Fire resistance assessment of building structures: performance-based approach in a BIM environment

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Abstract
Designers must investigate solutions that represent the best trade-off between the results of different design options. This entails a quantitative assessment of safety levels. Key Performance Indicators (KPIs) facilitate this assessment by providing a clear and concise visualization of safety levels in buildings. This paper concerns the fire safety design of buildings, focusing on the fire resistance of structural components. Technically, we developed a framework, integrated in a BIM environment, to implement performance-based assessments of structural elements, ensuring that fire safety objectives are met. Fire safety performances are tracked by means of a KPI identified for its representativeness. The visualization of the KPI in BIM models highlights critical elements and enables a quick refinement of design solutions. The outcome is a BIM information-rich model handed over to facility managers to track the performances of structural components and implement timely renovation actions during the operational phase of buildings.

Keywords: structural fire resistance, safety in buildings, performance-based approach, design phase, KPIs, BIM

1 Introduction
Basically, the performance of a building as a whole may differ from that of its individual components or sections. The performance of any part of a building, such as a subsystem, element or component may also affect the performance of a building as a whole. The relationship between any part of a building and its whole depends upon its intended or designed role (International Organization for Standardization, 2016). As a consequence, the designer is required to provide the most suitable design solution while considering the specific use of the building. This paper focuses on the design of fire resistance of a building's structural components. This process involves the assessment of a variety of fire scenarios. Among all the solutions evaluated over several fire scenarios, the one that represents the best trade-off must be selected. As suggested by regulations, a performance-based approach should be adopted, enabling a quantitative assessment of the effects of fire on buildings. Therefore, evaluating the fire resistance of individual structural elements, will ensure that the fire safety performances of the entire building are achieved for the intended role.

The aim of this paper is to develop a framework, capable of implementing performance-based procedures, to assess the behaviour of structural elements and the achievement of fire safety objectives in a BIM environment. This quantitative assessment is facilitated by the adoption of Key Performance Indicators (KPIs) and BIM tools. Indeed, KPIs can track building performances throughout the entire lifecycle and can take advantage of BIM to provide support to designers in terms of a comprehensive, clear, and immediate visualization of the safety level of structural elements within buildings. Furthermore, a graphical visualization of KPI values can effectively communicate the fire resistance level of structural components.

Therefore, this paper suggests a methodology and develops tools to answer the following research questions:

1. RQ1: is it possible to define and implement a framework to evaluate the resistance of structural elements of a building in case of fire at the design phase in a BIM environment?
2. RQ2: can a KPI be used to display in a BIM environment a quick and accurate assessment of structural fire resistance levels?

2 State of the art analysis

Previous research concerning fire safety engineering showed that the performance-based approach enables increasingly informed and targeted choices. For instance, it aids in selecting building materials (Giuriola, Andriotto and Grandis, 2015) and accurately predicting fire and smoke development, leading to optimized solutions for fire safety, reduced costs, and minimized social and environmental impacts (Cabova, Blesak and Wald, 2016). Particularly in complex buildings and in buildings that combine different uses, fire safety engineering (FSE) may be the only practical approach to achieve satisfactory fire safety standards (Fire Protection Association, 2008). Fire codes that primarily focus on achieving prescribed fire ratings are based on standard fire tests and have limited relevance to actual fire safety requirements (Memari and Mahmoud, 2018). These prescriptive design approaches often fail to provide sufficient information regarding the performance of structural elements or systems when exposed to elevated temperatures and actual fire actions in general. Moreover, existing structural design provisions do not comprehensively address the uncertainties associated with fire hazards. Hence, the latest research aims not only to quantify the structural reliability for specific performance objectives but also to ensure more cost-effective and safer structural design. The paper by Memari and Mahmoud (2018) elaborates on the development of a new framework for probabilistic performance-based analysis of fire combined with earthquakes.

