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Numerical study of vertical compartmentation in compartments in fire situations

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Abstract

The occurrence of fires can lead to accidents with high potential, and vertical fire compartmentation is a measure to reduce these incidents. Increasingly, computational numerical analyses play a crucial role in studying fire behavior for control and mitigation. The computational tool Fire Dynamics Simulator (FDS) is one of the main programs aimed at numerically analyzing fire spread. By using the FDS program, this research aims to numerically analyze the effectiveness of using horizontal projection and the combination of horizontal and vertical projections simultaneously, as specified in the Technical Instruction of the Fire Department of the State of São Paulo in combating the propagation of external vertical fire to the facade. Temperature measurements on the compartment facade were used to compare temperatures on the upper floor with the autoignition of material values commonly found in facades. Models with only horizontal projections showed greater effectiveness compared to models with the combinations of projections, mainly due to the presence of the spandrel component, which has a harmful effect on fire propagation. Despite the lower effectiveness of combination models for a fire with a heat release rate of 300 MJ/m², there would be no external vertical fire propagation.

Keywords: Fire Dynamics Simulator, computational numerical analyses, vertical compartmentation, projections, autoignition of materials.

1. Introduction

Historically, fires have caused significant disruptions and losses, but not long ago they were considered acts of fate (Pereira, 2020). This is a mistaken view, as nowadays fire safety in buildings is considered a science, and investments in research in this area are increasing (Tabaczenski, 2018). Therefore, it is essential to understand the behavior of a fire to study control measures, aiming to prevent its spread and maximize the protection of people's lives. In this context, technical standards for vertical fire compartmentation emerge, aiming to establish measures for controlling fire spread, known as projections that can be divided into vertical, horizontal, and a combination of both.

Numerical computational analyses are used to assess the effectiveness of control measures specified in the standards. These analyses enable comprehensive studies without the financial constraints associated with experimental studies due to their high costs. The Fire Dynamics Simulator (FDS) stands out as one of the main computational programs for numerical analysis of fire spread, widely used by researchers worldwide.

In Brazil, each state has its own regulatory standards, called Technical Instructions (or Technical Standards), which differ from Brazilian Standards (NBR) regulating the entire national territory. The Technical Instructions of the Military Police Fire Department of the State of São Paulo are known for their quality, and other states in the federation adopt their text. Therefore, this work considers Technical Instruction No. 09/2019 from São Paulo, which addresses horizontal and vertical compartmentation of buildings as the main national regulation.

According to the premises of Technical Instruction No. 09/2019 from the São Paulo State Fire Department, spandrels must provide a minimum separation of 1.20 m between openings on subsequent floors. In the case of using horizontal projections, this separation must be achieved by extending floor slabs, at least 0.90 m beyond the facade alignment (CBMESP, 2019). IT 09/2019 also allows the use of a combination of vertical and horizontal projections simultaneously, provided that the occupancy of these buildings is low risk (up to 300 MJ/m²) and meets a minimum summed dimension of 1.20m.

Thus, studying the vertical propagation of fires through numerical computational analyses allows verifying safety and evaluating the effectiveness of various vertical fire spread protection requirements outlined in Technical Instruction No. 09/2019 from the São Paulo State Fire Department.

Given the presented content, a computational numerical analysis of external vertical fire spread using FDS is justified to assess the effectiveness of control requirements (projections) outlined in IT 09/2019.

2. Standards for vertical fire compartmentation

In order to provide technical support for the vertical compartmentation parameters in this research, fire safety standards from four countries—Brazil, Portugal, the United States of America, and England were analyzed.

In Brazilian regulations, each state defines standards for vertical compartmentation through Technical Instructions (IT). The primary Brazilian IT addressing vertical and horizontal compartmentation is IT 09/2019 from the state of São Paulo. In Brazil, the use of vertical and horizontal projections, as well as a combination of both (fire load up to 300MJ/m²), is permitted. Figure 1 shows the models of projections allowed by Brazilian regulations.

