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Effects of Façade Geometry on Fire Spread

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Abstract. The geometry of building façades has become an increasingly significant design parameter in contemporary architecture due to the widespread use of glass, steel, and lightweight cladding systems. While these façade solutions improve aesthetics and energy performance, they may also influence fire development and vertical flame spread, particularly in high-rise buildings. This study investigates the effects of façade geometry on fire spread by evaluating different façade configurations under identical fire conditions. A performance-based fire engineering approach is adopted to analyze how geometric characteristics such as recesses, projections, cavity formations, and façade continuity affect flame behavior, heat transfer, and smoke movement. Numerical simulations are carried out using Fire Dynamics Simulator (FDS), a Computational Fluid Dynamics (CFD)-based software widely employed in fire safety engineering. Several façade geometry models are developed and subjected to the same fire scenario to enable a consistent comparison of fire propagation patterns. The simulation outputs, including temperature distribution, heat release behavior, and flame spread characteristics, are analyzed quantitatively using MATLAB. The results demonstrate that façade geometry has a substantial impact on fire spread mechanisms and may significantly alter the rate and direction of fire propagation. The findings highlight the necessity of considering façade geometry during the early stages of architectural design and emphasize the importance of integrating performance-based fire analysis with existing fire safety regulations. This approach contributes to the development of safer façade systems and supports informed design decisions for fire-resilient buildings.

Keywords: Façade geometry; Fire spread; Fire Dynamics Simulator (FDS); Performance-Based Fire Design; Computational Fluid Dynamics (CFD)

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INTRODUCTION

The façade design of buildings, which constitute a substantial portion of the built environment, has increasingly incorporated diverse geometrical forms as a result of evolving user expectations, advances in technology, and the opportunities offered by contemporary construction systems and materials. In addition to addressing functional, semantic, and aesthetic considerations, one of the most critical challenges associated with contemporary façades designed and constructed to satisfy a wide range of performance requirements has become fire safety. Within the framework of international and national regulations developed to enhance fire safety performance in the built environment, the adaptation of these regulations to emerging building technologies, innovative materials and systems, and novel architectural design approaches, together with their continued relevance, applicability, flexibility, and cost-effectiveness, has been widely discussed, particularly in the field of architecture. In this context, research on performance-based design approaches has continued to expand in pursuit of practical and effective fire safety solutions, and these approaches have increasingly been recognized and implemented as alternative methods in many countries.

Performance-based design is defined in the *SFPE (Society of Fire Protection Engineers) Guide to Performance-Based Fire Protection Engineering* as "(1) an engineering approach based on agreed-upon fire safety goals and objectives; (2) deterministic and/or probabilistic analysis of fire scenarios; and (3) the quantitative evaluation of design alternatives against fire safety goals and objectives using accepted engineering tools, methodologies, and performance criteria." This definition identifies three fundamental characteristics of performance-based design. The first is the specification of the desired level of fire safety for a building (or other structure) under fire conditions. The second is the definition of the building's "design basis." The design basis describes the types of fires, occupant characteristics, and building characteristics for which the building's fire safety systems are intended to provide protection. In performance-based design, these are referred to as "design fire scenarios." The third characteristic is the engineering analysis of the proposed design strategies to determine whether they achieve the intended level of safety under the design fire scenarios

The fire behaviour of contemporary façade systems, which differ significantly from traditional façade types and characteristics, therefore represents an important area of research. Within this context, transparent façades with inclined surfaces were identified as the focus of this study, and the objective was to develop a method for the quantitative evaluation of their fire performance. The proposed method is intended for application in next-generation building designs that aim to achieve performance-based fire safety. In contrast to the conventional prescriptive approach, which provides fire safety solutions within predefined regulatory limits, the proposed method offers a significant and effective alternative for the assessment and achievement of fire safety [1].

METHODOLOGY

In developing the proposed method, the nine-stage design process outlined in the *SFPE (Society of Fire Protection Engineers) Guide to Performance-Based Fire Protection Engineering* was adopted as the methodological framework. Since 1950, SFPE has been recognized as one of the leading organizations in the field of fire safety, conducting scientific, technical, and educational activities aimed at reducing fire risk.