As far as we move towards high-performance buildings, reinforcement and extension of the role of BIM is getting more and more pivotal to support performance-based design (Jung, Häkkinen and Rekola, 2018). In order to exploit the potential of BIM in fire safety engineering, industry manufacturers need to provide high-quality BIM objects with appropriate Levels of Development (LODs), specific to fire safety. Fire engineers and researchers must cooperate on future advancements, and building owners and managers need to be trained on how to exploit benefits of this technology (Davidson and Gales, 2021). Despite this, in civil and structural engineering information pertaining to the structural safety of buildings and other relevant data are often stored as non-structured documents, such as tables, drawings, and reports (Ciccone, Ciotta and Asprone, 2023). These authors proposed an openBIM approach for the integration of structural information based on the Industry Foundation Classes (IFC) schema, demonstrating an effective workflow for the delivery of information required by building authorities. Their approach aims to improve the integration and exchange of information within a BIM environment to obtain seismic authorisations. One of the biggest challenges concerns the exchange of information from BIM to simulation tools. To effectively represent and share data, one method concerns the development of a Dynamo™ code for a structural analysis tool called 'SteFi' (Beltrani, Giuliani and Karlshøj, 2018). Then, the results of the structural analysis were saved in an output file, which could be imported back into the BIM authoring tools, specifically Revit™, assigning the results into the corresponding fields of the design parameters. Although this framework has the advantage of leading to an informed choice of element sections, reducing construction costs and increasing design quality, it does not allow a graphical and intuitive visualization of the results from structural analysis directly in the BIM environment. Other studies focus on the integration of BIM for the automatic verification of safety conditions in case of fire, such as the 'BIMSCIP' prototype, that assesses structural safety in case of fire according to the standards of the Brazilian Fire Department (Porto *et al.*, 2018); another case of compliance of analysis timber buildings with fire regulations (Kincelova *et al.*, 2020), which applies fire safety in the Canadian context through the creation and execution of a method spanning from code-checking to automated analyses of the results. The limitations of these studies are twofold. In the first case, the verification of the Brazilian structural fire safety code concerns prescriptive regulations, which is less useful than the performance-based approach. The second case is limited to only a few areas of fire protection requirements, with no chance of an extension towards other areas such as the location of active protection systems.

In this paper we claim that a quantitative assessment of performances through KPIs would allow designers and managers to quickly evaluate safety levels. KPIs have become an essential element in assessing performance against various objectives in some engineering areas (Sharp, Ersdal and Galbraith, 2008). For example, their application to offshore facilities, to evaluate the reliability of equipment and safety systems. Another field is energy savings, which improves functionality and reduces maintenance costs in hospitals (Fotovatfard and Heravi, 2021), as well as providing a comprehensive quantification of energy flexibility (Marotta *et al.*, 2021).

From a legislative point of view, in Italy, the reference regulation is Ministerial Decree 3rd August 2015 (Ministerial Decree (D.M.) August 3, 2015, 2015). Fire resistance of structures is one of the fire safety measures mentioned by the Code. In fact, structures must resist for a predefined time under the action of a fire, depending on the intended use, typo of occupants, systems in place, the hazardous substances and other factors. The Code provides compliant solutions based on the building's classification. Alternatively, designers can provide a specific design solution for that building by adopting the performance-based approach. From an international perspective, the National Fire Protection Association (NFPA) in the United States provides comprehensive fire safety standards that are widely recognized and adopted globally. These codes emphasize the importance of a performance-based approach, to achieve required levels of safety.

3 Materials and methods

In order to answer the research questions formulated in Section no. 1, the framework, shown in section 3.1, has been worked out to assess structural elements in buildings. This can support a designer's choices when assessing the structural safety of buildings in the event of a fire, making him able to make quick decisions about what structural frame represents the best design choice. The step-by-step application of this framework is described in sections from no. 3.2 to no. 3.6.