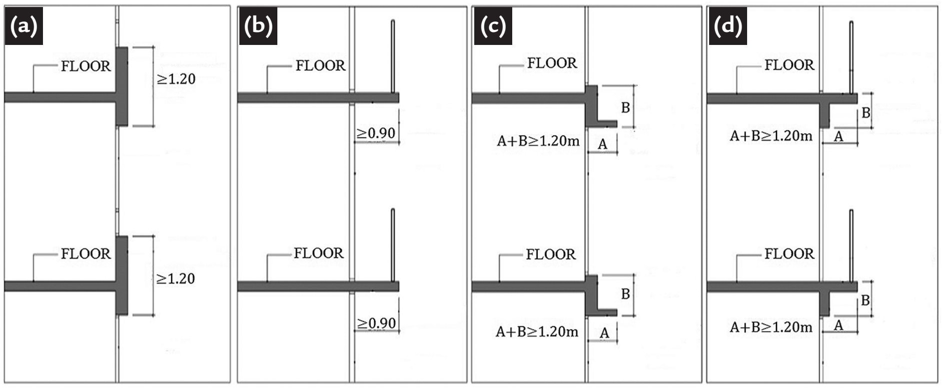

Figure 1 - Models of projections allowed by Brazilian regulations.
(a) Vertical projection only; (b) Horizontal projection only; (c) and (d) Vertical and horizontal projections simultaneously.

In Portuguese regulations, criteria for vertical compartmentation are outlined in Decree No. 1532/2008. In Portugal, the use of vertical and horizontal projections is allowed as passive protection measures for vertical fire containment.

In the United States of America, the National Fire Protection Association 5000 (2021) specifies fire protection measures. This regulation specifies that in buildings with 4 or more floors without sprinkler systems, either vertical or horizontal projections must be used.

The English regulation addressing fire safety criteria is the Building Regulations 2010 (2020). Unlike the other standards evaluated, this regulation allows only the use of horizontal projections.

Table 1 summarizes the dimensions of projections according to the analyzed standards.

Table 1 - Dimensions of analyzed fire projection.

Country	Reference Document	Minimum Vertical Projection (B)	Minimum Horizontal Projection (A)	Minimum total of projections (A+B)
Brazil	IT 09/2019	1.20	0.90	1.20
Portugal	Portaria N° 1532/2008.	1.10	1.00	-
USA	NFPA 5000	0.915	0.76	-
England	Building Regulations 2010	1.00	-	-

3. Methods

In this study, numerical simulations were conducted to assess the possibility of vertical fire spread externally to the facade in multi-story buildings. The simulations were performed using the Fire Dynamics Simulator (FDS), a free program developed by the Institute of Standards and Technology (NIST) and the VTT Technical Research Centre of Finland (MCGRATTAN *et al.*, 2021).

Nineteen numerical simulations were carried out. A reference model without any projections was first developed and then models with three different combinations of dimensions (always with a constant sum of horizontal and vertical dimensions) for each of the configurations in Figure 1 were evaluated. Comparative analyses among horizontal, vertical, and combined projection configurations were performed, taking into account the premises established in IT 09/2019, as well as models proposed by the author to validate fire behavior and discuss the results of the combined projection models. The fire load in this study was considered to be a constant factor, whereby its value was set at 300 MJ/m². Wood cribs were placed at the center of the compartment to simulate a uniform fire load distribution, as is usually performed in this kind of study. Table 2 presents the abbreviations and characteristics of the numerical models in this study.

Table 2 - Characteristics of numerical models.

ACRONYM	PROJECTIONS	DIMENSIONS
M-V0.0-H0.0	Without projection	0.00m
M-V0.0-H0.4	Horizontal projections	0.40m
M-V0.0-H0.6		0.60m
M-V0.0-H0.8		0.80m
M1-V0.6-H0.6	Sum of spandrel and horizontal projections - Model 1	0.60m + 0.60m
M1-V0.4-H0.8		0.40m + 0.80m
M1-V0.8-H0.4		0.80m + 0.40m
M2-V0.6-H0.6	Sum of spandrel and horizontal projections - Model 2	0.60m + 0.60m
M2-V0.4-H0.8		0.40m + 0.80m
M2-V0.8-H0.4		0.80m + 0.40m
M3-V0.6-H0.6	Sum of spandrel and horizontal projections - Model 3	0.60m + 0.60m
M3-V0.4-H0.8		0.40m + 0.80m
M3-V0.8-H0.4		0.80m + 0.40m
M-V0.4-H0.0-I	Lower spandrel	0.40m
M-V0.6-H0.0-I		0.60m
M-V0.8-H0.0-I		0.80m
M-V0.4-H0.0-S	Upper spandrels	0.40m
M-V0.6-H0.0-S		0.60m
M-V0.8-H0.0-S		0.80m

3.1 Compartment geometry

The proposed building geometry aims to replicate a compartment with internal dimensions of 3.00m x 3.00m and a height of 2.60m on the ground floor and 2.80m on the upper floor. These dimensions were chosen based on works by other authors, for example, Pasqualotto (2020) and Morgado and Rodrigues (2013) and are usual sizes for tests on vertical fire propagation. They also allow for a reasonable computational processing time, while much larger models could result in an extremely long simulation that would be unsuitable for the intended parametric study with the available computational resources. Walls and slabs of the compartment were modeled with a thickness of 0.20m. Considering the established measurements, a mesh size of 0.10m x 0.10m x 0.10m was adopted for the analysis of the models. Only projections were considered as obstructions on the front facade of the compartment.

