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PROCEDURES TO CONTROL FIRE SAFETY PERFORMANCES OF BUILDINGS IN A BIM ENVIRONMENT

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Abstract

During their lifecycle, buildings often require changes in use and layout. This scenario raises the need for continuous control of building performances in each phase. The transition from the traditional prescriptive method towards the performance-based approach would facilitate the management of building, thanks to the adoption of key performance indicators. KPIs can track building performances over their lifecycle. This paper showcases the application of such a procedure in the fire safety management. It includes the draft of a workflow and an information model to support that approach in a BIM environment, the integration of simulators, and the definition of KPIs.

Introduction and literature review

As long as performance-based fire management of buildings is embraced, a quantitative evaluation of safety levels in fire emergency preparedness is required. Performance thresholds can assess the level of safety in a building. In the current practice, they are associated with standard fire scenarios. On the contrary, the prescriptive approach provides a set of measures and standard calculation methodologies to certify that the minimum level of safety is met. The main drawback of this approach is that it does not account for the specificity of the scenario under evaluation. In fact, it does not account for the possible evolutions of a system.

Basically, the performance-based approach focuses on what requirements must be provided by an activity or a service, rather than on how they could be achieved. Hence, it allows designers and managers to consider the specificity of any use case and seeks to meet project objectives and requirements. Despite that, the performance approach is seldom practiced, but it could be facilitated by the structured information made available in a BIM environment. Tracking performances over time leads to the continuous assessment of KPIs. These ones measure to what degree predetermined objectives have been achieved.

This paper concerns the definition of a technological framework in a BIM environment that can implement performance-based procedures to assess the degree of achievement of fire safety objectives. This is expected to support decision-making in the management of fire emergency preparedness of buildings.

The performance-based approach

The implementation of the performance-based approach requires the preliminary analysis of the dynamic evolution of processes and the prediction of related building performances. Therefore, it requires that measurements of building performance satisfaction levels are put in place to monitor objectives to be achieved. Despite the limited application in the construction industry, some remarkable applications have been developed. The analysis of the mechanics of a building’s load-bearing frame structures was based on the coupling of multiple performance limit states and seismic hazard levels (Filiatrault et al., 2018). Another approach could control the combination of several objectives, such as energy performance, environmental performance, indoor air quality, lighting, and acoustics, to optimize their overall combination in building management (Jung et al., 2018).

Danzi et al., 2017, claimed that the performance-based approach applied to fire engineering must include risk assessment. The selection of fire scenarios is a critical element of the fire safety strategy, too. An application in fire safety engineering showed that the performance-based approach enables increasingly informed and targeted choices, even for the purpose of selecting building materials (Giuriola et al., 2015). In this case, such an approach enabled the investigation of fire behavior inside industrial buildings as a result of Computational Fluid Dynamics (CFD) outcomes. They estimated that the temperatures achieved in the building elements were lower than those ones assumed by the prescriptive approach. Consequently, this more accurate outcome allowed a more advantageous sizing of those components, as well as cost savings. Nowadays, efficient data exchange as enabled by BIM editing tools with performance evaluation tools represents a great opportunity for technical and process standardization.

Fire emergency management

In order to improve the management of fire safety in buildings, several research tracks have been put in place. First, BIM can enhance the management of fire-related emergencies, thanks to its advanced visualization and data storage capabilities (Wang et al., 2015). Also, a framework called "EvacuSafe" was developed to work out a risk index to assess the safety level of egress routes and compartments and to evaluate the evacuation safety performance of entire buildings (Mirahadi et al., 2019). In this work, it was shown that the shortest egress route of an evacuation seldom is the safest one. Finally, the IFC interoperable data format can facilitate information exchange to support real-time fire emergency management, using integrated sensors and occupants' feedback (Eftekharirad et al., 2018). This study suggested further extending the IFC schema to support fire emergency first responders by tracking the dynamic conditions of an endangered building.

Referenced Legislation

Two legislative bodies are referenced in this paper. The first one is the Italian Decree dated 2015, August 3rd called the "Fire Prevention Code". It is made of two parts, one concerning the prescriptive approach and another one concerning the performance-based approach. It consists of ten sections, each one dealing with a specific fire prevention measure. Every section requires the implementation of a risk assessment procedure in every compartment and every activity of a building. As a response to this, fire professionals may adopt either any compliant solutions suggested in the prescriptive section or respond to the risk assessment results and set the performances above the required thresholds. This decree wishes to standardize the fire prevention vocabulary, too, and it is compliant with several international standards and previous national standards. The other reference is the American Fire Protection Standard NFPA 101, released in 2021. Chapter no. 5 therein, states that if any design meets the performance criterion set for each fire scenario, then it meets the objectives. A performance-based project must successfully handle several fire scenarios. NFPA 101 provides a range of eight fire scenarios as candidates for being analyzed. The designer or manager is expected to pick out those scenarios that most resemble the actual behavior of the building system.