3.1 The technical framework

A representation of the overall framework is depicted in Figure 1. As a result of the framework in Figure 1, several design solutions can be compared and the best trade-off for a building can be picked out. In order to implement the performance-based approach, a KPI should be identified as a first step (step no. 1), as described in detail in the 'Definition of a KPI' section. The main process is divided into two main sections: 'Design BIM model' and 'Fire resistance assessment'. Within

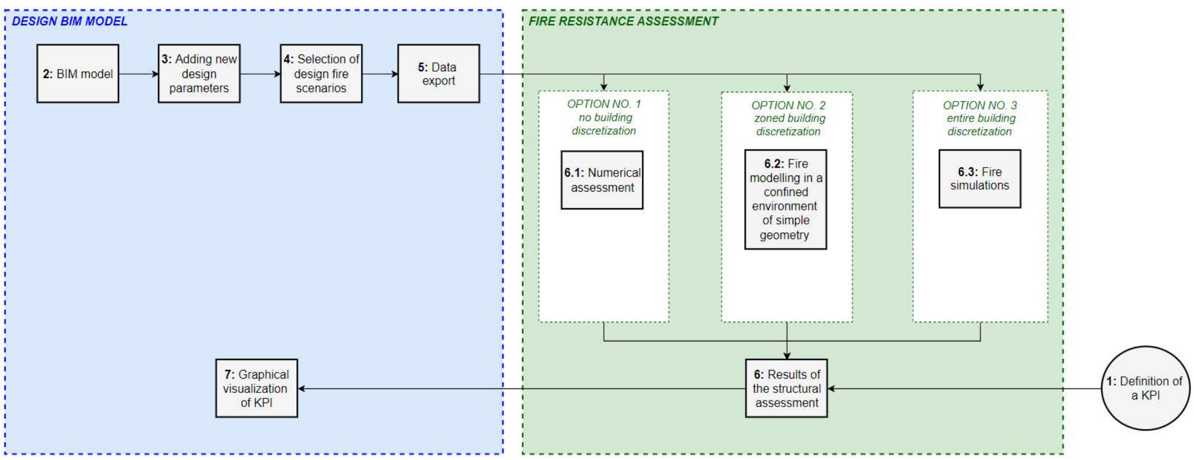

Figure 1. Conceptual representation of the framework to handle any fire scenario

the BIM environment, the model of the building must be implemented. In the application proposed in this paper, it was developed through the authoring software Revit™ (step no. 2), described in Section no. 4. In order to apply the proposed methodology, it is necessary to define and integrate new design parameters into the BIM model (step no. 3). A selection of these parameters will be suggested in the 'Property set' section. The next step requires that the designer selects the most serious fire scenarios that can be expected (step no. 4). Then, each identified scenario will be evaluated in terms of structural assessment. For further structural evaluation, the necessary data were extracted directly from the BIM model of the building (step no. 5). Dynamo™ was used for this step and the process will be described in the 'Data export' section. At this point, the designer proceeds with the fire resistance assessment, for which three alternative procedures can be available. In the case of option no. 1, the building is not discretized, but a uniform temperature is considered. A nominal fire, such as the standard ISO 834 fire curve, was used. This curve represents the average hot gas temperature trend under generalized fire conditions. The trend of the ISO 834 curve will be considered up to a given time moment. Using this fire curve, temperature trends inside the building were calculated (step no. 6.1). For these calculations, EN 1993-1-2:2005 (Eurocode 3, 2005) was taken as the reference standard. The entire calculation procedure provided by Eurocode 3 was implemented within the BIM environment using Dynamo™, a Revit™ plug-in. These procedures will be described in detail in the 'Structural computation' section. The second available option (step no. 6.2) was not implemented in this paper because it is valid for buildings with simple geometry, which is not the case of the pilot used in this study. Finally, option no. 3, involves height and floor plan discretization. Simulation tools can be used for these evaluations, to obtain the fire curve specific to the selected fire scenario, resulting in a natural fire curve. Once the input listing was created, the simulation was started (step no. 6.3). The results obtained from the structural assessment was imported into the BIM environment (step no. 7), as described in the 'Graphical visualization of structural assessment into the BIM environment' section. In this way, structural elements that are critical, because they do not meet the predetermined KPI threshold, can be displayed directly in the BIM model and the designer can compare several design alternatives.