3.2 Studied projections

The projections analyzed in this study are those specified in IT 09/2019, with variations in their dimensions. An additional model was developed to broaden the scope of the analysis. The characteristics of the numerical models in this research are specified in Table 2.

For models with horizontal projections, slab extensions of 0.80m, 0.60m, and 0.40m were introduced. A model without any type of extension, i.e., without any projection, was also simulated. For models with upper spandrels, walls were inserted on the upper floor with dimensions of 0.80m, 0.60m, and 0.40m. In models with spandrels, simulations were also conducted with lower spandrels, where obstructions were placed just above the opening of the lower floor, with dimensions of 0.80m, 0.60m, and 0.40m. Figure 2 presents examples of models with horizontal projections, upper spandrels, and lower spandrels.

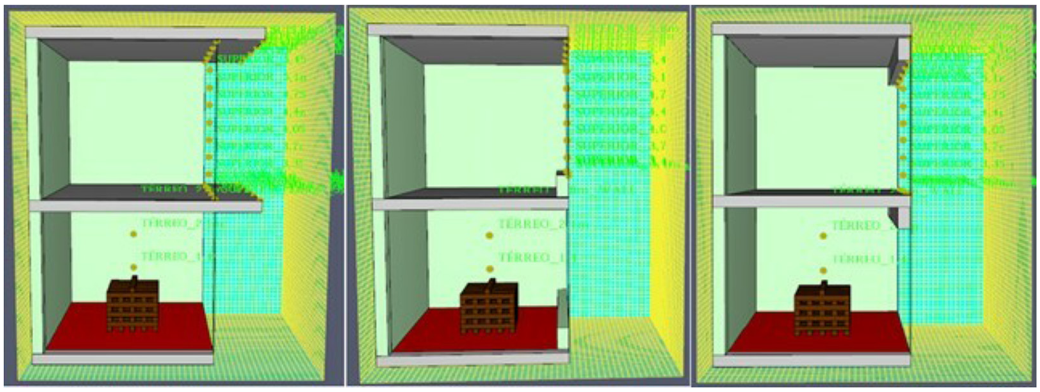

Figure 2 - Models with horizontal, upper vertical, and lower spandrels.

For models with combined projections, two patterns specified in IT 09/2019 and a third proposed by the author were analyzed. For these projection models, the minimum limits established by IT were considered, where the sum of the spandrel portion with the horizontal projection must be greater than or equal to 1.20m. IT does not establish minimum criteria for the vertical and horizontal portions of combined projection models; thus, dimensions were determined by the authors to meet the minimum sum specified in the standard. Figure 3 shows models 1, 2, and 3 of vertical compartmentalization by combined projections, respectively.

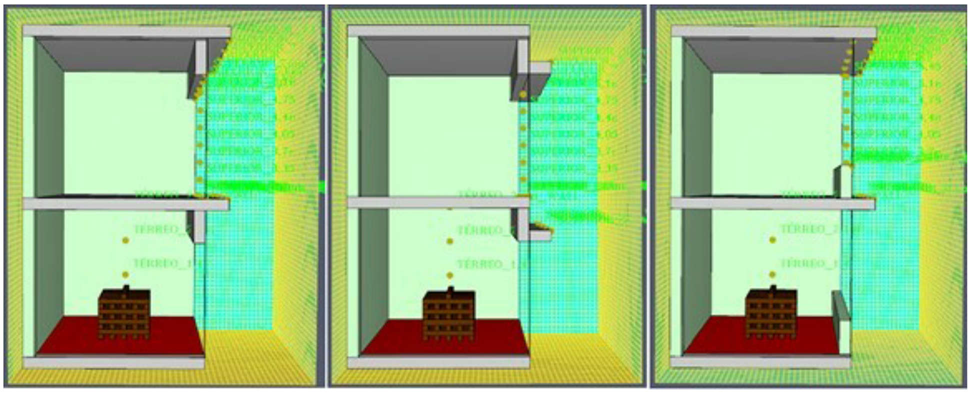

Figure 3 - Vertical compartmentalization by combined projections.