Research questions

The research work reported in this paper suggests a methodology, which is compliant with both the aforementioned Italian and American standards, to verify the level of fire preparedness of a building in the fire safety domain. The main contribution of this methodology consists of the definition of reliable KPIs. Another contribution consists of the analysis of what information must be collected to track them over the lifecycle. The methodology takes advantage of simulation tools and of a BIM environment both for design development and for monitoring of the KPIs. Thanks to KPIs tracking, a facility manager can make decisions on how to keep fire emergency preparedness at the required level. The tests reported in the next sections have been evaluated in the case of two fire scenarios.

Materials and methods

The first contribution included in this section is a project workflow that covers the design and the operational phases. The former must set KPIs at their design values, as a result of comparisons among project alternatives. The latter should track actual KPIs across the lifecycle of an asset and monitor the compliance with project's objectives. Also, an information model that can manage information from different sources to feed the suggested workflow was worked out. Finally, the application of this approach for KPI tracking and monitoring has been showcased in the case of a real building project.

The project workflow

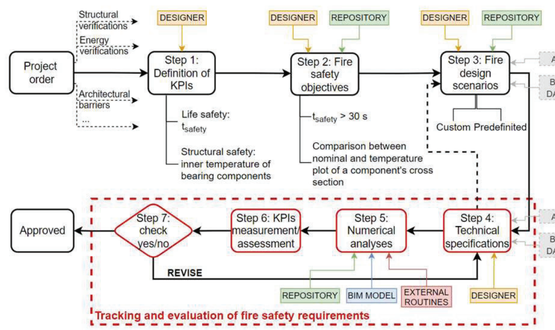

Figure 1 – Diagram of the project workflow

As depicted in Figure 1, the project workflow is supposed to start from the project commitment and concerns fire safety management only. According to the performance-based approach, KPIs must be identified as a first step. In the domain of fire safety engineering, KPIs concern life safety (i.e., do not harm people), and structural safety (i.e., structural integrity against collapses). Their quantitative definition is the subject of step no. 2, as will be reported in detail in the next section. In the third step, the designer is in charge of sorting out the list of applicable fire design scenarios, that must be used as references for the validation of and comparison among design options. Scenarios usually are derived from regulations, though they could be customized to the specific case. Advanced technologies such as AI and big data, may help in the definition of applicable scenarios, based on statistics and outcomes from risk analyses of previous similar scenarios. The results from the third step should advise designers on what technical specifications must be required. They are provided as input into numerical simulations of step no. 5. If the simulation outcomes show that the KPIs fall within the required thresholds, then the previously defined technical specifications meet the objectives, and the project can be approved at step 7. In the opposite case, it must be reiterated once new technical specifications have been defined, to be repeated until the KPIs can be approved. The loop marked by the red dashed rectangle in Figure 1 enables not only the validation of the design but also the process of tracking and continuous improvement of a building's fire safety performances in the operation phase, which is the core of this paper.

Several input sources must be assumed. Information could be provided by the BIM model via the IFC interoperable format (light blue in Figure 1), by the designer (orange), by a repository containing standards and regulations and other external sources (green), or even by executable algorithms (pink). In the near future, artificial intelligence and big data (grey) could help arrange input values into steps no. 3 and no. 4, due to their huge computing capabilities that make quick processing of a big amount of data and time series feasible. A deeper analysis is shown in Figure 2 and will be discussed in the "Information model" sections.

Definition of the KPIs and performance tracking

The definition of KPIs at step no. 1, derives from the requests in terms of performances made by relevant regulations and guidelines. The two references mentioned in the previous section are Italian legislation and US NFPA. The first one requires that both life safety and structural safety are assessed. Life safety is the subject of Section M of the Italian Decree 03/08/2015, while structural safety is the subject of UNI EN 1991-1-2:2004. Likewise, the US NFPA 101 entitled "Life Safety Code" rules the approach for life safety in Chapter 5. Taking both references into account, the first KPI, which concerns life safety, was set as the difference between ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time). ASET usually depends on environmental parameters, such as visibility range due to smoke, maximum exposure temperature, toxic gas concentration, and maximum heat radiation. RSET is the sum of detection time, alarm time, evacuation delay/pre-movement time, and movement time. An egress system is considered effective until ASET > RSET. The KPI computed in the application of this paper as the difference between ASET and RSET was not assessed as a distributed value in space. Rather, it was controlled at selected locations in the building (Schröder, 2020).
The second KPI assessed structural safety through temperature values reached by building components. This was estimated from the temperature of the surrounding air-gas mixture calculated using the Wickstrom equation provided in the Italian standard UNI EN 1991-1-2:2004. The purpose of the definition of KPIs is to track overall performance. Hence, they must be defined numerically. For this reason, step no. 2 of Figure 1 concerns the threshold values of these KPIs. The difference between ASET and RSET is the first KPI "t_{safety}" and was set as suggested by the Italian Decree 03/08/2015 (Chapter M.3.2.2):