3.2 Definition of a KPI

KPIs are the means to monitor whether fire safety objectives are still met whenever changes are made in a building or in a building design. Having set fire structural safety as the aim of our work, fire resistance, expressed in units of time, was chosen as the KPI. The KPI was selected among the parameters used for structural computations, as it was sufficiently sensitive to changes and representative of safety conditions. In particular, the final verification involved comparing the fire resistance time of the element relative to the critical temperature identified along the temperature trend in components subjected to a fire curve, against the fire resistance time of the element determined based on the building use. By identifying the critical temperature along the air-gas mixture temperature trend over time inside the building, the maximum fire resistance time can be obtained. Comparing this time with the fire resistance time related to the building's fire load provided our KPI value. If the time relative to the critical temperature identified along the temperature trend in the building was greater than the time relative to the use of a building, their difference (that is our KPI value) was higher than zero, indicating that the verification was satisfied. Otherwise, the verification was not fulfilled.

3.3 Property set

The proposed method involved adding a new property set associated with the building's BIM model. Specifically, design parameters associated with Revit™ families were added. These parameters, which were necessary for structural evaluations, were added to the families of columns and beams that make up the structural frame. The added parameters served as input for the structural computations, including the calculation of the critical temperature for steel columns and beams, as well as the temperature reached by these structural elements when subjected to a fire curve. The added parameters (listed in Table 1) served as inputs for the

Table 1. Design parameters added to the beams and columns of the building BIM model

Beams		Columns	
G1	VOLUMIC_MASS	G1	ELEMENT_SURFACE_EMISSIVITY
G2	ELEMENT_SURFACE_EMISSIVITY	G2	GAS_EMISSIVITY
Q	GAS_EMISSIVITY	Q	CONVECTION_HEAT_EXCHANGE
PSI	CONVECTION_HEAT_EXCHANGE	PSI	CHARACTERISTIC_YIELD_STRESS
AREA	WX_PLASTIC	AREA	STEEL_ELASTIC_MODULUS
SPECIFIC_HEAT	CHARACTERISTIC_YIELD_STRESS	SPECIFIC_HEAT	INERTIA_MOMENT_X
		VOLUMIC_MASS	INERTIA_MOMENT_Y
			INFLUENT_AREA

structural computation step illustrated in Figure 1. Four more parameters, named 'FIRE_LOAD,' 'REI,' 'EUROCODE_3,' and 'FDS,' were added to accommodate the outcomes of the computation. The 'FIRE_LOAD' parameter was associated with the fire load based on the use of the room where the structural elements were located; the 'REI' parameter was associated with the relative fire resistance time based on the fire load according to the Italian fire prevention code (D.M. 03/08/2015); and 'EUROCODE_3' and 'FDS' parameters were assigned the value '1' if the verification, based on the KPI value, was satisfied, whereas the value '0' if that verification was not satisfied, as determined by the Dynamo™ flow.

3.4 Data export

Depending on the option chosen for structural assessments, different data were exported from the BIM model. In order to carry out fire simulations, FDS (Fire Dynamics Simulator) software was chosen. It is a field model and was developed by the Fire Research Division at the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST). It requires as input a listing containing building geometry, component materials with their properties, fire characteristics, and details of temperature sensor placement. FDS operates based on a single ASCII text file (listing), which is organized into 'name lists,' providing all necessary information to describe the fire scenario. Parameters are specified within this input file using records formatted from the 'name list.' The input listing was automatically generated by exporting data from the BIM model through the Revit™ Dynamo™ plug-in. Initially, the coordinates of the building components were exported, followed by associating materials with the components along with their thermal properties. Finally, the coordinates of the temperature sensors placed for detection were exported. A Python script, integrated into the Dynamo™ flow, was employed to organize and format the data extracted from the BIM model into the appropriate 'name list' format.

3.5 Structural computation

Eurocode 3, Part 1-2 (Eurocode 3, 2005), which deals with the structural design in case of fire of steel structures, was taken as a reference for structural computations (option no. 1). For the purpose of this paper, the simplified calculation model provided in paragraph 4.2 of this standard was adopted. Specifically, verification was performed in the temperature domain using the critical temperature method (paragraph 4.2.4 of Eurocode 3). The critical temperature, equation (1), is given by:

$$\theta_{a,cr} = 39.19 \; \ln\left[\frac{1}{0.9674\;{\mu_0}^{3,833}} - 1\right] + 482 \qquad (1)$$