3.3 Fire load

To replicate the fire load, the "wood equivalent" methodology was used, where wood is used to simulate the combustible material required for the environment under study. Eight layers of 5 units and one layer of 1 unit of wood were arranged to simulate the fire load of 300 MJ/m². Table 3 presents the characteristics of the wood used as combustible material.

Table 3 - Wood used as combustible material for 300 MJ/m².

DESCRIPTION		UNITS	VALUE
Characteristics of the wood	Density	kg/m³	369.60
	Calorific Potential	MJ/kg	17.90
Geometry of wooden pieces	Width	m	0.10
	Length	m	1.00
	Thickness	m	0.10
	Volume	m³	0.01
Overall	Compartment Area	m²	9.00
	Total Fire Load	MJ	2712.51
	Specific Fire Load	MJ/m²	301.39
	Quantity of elements	un.	41.00

3.4 Mechanism for temperature measurement

Temperature measurement was performed using mechanisms capable of measuring the temperature of the gases in the ignited compartment. Mechanisms capable of measuring the surface temperature of solids, called wall temperature, were also placed on the lower surface of the floor where the fire originated and at the ends of the vertical and horizontal projections, allowing the analysis of temperature at these positions. Flat temperature measurement mechanisms, called slices, were placed in the central longitudinal direction of the building, central transversal direction, and front facade of the compartment (Figure 4).

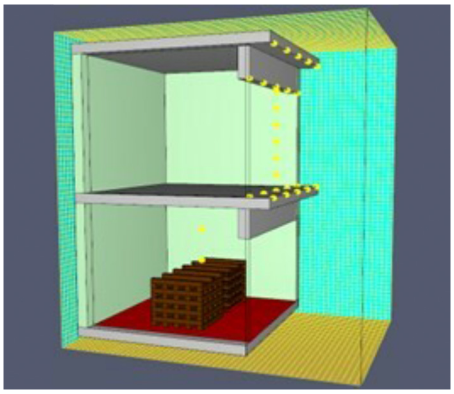

Figure 4 - Temperature measurement mechanisms.

Device names were established for the temperature measurement mechanisms. The "SUPERIOR_4.4 m" mechanism aims to measure the temperature of gases and is located on the upper floor of the compartment at a height of 4.40m from level 0. The "LOWER_2.8 m_WALL" mechanism aims to measure surface temperature in solids and is located on the lower floor of the compartment at a height of 2.80m from level 0.

4. Results

This study focused on modeling numerical scenarios using FDS, allowing for simulations to assess the effectiveness of projections combinations as a passive fire protection measure. Three scenarios with different projection combinations were compared, alongside a scenario featuring only a horizontal projection, adhering to the dimensions specified in IT 09/2019. Table 4 provides details for each scenario.

Table 4 - Analyzed scenarios.

MODEL	SCENARIO 1		SCENARIO 2		SCENARIO 3	
	ACRONYM	DIMENSIONS	ACRONYM	DIMENSIONS	ACRONYM	DIMENSIONS
Horizontal projections	M-V0.0-H0.4	0.40m	M-V0.0-H0.6	0.60m	M-V0.0-H0.8	0.80m
Sum of spandrel and horizontal projections - Model 1	M1-V0.8- H0.4	0.80m + 0.40m	M1-V0.6- H0.6	0.60m + 0.60m	M1-V0.4- H0.8	0.40m + 0.80m
Sum of spandrel and horizontal projections - Model 2	M2-V0.8- H0.4	0.80m + 0.40m	M2-V0.6- H0.6	0.60m + 0.60m	M2-V0.4- H0.8	0.40m + 0.80m
Sum of spandrel and horizontal projections - Model 3	M3-V0.8- H0.4	0.80m + 0.40m	M3-V0.6- H0.6	0.60m + 0.60m	M3-V0.4-H0.8	0.40m + 0.80m

Figures 5 and 6 depict temperature results measured on the facade at device "SUPERIOR_5.1 m" for scenario 1 and the fire behavior, respectively.