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

The second KPI was computed by means of the Wickstrom equation suggested in Annex A of UNI EN 1991-1-2:2004 as follows:

$$\theta_g = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \quad (2)$$

The basic assumption of Equation 2 is that the presence of fire affects the temperature of building components but does not affect the stress field across their cross sections. Therefore, in this simplified calculation, the consequences generated by cracks in concrete components were neglected, for the purpose of this paper. The main input of this calculation is given by the temperature values of the air-gas mixtures surrounding structural elements, as dictated by the standard UNI EN 1992-1-2:2019 - Annex A. This standard has developed reference isothermal plots across structural elements depending on required resistance times (labeled "Rxx", which can be set at R30, R60, R90, and R120). That isothermal plot that falls closest to the computed rounded-up time value resulting from numerical simulations, was compared with the trend estimated through numerical simulations in order to work out how thick the concrete layer covering reinforcing bars must be (as shown in the "simulations" section).
The third step in Figure 1 concerns the selection of fire design scenarios. A designer is supposed to make a choice according to the use, layout, type of building, and management policy. In the case of life safety, suggestions are provided by NFPA 101 (section 5.5.3). In this paper, three of the eight scenarios listed in NFPA 101 were selected. Additionally, three structural safety scenarios in three different compartments were checked, as described in the "Definition of fire scenarios" section. In this case, a designer is supposed to trigger at least one fire inside every compartment and perform the simulations required by UNI EN 1991-1-2:2004.
At this juncture, the system is ready to get as input the technical specifications for the project mentioned in step no. 4, to perform numerical simulations (step no. 5), to collect simulation outcomes that assess the KPIs (step no. 6), and to trigger the verification step no. 7. The steps numbered from no. 4 until no. 7, that are marked by a dashed rectangle in Figure 1, shall be repeated during both the design and management of a building, to warn the person in charge as long as any performance requirements are no longer met. Changes in the building can be planned at the technical specifications step no. 4.
According to the technology stack supporting this paper, the numerical analyses of life safety performed at step no. 5 were carried out through the software FDS (Fire Dynamics Simulator). It was developed by the Fire Research Division at the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST). In the input file, data on smoke visibility range, maximum exposure temperature, toxic gas concentration, and maximum heat radiation from all occupant exposure, and placing of sensors along all escape routes, were requested. As a result of the simulation, it returns an on-screen visualization in Smokeview (SMV) and some ".csv" files including values of the environmental parameters. Then, ASET, RSET, and the first KPI were computed from Eq. 1 at every sensor's location.
The numerical analysis regarding the structural safety subject of step no. 5 was performed in an Excel worksheet implementing the Wickstrom equation (Eq. 2). Required input values are several compartment parameters, which returns the plot of the air-gas mixture temperature over time. This plot was compared with the standard nominal plot connected with the material certification curve. In case the Wickstrom curve exceeds the nominal curve, the

concept of time-equivalence must be applied (UNI EN 1991-1-2:2004, Annex F) to estimate the equivalent fire exposure time and to compare it with the time of exposure certified for the involved material at that given temperature. In case such limits have been exceeded, the designer is required to ponder on whether some corrective actions are required. As already mentioned, the simplified computational approach adopted for the purpose of this paper does not affect the validity of the overall workflow. In fact, simulations must estimate KPIs, and the more accurate simulations are the more reliable the assessment of KPIs is. This paves the way for the enhancement of calculation methods in future the next of this research work.