and depends on μ_0, which is the ratio of design action to design strength. Subsequently, the temperature development in the structural steel element was calculated. To determine this trend, the equation defined in Eurocode 3, Part 1-2, paragraph 4.2.5 was solved incrementally. Two different equations apply: the first one to be used for unprotected steel structures (paragraph 4.2.5.1) and another one to be used for protected steel structures (paragraph 4.2.5.2). The assumption underlying the computation is to consider the temperature uniformly equivalent in the sections considered. For the evaluations made in this paper, building components were assumed as unprotected, hence only the formula in paragraph 4.2.5.1 of Eurocode 3 applies (equation 2):

$$\Delta\theta_{a,t} = k_{sh}\frac{A_m/V}{c_a\rho_a}\dot{h}_{net,d}\Delta t \tag{2}$$

Input variables include the geometric characteristic of the element (k_{sh}, A_m, and V), the intrinsic properties of the material (c_a and ρ_a) and the heat flow where the fire curve was applied, that is, the ISO 834 fire curve for the option no. 1 and the fire curve achieved by the simulation tool for option no. 3.

These calculations were carried out within the BIM model. Specifically, three different Dynamo™ flows were implemented. The first one identified the minimum fire resistance class of the elements based on the building use. This class indicates the time span (measured in minutes) for which the element is capable of maintaining its load-bearing capacity. Figure 2-a shows the pseudocode of the realized Dynamo™ flow. Within this flow, a Python node was utilized, where the script to determine the fire load, in relation to the use of the building, and its relative fire resistance class was inserted. Through the second flow, the critical temperature and temperature trends in the beams, were estimated using the specific fire curve. The pseudocode for this flow is shown in Figure 2-b. Finally, Figure 2-c shows the pseudocode of the third flow, which was used to determine the critical temperature and temperature trends in the columns.

As for the third option, temperatures were not calculated following the Eurocode 3 procedure, but the temperatures calculated using the FDS simulation tool were imported. FDS generates output files in '.csv' format that contain the temperatures recorded by the sensors placed on structural elements. To import these temperatures into Revit™, the 'csv' files were first converted into Excel format. Subsequently, each temperature trend was associated with its respective structural element. Once again, the fire resistance relative to the critical temperature along the temperature trend obtained from FDS was compared with the fire resistance relative to the fire load. For the sake of clarity, Table 2 shows the information, tools, input, and output involved in the process of assessing the fire resistance of the two design options of the illustrative example discussed in Section 4.

