increased further, even if some but smaller areas are still unsafe, due to the position of the exits close to the fire hearth, and eighteen points are still red-coloured. This gives a hint to the designer about the number of emergency exits required and their location for a safe escape of the occupants. Comparing Figures 5-d, 6-a, and 6-b with Figures 8-a, 8-b, and 8-c, respectively, we can see the correspondence between the maps obtained through Python and the representation obtained once the maps are imported into the BIM model.

In the 'LS2 scenario', on the other hand, the maps obtained with Python show that the safety conditions are maintained even when increasing from 38 occupants inside the library (Figure 7-a), where only one point is unsafe, to 88 occupants (Figure 7-b), while leaving the number of exits unchanged. In the third hypothesis (Figure 7-c) where a glass wall is inserted, four unsafe points are seen close to the fire hearth, but there is no glass breakage due to the thermal action of the fire. This shows the designer that the fire that occurs inside the library does not spread rapidly along the escape routes. In the same way as the 'LS1 scenario', the maps imported into the BIM model were also obtained for the 'LS2 scenario'.

Thanks to the visualisation of the maps directly in the BIM model, a single working environment is created where even non-experts in fire simulation software can visualise the results clearly and immediately. In addition, the designer can compare different design solutions for each design fire scenario based on quantitative results (KPI values) that refer to the entire building. Thus, the safety of the occupants is assessed at every point, visualising the points and areas with critical conditions for them. The latter occurs when the KPI threshold is exceeded, that is in case the consequences of combustion result in environmental conditions that reduce the time available for occupants to get to a safe place.

Conclusions

In this paper, an approach has been proposed for assessing occupant safety in case of fire during the building design phase. This approach aims to go beyond the current concept of ASET/RSET evaluated only at specific points. Furthermore, current assessments do not supply insights into the zones or points where conditions become critical for occupants but instead offer a global evaluation of the safety of evacuation routes. The graphical visualisation of the KPI, in the form of maps, enables designers to immediately pinpoint those locations in the building that are critical for the occupants. This assessment was carried out by spatially discretizing the entire building, thus considering every point in the layout. Furthermore, thanks to the visualisation approach, the designer can quantitatively assess the assumed design solutions over numerous design fire scenarios. The KPI initially chosen to monitor fire safety objectives was mapped inside a BIM environment, importing maps created through Python. The KPI enriches the design model, and the entire method provides support to the designer when looking for the best trade-off, which is meant to implement the approach of performance-based design. In this way, the designer's decisions can be made quickly in a complex environment and a single collaboration environment can be created by importing the results of fire assessments directly into the BIM environment. One possible recommendation for future research involves identifying additional KPIs related to the other domains of FSE, such as structural safety. Another interesting aspect would be to implement the whole procedure within an open software and computing environment.

References

Del Prete, I., Cefarelli, G., Nigro, E., 2016. Application of criteria for selecting fire scenarios for structures within fire safety engineering approach. J. Build. Eng. 8, 208–217. https://doi.org/10.1016/j.jobe.2016.10.010

D.M. 03/08/2015, 2015. Codice di Prevenzione Incendi. https://www.vigilfuoco.it/aspx/page.aspx?IdPage=10259

Fire Protection Association, 2008. Approved Document B (Fire safety) Volume 2. https://assets.publishing.service.gov.uk/media/639ae876e90e0721839ea637/Approved_Document_B__fire_safety__volume_2_-_Buildings_other_than_dwellings__2019_edition_incorporating_2020_and_2022_amendments. pdf

Kemloh Wagoum, A.U., Chraibi, M., Zhang, J., Lämmel, G., 2015. JuPedSim: an open framework for simulating and analyzing the dynamics of pedestrians. 3rd Conf. Transp. Res. Group India 3rd CTRG.https://www.researchgate.net/publication/28937 7829

Kong, D., Lu, S., Frantzich, H., Lo, S.M., 2013. A method for linking safety factor to the target probability of failure in fire safety engineering. J. Civ. Eng. Manag. 19, S212–S221. https://doi.org/10.3846/13923730.2013.802718

Malagnino, A., Corallo, A., Lazoi, M., Zavarise, G., 2022. The Digital Transformation in Fire Safety Engineering over the Past Decade Through Building Information Modelling: A Review. Fire Technol. 58, 3317–3351. https://doi.org/10.1007/s10694-022-01313-3

Mirahadi, F., McCabe, B., Shahi, A., 2019. IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling. Autom. Constr. 101, 1– 16. https://doi.org/10.1016/j.autcon.2019.01.007

National Fire Protection Association, 2017. NFPA 101 - Life Safety Code. https://www.nfpa.org/codes-and-standards/1/0/1/nfpa-101

Poon, S.L., 2014. A Dynamic Approach to ASET/RSET Assessment in Performance based Design. Procedia Eng., 2013 International Conference on Performance-based Fire and Fire Protection Engineering, Wuhan (ICPFFPE 2013) 71, 173–181.https://doi.org/10.1016/j.proeng.2014.04.025

Schröder, B., Arnold, L., Seyfried, A., 2020. A maprepresentation of the ASET-RSET concept. Fire Saf. J. 115, 103154. https://doi.org/10.1016/j.firesaf.2020.103154

Sun, Q., Turkan, Y., 2020. A BIM-based simulation framework for fire safety management and investigation of the critical factors affecting human evacuation performance. Adv. Eng. Inform. 44, 101093. https://doi.org/10.1016/j.aei.2020.101093

Wang, S.-H., Wang, W.-C., Wang, K.-C., Shih, S.-Y., 2015. Applying building information modeling to support fire safety management. Autom. Constr. 59, 158–167. https://doi.org/10.1016/j.autcon.2015.02.001

Wilkinson, P., Glockling, J., Bouchlaghem, D., Ruikar, K., 2013. Using business impact analyses to enhance resilient fire engineering building design. Archit. Eng. Des. Manag. 9, 229–249. https://doi.org/10.1080/17452007.2012.738043

Yakhou, N., Thompson, P., Siddiqui, A., Abualdenien, J., Ronchi, E., 2023. The integration of building information modelling and fire evacuation models. J. Build. Eng. 63, 105557. https://doi.org/10.1016/j.jobe.2022.105557

Zehfuβ, J., 2020. Leitfaden Ingenieurmethoden des Brandschutzes. https://www.vfdb.de/media/doc/technischeberichte/TB_04_01_Leitfaden_IngMethoden_4Auflage_2020-03-26.pdf