The information model

The entity-relationship diagram depicted in Figure 2 shows the entities, which could be a logical record type, a table of data, or even real-world entities, that must be processed and linked to support the workflow suggested by Figure 1. The main sources of involved entities are the BIM model of the building, the designer, the repository, external routines, and simulation tools. Most of these blocks are inputs for the simulation tools, which return the values required to estimate KPIs regarding life and structural safety. The entity-relationship diagram includes information about the cardinality of such relationships. In fact, a defined set of symbols and connecting lines, is used to represent the interconnection between entities, relationships, and their attributes. In this case, to explain the cardinality, were used the relationships 1::1, 1::1-n and 1::0-n, which mean, respectively, each entity corresponds to one entity, each entity corresponds to one or more entities, and each entity corresponds to zero or more entities. The colours of the blocks shown in Figure 2 are coherent with the ones depicted in Figure 1 to identify the inputs involved at every step of the workflow. It is assumed that the BIM model of the building is available, and that data can be exchanged by means of the IFC interoperable format (light blue). Some of those data will be sent to the simulation tools as input. In this paper, the feasibility of this information exchange was shown using the plug-in Dynamo built in Autodesk Revit™. Some of the required data have been extracted directly from the BIM model (e.g., material types, size of building components). Some other information, not readily available in the BIM model, must be generated through external routines (pink). This is the case of door-occupant association and compartment size. In the first case, the external routine may acquire information from the door entity and the occupant entity and generate this association by means of customized procedural or logical algorithms. Other information is available in the legislation or technical literature (green) and was manually entered by the designer. Finally, the designer is in charge of choosing fore scenarios, either predefined or customized (orange), as inputs to start simulations and assess KPIs. The depicted diagram in Figure 2 does not show every attribute of the entities, although it was defined by the authors. One example is expanded in the same Figure 2 and concerns the materials entity. Here, the purple dot means that such data are required for the life safety simulator, whereas the brown ones are required for structural safety. The top of the table contains the title, the primary key, and foreign keys. Any entity that belongs to the IFC schema was analyzed within the well-established 2x3 version of the schema, developed, and maintained by BuildingSMART.

The validation and the pilot building

The feasibility of the suggested workflow was showcased using a real building as the pilot building. The validation described in the next section shows how KPIs change over time as a consequence of decisions that can be made across the lifecycle of the building. One example is the comparison between several sets of technical specifications at the design phase, concerning some components that affect the fire safety performances of the building under assessment.

The pilot case used for validation is a building located on the campus of the Polytechnic University of Marche (Ancona, Italy), which hosts the School of Medicine

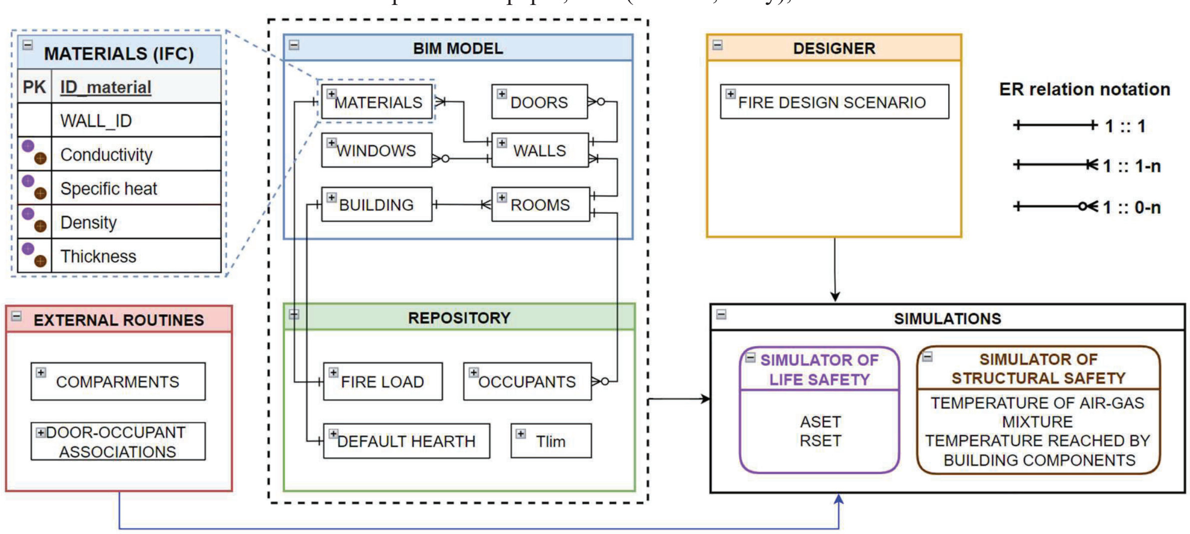

Figure 2 – Schematics of the information model

(Figure 3). It is an eight-level building, including the basement. The main activities carried out therein are teaching, research, library, and ancillary services.

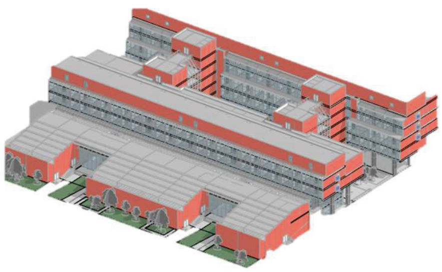

Figure 3 - 3D model of the pilot building

Example of application on a case study

Definition of fire scenarios

Table 1 reports the list of scenarios selected for both life and structural safety scenarios. In order to showcase the process of tracking fire safety requirements, simulations were split into two subsets. The first set includes "base scenarios", and it represents the initial status of the building. The second set was called "alternative scenarios", and they were compared pair-wisely with the first subset, to simulate how KPIs can be changes due to a change of building status, as a consequence of a decision made either at the design phase or operation phase (Figure 1). Regarding life safety, three out of the eight predefined types of scenarios were chosen from the NFPA 101, namely:

- scenario no. 2, which describes a fire that develops through the burning of a material with an ultrafast growth curve, located along a major egress route. The doors were assumed open at the time the fire starts spreading. This scenario must address the simulation issue, paying specific concern to people's egress problems. In fact, due to the hypothetical rapid spread of the fire, some egress routes are supposed to be obstructed, and this scenario evaluates the capability of finding effective alternative egress routes and the consequences on the asset;
- scenario no. 3 describes a fire that starts in a room in which nobody is present under regular use of the building. However, because of its location, the fire may endanger other individuals in near rooms. Hence, the fire may migrate into other potentially crowded rooms in the building;
- 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.

Basic scenario no. 2 was labeled LS1 in Table 1. The fire was located on the ground floor in "corridor 36" among classrooms, offices, and the library (Figure 4-a). In the corresponding alternative scenario (LS1_alt), a change of use is assumed for "room 33" located close to the fire ignition place. Indeed, the latter may be converted from an office with a capacity of 11 people into a classroom with a capacity of 40 people. This would cause a greater flow of occupants forced to go through the "corridor 36" egress route.

The third type of scenario (labeled LS2) places the fire on the second floor in a "laboratory 102" adjacent to "classrooms 99" (Figure 4-b). In the alternative scenario LS2_alt, the fire is expected to start in "lab 104", located adjacent to "lab 102", and "lab 104" will be converted into a multi-purpose space for students with an increase in the number of occupants from 10 to 50.

The type of scenario no. 6 (i.e., LS3) the fire was placed on the fifth floor of the building within "laboratory 356" along "corridor 327" that hosts more laboratories, offices, and restrooms (Figure 4-c). In the alternative scenario LS3_alt, a change of use was assumed, leading to an increase in fire load, while keeping the number of occupants unchanged. In detail, "lab 356" where the fire is planned to start will be converted into a paper storage room, raising from a fire load of 875 MJ/m^2 up to 1824 MJ/m^2.

The input concerning activity, occupants, and fire were defined as shown in Table 1.

Table 1 - Input and simulation outcomes concerning life and structural safety scenarios

LIFE SAFETY						
	LS1	LS1_alt	LS2	LS2_alt	LS3	LS3_alt
fire position	36	36	102	102	356	356
activities	corridor	corridor	laboratory	laboratory	laboratory	paper storage
growth rate [s]	75	75	75	75	75	75
fire load [MJ/m^2]	347	347	875	875	875	1824
occupants involved	1050	1079	387	427	87	87
ASET	(VIS_S13) 595.7 (VIS_S15) 354.2 (VIS_S17) 557.9 (VIS_S1) 279.3 (VIS_S4) 161.1	(VIS_S13) 595.7 (VIS_S15) 354.2 (VIS_S17) 557.9 (VIS_S1) 279.3 (VIS_S4) 161.1	(VIS_S3) 525.7 (VIS_S2) 427.7 (VIS_S7) 513.8	(VIS_S3) 462.7 (VIS_S2) 436.8 (VIS_S7) 508.9	(VIS_S7) 220.5 (VIS_S2) 196.7	(VIS_S7) 236.6 (VIS_S2) 210.7
RSET	(VIS_S13) 247.4 (VIS_S15) 198.0 (VIS_S17) 255.0 (VIS_S1) 287.7 (VIS_S4) 199.5	(VIS_S13) 247.4 (VIS_S15) 176.0 (VIS_S17) 248.8 (VIS_S1) 288.0 (VIS_S4) 185.0	(VIS_S3) 58.0 (VIS_S2) 275.4 (VIS_S7) 278.9	(VIS_S3) 64.0 (VIS_S2) 283.8 (VIS_S7) 285.2	(VIS_S7) 357.3 (VIS_S2) 357.3	(VIS_S7) - (VIS_S2) -
tsafety	(VIS_S13) 348.3 (VIS_S15) 156.2 (VIS_S17) 302.9 (VIS_S1) **-8.3** (VIS_S4) **-38.4**	(VIS_S13) 348.3 (VIS_S15) 178.2 (VIS_S17) 309.1 (VIS_S1) - **8.6** (VIS_S4) **-23.9**	(VIS_S3) 467.7 (VIS_S2) 152.3 (VIS_S7) 234.9	(VIS_S3) 398.7 (VIS_S2) 153.1 (VIS_S7) 223.7	(VIS_S7) -136.7 (VIS_S2) -160.5	(VIS_S7) - (VIS_S2) -