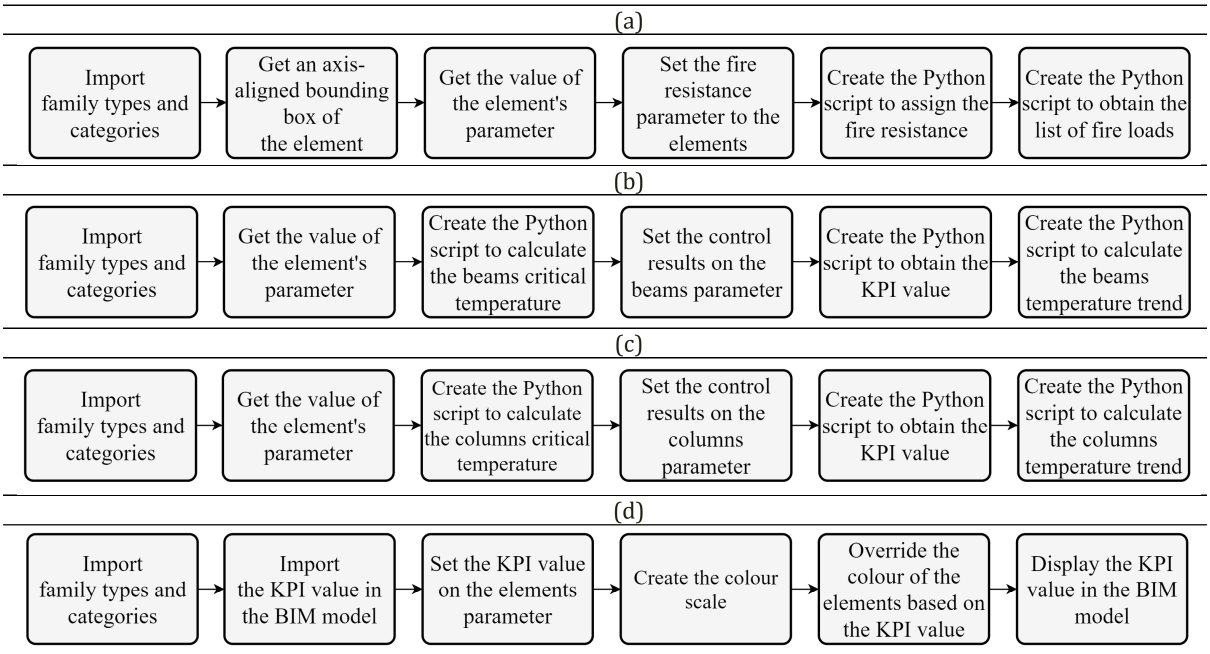

Figure 2. Detail of the steps necessary for the structural computation with Dynamo™ and Python

Table 2. Data taken for structural computation

	Option no. 1	Option no. 3
Input	BIM model ISO 834 standard fire curve	BIM model
Computation	Dynamo™ script	Fire simulation tool Dynamo™ script
Output	Critical temperature of structural components Temperature trend inside building Fire resistance of structural components	Actual fire curve Critical temperature of structural components Temperature trend inside building Fire resistance of structural components

3.6 Graphical visualization of structural assessment into the BIM environment

Once the outcomes of computations were obtained, they were displayed within the BIM model. Dynamo™ was also used for this step, and a flow was created to assign distinct colours to the structural elements. If the KPI value is higher than zero, the fire resistance associated with the critical temperature along the temperature trend in structural elements is higher than the fire resistance relative to the fire load. In this case, the KPI was assigned the value 'true,' and consequently, the parameters 'EUROCODE_3' or 'FDS' were assigned the value '1'. This assignment results in the element being coloured green. Conversely, when the KPI was less than 0, it took the value 'false', and the components were red-coloured. Figure 2-d shows the pseudocode related to the Dynamo™ flow used to apply the colour scale to every component. By displaying the results directly within the BIM model, the designer was able to make decisions quickly and accurately, comparing several design solutions and choosing the one that represents the best trade-off for the specific building.

4 Application on a case study

The feasibility of the proposed framework was assessed using a pilot building as the case study. It is a 5-level building which hosts offices that are not open to the public (inspired by the project available at: https://openifcmodel.cs.auckland.ac.nz/). It is composed of a structure with steel beams and columns. For the purposes of this paper, the experiment was limited to one area only of the building: the entrance hall, which extends along the full height of the building. Figure 3-a displays the 3D model of the building, while Figure 3-b (ground floor) highlights in red the area where the proposed methodology was showcased.

4.1 Fire scenarios

Fire scenarios represent the most severe but realistic events that could occur during the activities assumed within the building. Many of these scenarios can occur in complex buildings. As mentioned earlier in 'The technical framework' section, the initial analysis did not involve the selection of a specific real fire scenario; instead, the standard ISO 834 fire curve was utilized. Consequently, structural elements were subjected to a uniform temperature distribution. Concurrently, an analysis considering a real fire scenario was also conducted. For the purposes of this paper, a single fire scenario was selected, wherein the fire hearth was positioned at the centre of the entrance hall. The hall extends across the full height of the building, narrowing in

(a)	(b)