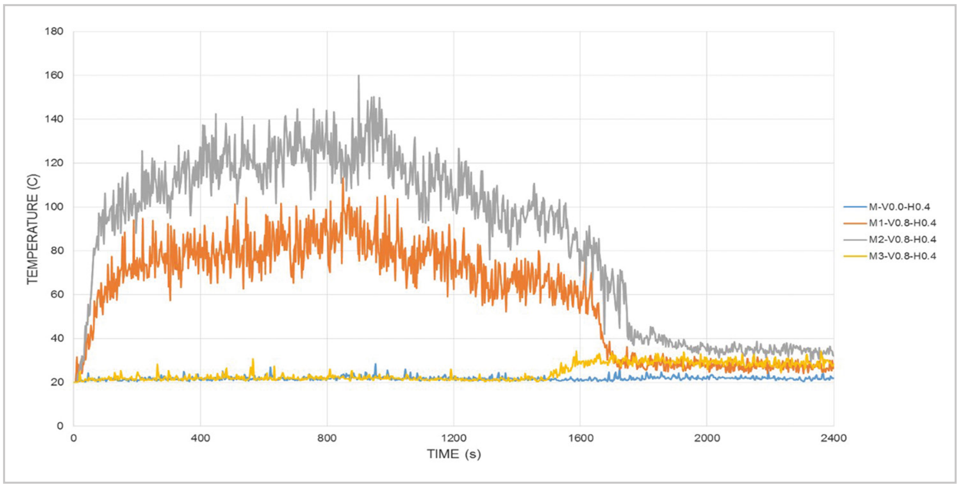

Figure 5 - Temperature versus time curve for scenario 1.

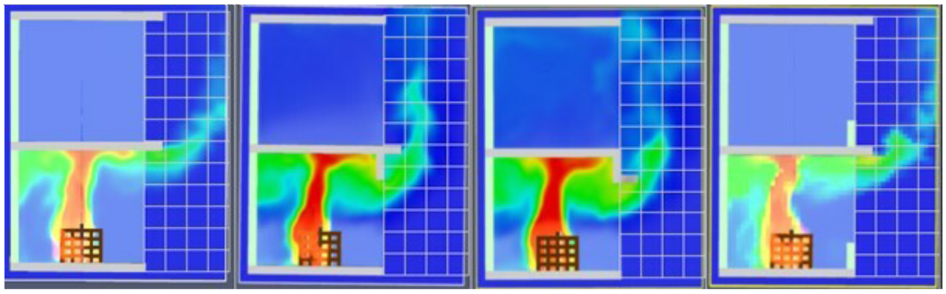

Figure 6 - Fire behavior for scenario 1 with a grid scale of 50 cm.

Table 5 displays the maximum temperatures for scenario 1.

Table 5 - Maximum temperatures for scenario 1.

Model	Maximum temperature (°C)	Time (s)
M-V0.0-H0.4	28.49	952.80
M1-V0.8-H0.4	112.99	849.61
M2-V0.8-H0.4	159.85	900.01
M3-V0.8-H0.4	34.23	2359.21

Simulations indicated that standalone horizontal projection was more effective in containing vertical fire propagation compared to combination projection models. The fire tended to move away from the building.

Figures 7 and 8 show temperature results on the facade at device "SUPERIOR_5.1 m" for scenario 2 and the fire behavior, respectively.

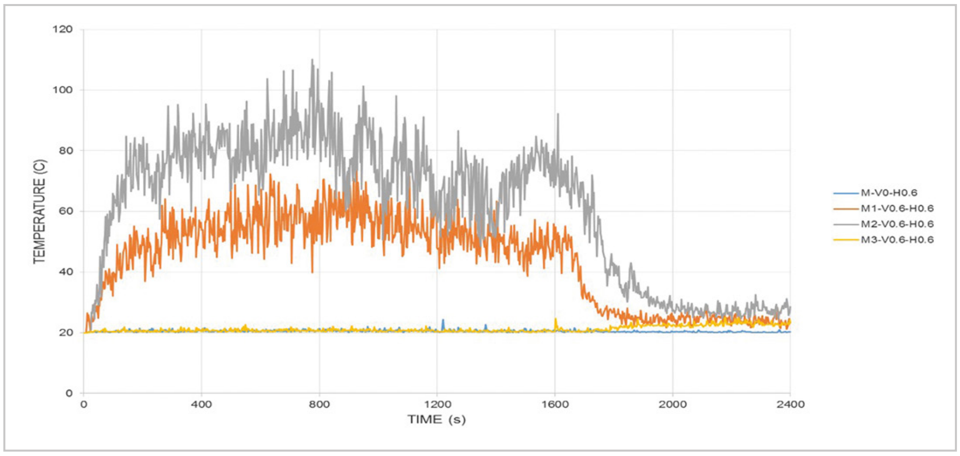

Figure 7 - Temperature versus time curve for scenario 2.