STRUCTURAL SAFETY						
	SS1	SS1_alt	SS2	SS2_alt	SS3	SS3_alt
A_v [m^2]	**45.7**	**56.3**	**59.4**	**52.8**	68.2	68.2
h_{eq} [m]	3.2	3.2	2	2	2	2
A_t [m^2]	848.5	848.5	725	725	1050	1050
A_f [m^2]	242.5	242.5	250	250	400	400
ρ [Kg/m^3]	2500	2500	2500	2500	**2500**	**800**
c [J/Kg K]	1100	1100	1100	1100	**1100**	**1000**
λ [W/mK]	2.3	2.3	2.3	2.3	**2.3**	**0.36**
fire load [MJ/m^2]	700	700	2179	2179	1075	1075
activities	bar	bar	archive	archive	laboratory	laboratory
maximum temperature [°C]	824	872	1067	1051	942	1339
time equivalence [min]	26.3	22.7	71.5	75.0	**43.9**	**76.8**
concrete cover thickness [mm]	15	15	30	30	**20**	**30**

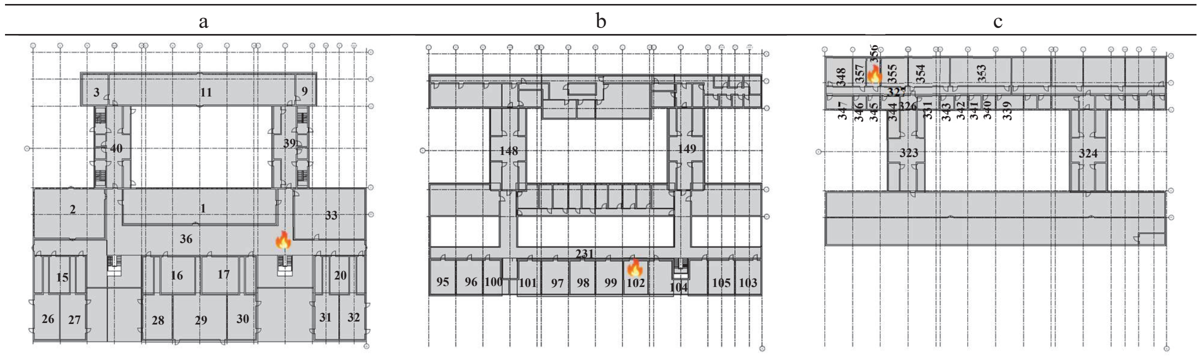

Figure 4 - Ground floor, second floor and fifth floor of the pilot building

Most of the input data have been retrieved from values estimated in relevant literature and regulations, e.g., fire load from UNI EN 1991-1-2:2004, and power of the fire and rate of fire growth from D.M. 03/08/2015.

Regarding the structural safety area of focus, a designer was supposed to place one fire inside every compartment and perform simulations. Hence, three basic fire scenarios plus three corresponding alternative ones were identified, as listed in Table 1. Other data are the total area of vertical openings on the walls (A_v), the weighted average of window heights (h_{eq}), the total compartment area (A_t), the floor area (A_f), the unit mass of the external compartment surface (ρ), the specific heat of the compartment surface (c) and the thermal conductivity of the compartment surface (λ), that is the set of parameters required to calculate Eq. 2. In the case of scenario SS1, the fire ignites in the bar compartment on the ground floor. In the SS1_alt, the area of openings has been increased from 45.7 m^2 to 56.3 m^2. In scenario SS2 the fire ignites inside the archive/office compartment on the first floor. In the SS2_alt the area of openings decreased from 59.4 m^2 to 52.8 m^2. Scenario SS3 involves the fire ignition inside the laboratories along with the office compartment on the third floor, whereas in SS3_alt a change of material for the compartment walls is assumed with a consequent change of the parameters ρ, which decreases from 2500 to 800 kg/m^3, c that decreases from 1100 to 1000 J/Kg·K and λ decreasing from 2.3 to 0.36 W/m·K.

In scenarios SS1 and SS3, the fire loads of the bar (700 MJ/m^2) and of the laboratory (875 MJ/m^2) activities were estimated from the database of *ClaRaf 3.0*, that is the application program for calculating the design-specific fire load developed by the Passive Protection Area of the DCPST (Central Directorate for Prevention and Technical Safety) of the National Italian Fire Department. In the case of SS2, the fire load for the archive (1824 MJ/m^2) was retrieved from the standard UNI EN 1991-1-2:2004. The fire load values for the activities must be added to the load related to the materials inside the compartments.

Simulations

The results of two simulations conducted out of the total six are reported in Table 2 because they turned out as some of the most representative ones.