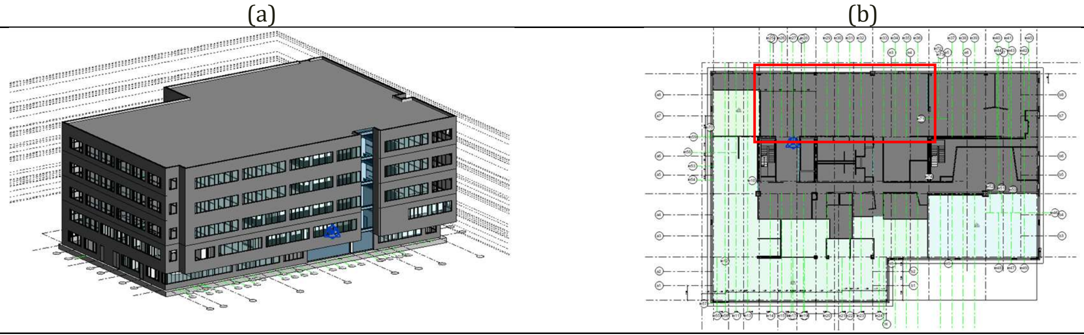

Figure 3. 3D model (a) and ground floor (b) of the pilot building

the top two floors where a mezzanine is present. The tested fire scenario involved the ignition of a wooden element for a duration of 900 seconds. Two cases were provided for both methodologies: the first case, labelled 'SS1 scenario,' and the second, labelled 'SS2 scenario.' The distinction between these scenarios lay in the choice of structural element sections, which was part of the design process. Regarding the fire simulation, the fire hearth location remained unchanged.

4.2 Scenario SS1

In this first scenario, different sections were assumed for the beams and columns based on the elevation and length to be covered. For the beams, HEA 200, 340, 450, 500, and 550 type sections were chosen, while all columns were of the same HEA 160 type section.

4.2.1 Option no. 1

Once the parameters were added, as described earlier in the 'Property set' section, the critical temperature and the temperature reached inside the building, which responds to the ISO 834 standard fire curve, were calculated, as mentioned above in the 'Structural computation' section. The trend of the ISO 834 curve was considered up to a time of 900 seconds. Figure 4 directly shows the final graphical visualization of the results within the BIM model. Specifically, Figure 4-a displays the area of the building subject to the calculations which corresponds with the entrance hall, while Figure 4-b shows only the structural skeleton, with beams and columns visible for a clearer understanding of the results. The coloured scale depends on the result obtained through the Dynamo™ scripts. If the parameter 'EUROCODE_3' was assigned the value '0', the element was coloured in red; if it was assigned the value '1', it was coloured in green.

4.2.2 Option no. 3

The results of the FDS simulations were imported into the BIM model. Figure 4-c depicts the Revit™ screenshot, where the real fire curve from FDS replaces the previously used ISO 834 fire curve. Again, the same colour mentioned above were used to represent the results of the verification.