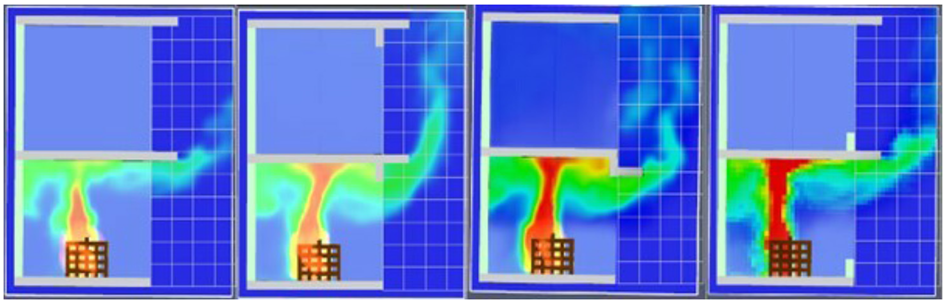

Figure 8 - Fire behavior for scenario 2 with a grid scale of 50 cm.

Table 6 displays the maximum temperatures for scenario 2.

Table 6 - Maximum temperatures for scenario 2.

Model	Maximum temperature (°C)	Time (s)
M-V0.0-H0.6	24.32	1219.21
M1-V0.6-H0.6	76.19	926.40
M2-V0.6-H0.6	110.07	775.20
M3-V0.6-H0.6	25.11	2179.20

Once again, standalone horizontal projection proved more effective in containing vertical fire propagation than combination projection models. Importantly, compared to scenario 1, temperatures on the facade in scenario 2 were lower due to a larger horizontal projection.

Figures 9 and 10 present temperature results on the facade at device "SUPERIOR_5.1 m" for scenario 3 and the fire behavior, respectively.

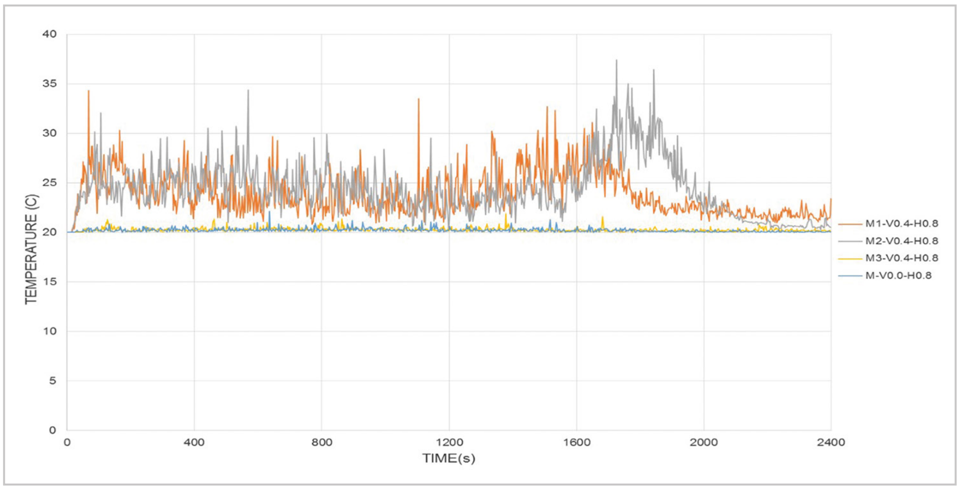

Figure 9 - Temperature versus time curve for scenario 3.

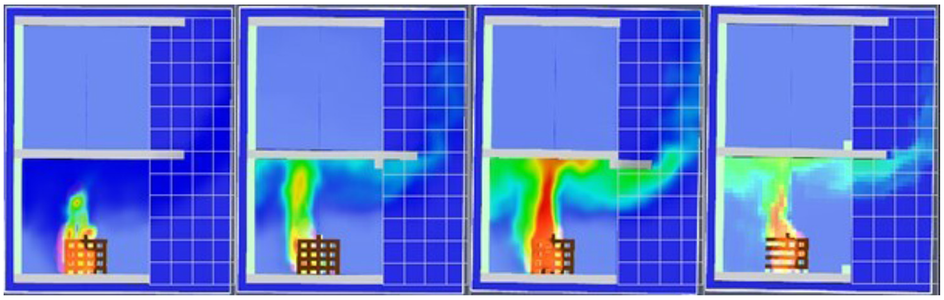

Figure 10 - Fire behavior for scenario 3 with a grid scale of 50 cm.

Table 7 displays the maximum temperatures for scenario 3.

Table 7 - Maximum temperatures for scenario 3.

Model	Maximum temperature (°C)	Time (s)
M-V0.0-H0.8	22.06	636.01
M1-V0.4-H0.8	34.30	67.21
M2- V0.4-0.8	37.36	1725.60
M3- V0.4-0.8	21.85	1377.61

Similarly, standalone horizontal projections outperformed combination projection models in scenario 3, except for the M3-V0.8-H0.8 model, which performed slightly better. Still, this difference can be considered equivalent to the M-V0.0-H0.8 model due to the small percentage difference in maximum temperature. In scenario 3, where horizontal projections were larger, temperatures on the facade were lower than those in scenarios 1 and 2.