Table 2 - KPI results for the life safety scenario

	KPI - t_{safety}		
Sensor	LS1	LS1_alt	LS1_smoke_extractors
VIS_S13	348.3 s	348.3 s	472.0 s
VIS_S15	156.2 s	178.2 s	450.5 s
VIS_S17	302.9 s	309.1 s	425.3 s
VIS_S1	**-8.3 s**	**-8.6 s**	**423.9 s**
VIS_S4	**-38.4 s**	**-23.9 s**	**444.9 s**

The first one is the LS1, where the 10-meter visibility threshold was exceeded (Table M.3-2 in D.M. 03/08/2015). As a result of the simulation carried out by FDS, it was possible to determine the ASET that corresponds to the time when the first threshold of the least performing environmental parameter was exceeded. RSET was obtained as the time when the last occupant leaves the compartment of the building and gets to a safe place. In this way, it is possible to calculate the first KPI. VIS_S1 (the acronym VIS stands for visibility, while S stands for sensor; progressive numbers follow) and VIS_S4 sensors, positioned along the "corridor 36" on the ground floor, return ASET values of 274.34 s and 161.05 s, respectively, and RSET values of 287.73 s and 199.53 s. The differences are reported in bold in Table 2. In this case, the KPIs do not verify because, as shown in Eq. 1, ASET had to be higher than RSET of an amount equal to 30 s. Hence, a decision must be made to improve it.

The decision made by the designer and simulated in this paper may involve the integration of two smoke extractors at the fire exits. In this way, a safe condition is met because ASET has increased. The KPI became greater than 30 seconds, in particular in VIS_S1 KPI raised up to 423.9 s, and in VIS_S4 it increased up to 444.9 s (Table 2). For the sake of completeness, diagrams are provided where visibility trends can be visualized in the five sensors placed along the egress routes (corridor 36).

Figure 5-a represents the visibility of the LS1 scenario and Figure 5-c of the LS1_smoke_extractors scenario. In this way, the decision made to include smoke extractors allows the designer to meet the visibility threshold values as high as 10 meters. As it was not exceeded over the simulation time, consequently the value of ASET increased and the KPI met the required threshold. In addition, Figure 5-b represents the screenshot taken from Smokeview, where the visibility trend on the ground floor

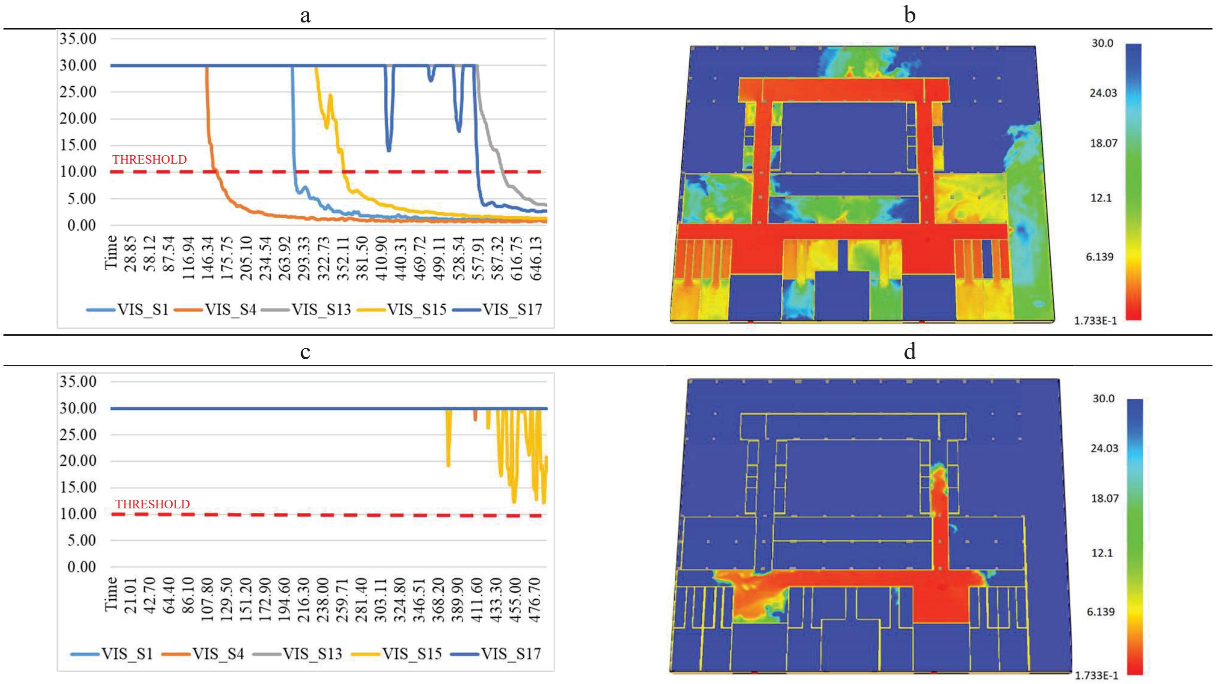

Figure 5 - Visibility diagrams and Smokeview screenshots for the basic LS1 and LS1 smoke extractors scenarios

for the LS1 base scenario is depicted. The legend quantifies visibility in length. Figure 5-d depicts the LS1 smoke extractors scenario. Similarly, those areas where the 10-meter visibility threshold was exceeded at the end of the simulation have been depicted here.