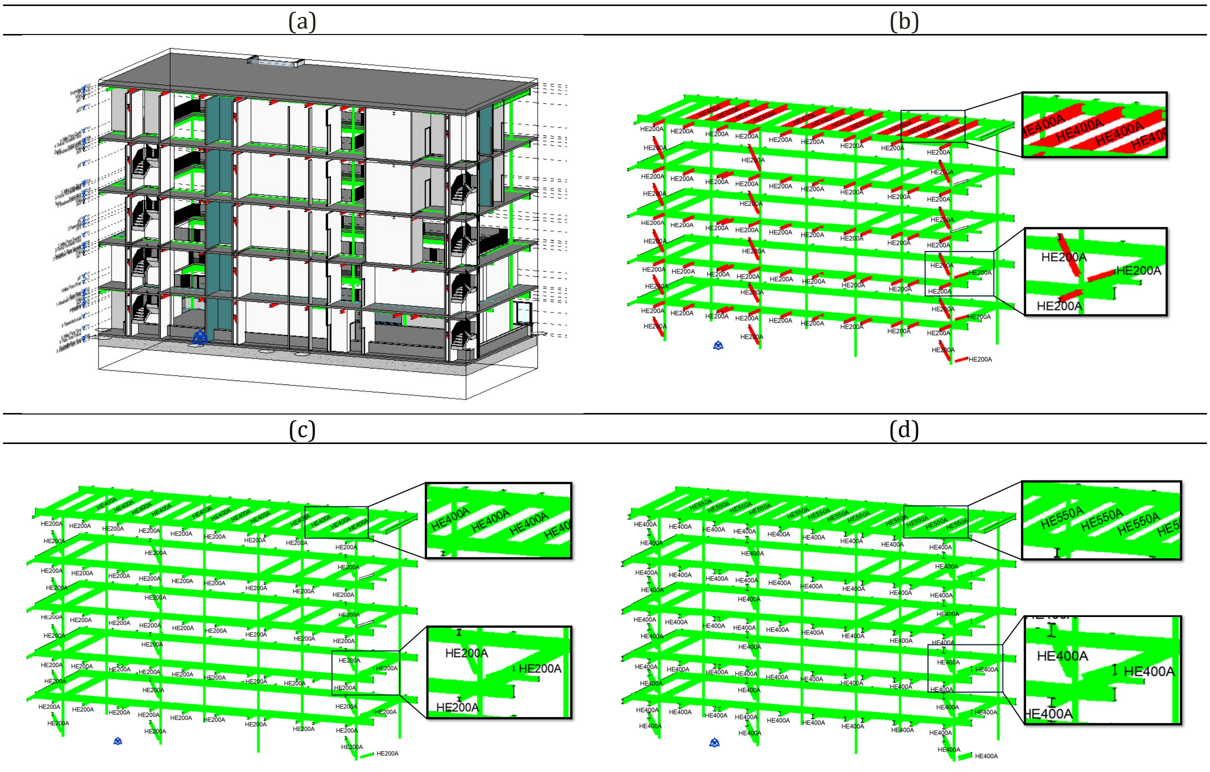

Figure 4. Visualization of the building area under consideration for calculations (a) and the results of the 'SS1 scenario' for the option no. 1 (b) and option no. 3 (c) and of the 'SS2 scenario' for option no. 1 (d) taken from Revit™

4.3 Scenario SS2

4.3.1 Option no. 1

As a result of the first analysis of the 'SS1 scenario', some sections of the beams were changed because, as shown in Figure 4-b, not all of them passed the verification. Specifically, HEA 200 sections were replaced with HEA 400 sections for several beams and bracing, and HEA 400 sections in the roof were replaced with HEA 550 sections. As a consequence, all sections met the KPI threshold in this second scenario (Figure 4-d).

4.3.2 Option no. 3

Regarding the fire simulation, since everything was already checked in the 'SS1 scenario', the sections of the structural elements were not changed, and no further evaluation was conducted.

5 Discussion

Thanks to the results reported in the previous 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 structural elements inside the building in case of fire. Regarding the 'SS1 scenario', in the first analysis, not all structural elements met the KPI threshold. This is evident in the temperature calculations following Eurocode 3 and using the standard ISO 834 fire curve, as illustrated in Figure 4-b, where some structural elements are marked in red. As previously mentioned, the red elements indicate that they do not meet the KPI threshold. In such cases, the designer is prompted to make a decision. Consequently, a second scenario (SS2 scenario) was considered, wherein those elements that did not meet the KPI threshold were replaced with elements of larger cross-sections. Utilizing the Dynamo™ script again for structural computation, it was observed in Figure 4-d that all structural elements met the KPI threshold. The analysis conducted concurrently on the same scenarios, using a fire simulator to obtain the temperatures reached inside the building subjected to a real fire curve, revealed different outcomes. In the 'SS1 scenario', all elements met the KPI threshold (Figure 4-c), indicating that the fire curve inputted to the simulation, which involves burning a woody material, resulted in much lower temperatures than the standard ISO 834 fire curve. Consequently, no fire simulation was conducted for the 'SS2 scenario', which featured larger structural sections. In addition, by visualizing the maximum temperature to which each structural element is subjected for a given fire scenario, the designer can select the structural sections that represent the best trade-off. This performance-based approach leads to a more effective and economical design compared to conventional fire curves.

6 Conclusions

In this paper, an approach was proposed for assessing the structural safety in case of fire during the building design phase. The results of structural evaluations, presented graphically within the BIM environment using the established KPI, enable designers to promptly identify critical elements within the building. Consequently, designers can compare several design solutions for each design fire scenario based on quantitative results (KPI values) that encompass the entire building. The KPI not only provides an immediate assessment of structural fire resistance but also aids designers in selecting the most suitable structural elements for the specific building, thereby achieving the optimal design. By visualizing the KPI directly in the BIM model allows even non-experts in fire simulation software to clearly and promptly interpret the results.

One possible recommendation for future research involves identifying additional KPIs related to other domains of fire safety engineering. Similarly, the KPI value can be utilized during the building's operational phase. The facility manager, inheriting the same KPI, can continually monitor the building's performance, ensuring compliance throughout its life cycle.

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