The observed temperatures and fire behaviors in the presented scenarios can be explained considering Yokoi's (1960) findings, where a scenario with a contained wall at the upper part of the facade in the burning floor tends to make hot gas rise near the building's facade, leading to increased temperatures on the upper floor. According to Guimarães (2022), openings in burning floors influence upper floor temperatures, with larger openings providing lower temperatures and smaller openings resulting in higher temperatures. Thus, the projection combination models studied in this research cannot be considered equivalent, as they do not exhibit the same effectiveness in vertical external fire compartmentation. It is important to emphasize that, while horizontal projections always reduced the temperatures on the top floor, the use of vertical compartmentation with a larger spandrel dimension can be detrimental, echoing findings from Yokoi (1960) and Guimarães (2022). It emphasizes the importance of normative limits for the optimal use of these models.

5. Discussion

Based on the results presented in section 4, a study was conducted to validate the behavior of the aforementioned fire. For this analysis, a single scenario was considered, allowing for an examination of the model without projections, as well as three models with lower spandrels and three models with upper spandrels, totaling the 7 models analyzed. It is important to note that all 7 models are listed in Table 2.

Figures 11 and 12 show the values of temperatures on the building's facade measured at the "SUPERIOR_5.1 m" device for the seven models and the fire behavior, respectively.

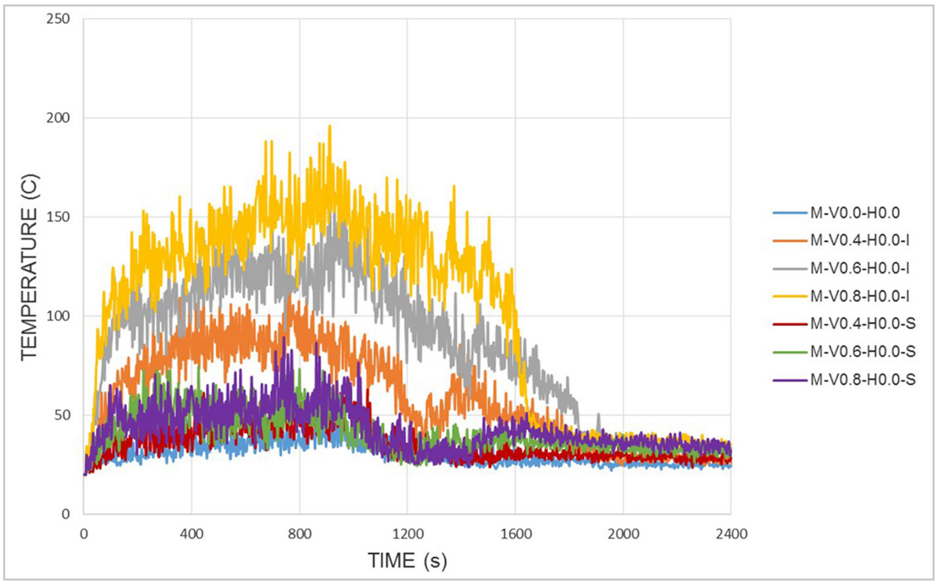

Figure 11 - Temperature versus time curve for the model without projections and models with lower and upper spandrels.

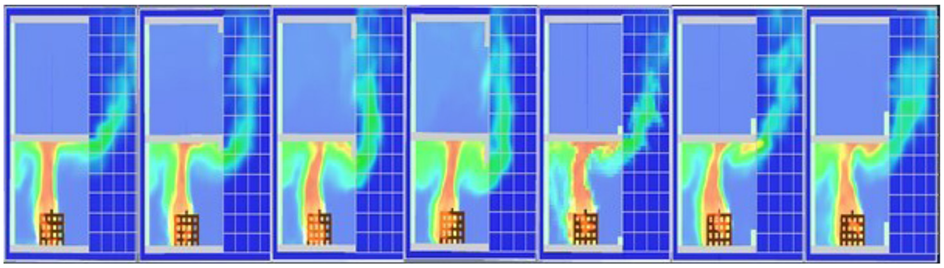

Figure 12 - Fire behavior for the model without projections and models with lower and upper spandrels.

Table 8 presents the maximum temperatures for models without projections and models with lower and upper spandrels.

Table 8 - Maximum temperatures for models without projections and models with lower and upper spandrels.