In the structural safety SS3 scenario, the maximum temperature occurs at the time 53 minutes (Figure 6-a), that is as soon as the cooling phase begins. The temperature reaches 0°C after about 130 minutes. In the SS3_alt scenario (Figure 6-b), the maximum temperature is reached at a time equal to the base scenario, but this decreases dramatically to 0°C in a few seconds (about 5 s). The Wickstrom curve is represented in the diagrams by red plots, while the nominal plot is blue.

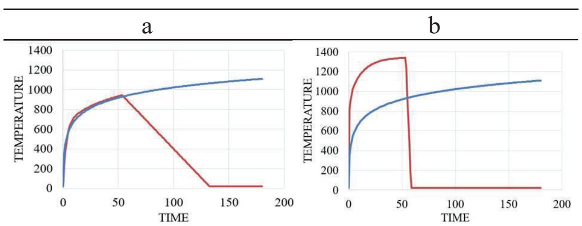

Figure 6 - SS3 base and alternative scenario

As the Wickstrom curve exceeds the nominal one, the equivalent time must be estimated. The latter, as listed in Table 1, is 43.9 minutes in the SS3 scenario, hence considering the closest isotherms diagram available for R60, a 20 mm thick concrete cover is required on the outer side of the 30x30 cm type columns (Figure 7-a). In the alternative SS3_alt scenario, there is an equivalent time of 76.8 minutes, hence considering the closest isotherms diagram available for R90, a 20 to 30 mm thick concrete cover is required (Figure 7-b). Figures 7-a and 7-b show the isotherms diagrams concerning the 30x30 cm columns. The isotherm at 500°C and the corresponding concrete cover thickness has been highlighted in Figure 7.

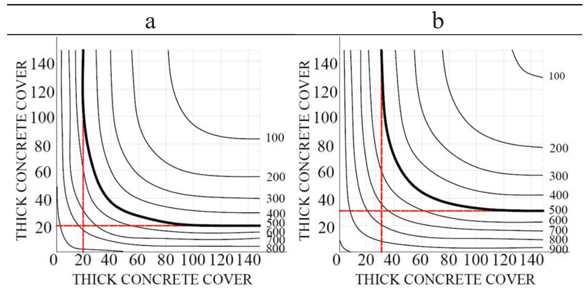

Figure 7 - Temperature trend inside 30x30 cm columns, R60 e R90 [adapted from UNI EN 1992 :1-2 :2019]

Results of the validation

The simulations reported in the previous section showed that the system can advise designers in terms of impacts of design or usage changes on the fire safety performances of a building in its lifecycle. As long as the life safety's LS1 scenario was not met, this led to the non-verification of the corresponding KPI, and therefore an action by the designer or facility manager was required, according to the workflow included in Figure 1. In this case, smoke extractors were placed at the emergency exits to get back a compliant KPI. Regarding the structural safety's SS3 scenario, actions were taken because of the insufficient performances determined by the alternative scenario. In this regard, an increase in the thickness of the column's concrete cover would fix the issue. Thus, the integration of simulations and KPIs in the workflow were used to quantify the effects of technical choices and warn the person in charge whether performance requirements were not met, thus implying that technical specifications would ask for a revision. The main current limitation of this approach is that the required time to execute simulations regarding life safety ranged between 48 and 96 hours. Hence, this approach cannot be applied in real-time, but it can constitute a decision support system to support the design and operational phases of buildings.

Conclusions and future works

In this paper, a technological framework has been developed that is capable of tracking and evaluating the degree to which fire safety requirements are met in the lifecycle of buildings. The proposed approach suggests a continuous control of fire safety performance compliance, thanks to the application of "performance-based" procedures. It also includes the development of an information model suitable for the digitization of information and processes related to life and structural safety. The presence of an information model facilitates the actual implementation of the performance-based approach that must follow the dynamic process evolution and thus on the rigorous, quantitative, and scientific prediction of building performances. As a result, solutions are identified downstream of fire safety objectives, required performance levels, analysed scenarios, and application of an appropriate simulation model to achieve the performance levels represented by KPIs. This approach was showcased as a way to quantify the effects that technical choices may have at the design and operational stages. This paper has validated the proposed approach recalling both the design and operational phases of a building. Indeed, during its lifecycle a building could be subject to numerous changes that could negatively affect fire performances. Therefore, by tracking KPIs it would be possible to assess these changes quantitatively and support facility managers that must react fast in a complex and evolving system. As reported earlier, automation could be integrated in later stages thanks to the use of artificial intelligence and big data analytics.

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