Model	Maximum temperature (°C)	Time (s)
M-V0.0-H0.0	55.36	866.41
M-V0.4-H0.0-I	22.99	763.21
M-V0.6-H0.0-I	162.19	928.80
M-V0.8-H0.0-I	195.82	912.00
M-V0.4-H0.0-S	68.41	979.21
M-V0.6-H0.0-S	74.34	424.81
M-V0.8-H0.0-S	89.08	741.60

The results shown in Figures 11 and 12 indicate that models with lower and upper spandrels acting alone were able to increase temperatures on the upper floor compared to the model without projections which can be counterintuitive. As the spandrel increases, temperatures can rise on the top floor. This aligns with the results presented in section 4, as well as findings from Yokoi (1960) and Guimarães (2022).

It's worth mentioning that, in cases of lower spandrels, higher temperatures on the upper floor were obtained compared to models with upper spandrels. This behavior was also identified in the studies by Yokoi (1960) and Guimarães (2022), where the presence of a wall (lower spandrels) just above the burning floor, combined with lower facade opening rates, led to the tendency of hot gas rising near the building's wall, increasing the temperature on the upper floor. Additionally, the influence of lower facade opening rates also caused a tendency for higher temperatures on the upper floor.

The fire behavior regarding temperatures presented earlier for the scenario under analysis, can be supported by the findings of these authors: Yokoi (1960), and Guimarães (2022). Thus, it can be considered that the projection combination models in IT 09/2019 and the model proposed in this study are not equivalent, as the dimensions and configurations of a spandrel directly influence the temperature of the upper floor. Considering this, it is emphasized that spandrels tend to cause an increase in the temperature on the upper floor in case of fires, and options for projection combinations with larger proportions of lower spandrels will have lower efficiency in containing the spread of external vertical fire than options with upper spandrels.

6. Conclusions

In this study, the effectiveness of a horizontal projection model, three combination projection models, a model without any projections, and finally, two models with only the spandrel portion of the combination projection models were analyzed using the Fire Dynamics Simulator (FDS).

In the comparative analysis of temperatures on the upper floor, considering the options with combination vertical and horizontal projections, showed that this model, when using a larger horizontal projection portion, presented better results. Thus, it can be concluded that the different models are not equivalent. This can be explained by the excellent effectiveness of horizontal projections, while lower spandrels have a detrimental effect on fire containment. Therefore, models with a portion of this lower spandrel are less efficient than others. Despite this difference, the IT 09/2019 does not account for the increased efficiency of horizontal projections when compared to vertical spandrels in situations where both projections are used simultaneously.

It's also important to note that a larger portion of the lower spandrel, analogous to a beam above the opening, tends to attract gases with high temperatures closer to the compartment, causing the temperature on the upper floor to rise. This behavior is associated with the fact that higher temperatures in cases with larger portions of the lower spandrel may indicate lower oxygen availability inside the compartment. In fire situations where openings are smaller, the fuel (wood) tends to burn more slowly, causing a longer-lasting fire that can raise temperatures on the upper floor. Conversely, wider openings would lead to the opposite effect, creating an abundance of oxygen inside the burning compartment and resulting in a shorter-lived fire with lower temperatures on the upper floor.

In the case of the isolated analysis of models without projections, with lower spandrels, and with upper spandrels, it was possible to confirm the behavior mentioned earlier. It was also found that there is no equivalence between the combination projection models. The dimension and position of a spandrel have a direct influence on the temperature of the upper floor, while the horizontal projection contributes to better compartmentalization.

It is worth mentioning that the model with only the lower spandrel (similar to a beam above the opening) obtained higher temperatures on the upper floor compared to the model with upper spandrels (similar to a parapet on the upper floor). This type of flame behavior emerging through the opening was also reported by Yokoi (1960) and Guimarães (2022).

Considering that, in the numerical studies of this research, the highest temperature found was 159.85 °C at 900.01 seconds for model M2-V0.8-H0.4, and according to Lawson (2009), temperatures between 250 to 399 °C are required for the autoignition of materials, such as fabrics and cotton. It can be affirmed that for the models analyzed in this study with a fire load of 300 MJ/m², there would be no vertical fire propagation to the upper floor of the analyzed compartment. With this temperature, there would still be discomfort and severe burns to human skin, as temperatures around 100 °C are required for these occurrences, according to Lawson (2009).

Considering the conclusions presented above, it is important to highlight that this study has some limitations, such as not considering wind, a small compartment, and a low fire load. Therefore, further studies are necessary to provide more scientific arguments for the conclusions presented.

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