Through the evaluation of data obtained from a comprehensive and systematic literature review, the parameters governing the relationship between façade geometry and fire spread were identified. Based on these findings, the methodological framework and interrelationships underlying the proposed performance-based fire safety approach were established (Figure 1).

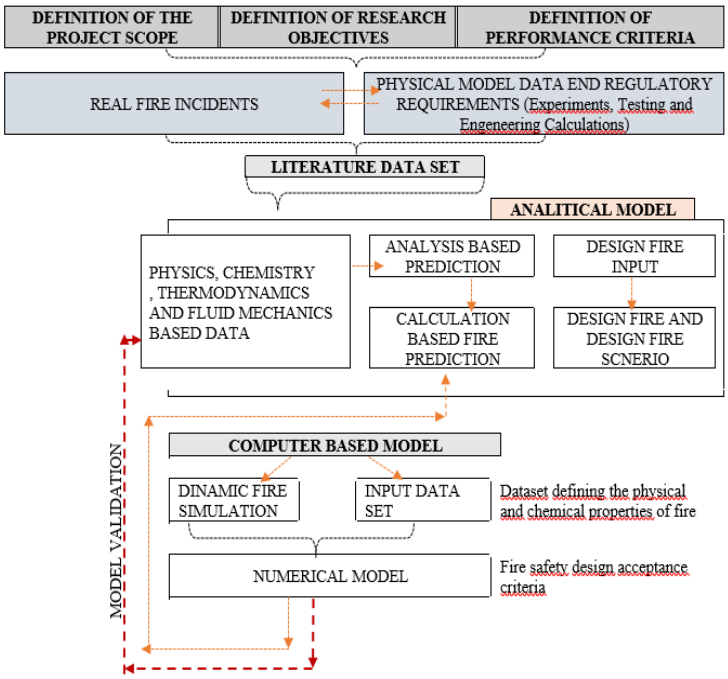


FIGURE 1. Flowchart illustrating the methodological framework and relationships underlying the fire safety concept.

Based on the premise that each fire follows its own unique progression, the systematic methodology illustrated in Figure 2 first defines the scope of fire safety for each individual design and establishes the corresponding objectives and goals, followed by the determination of performance criteria required to achieve these objectives.

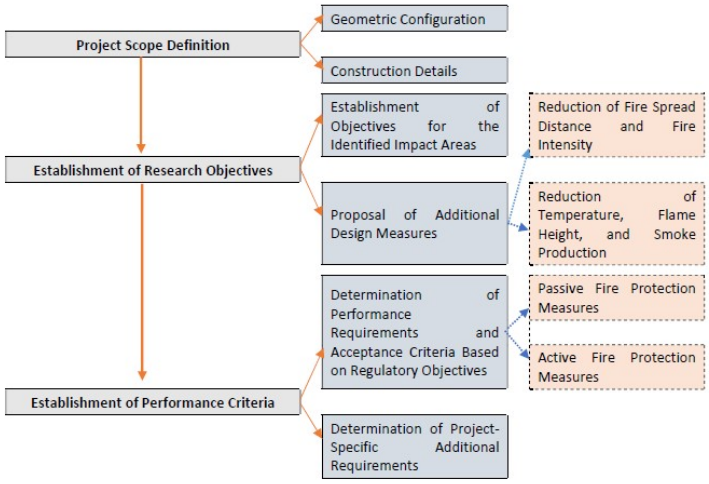


FIGURE 2. Flowchart of the proposed systematic methodology.

The project scope definition involves identifying the presence of geometric configurations and construction details that may contribute to fire growth in terms of flame spread rate, smoke movement, fire intensity, and fire temperature, as well as to the expansion of the fire-affected area through vertical fire spread between building storeys or horizontal fire spread to adjacent buildings at the urban scale. Following the identification of potential risk areas, the threshold values of the parameters required to improve fire performance within the identified impact areas are established, and the corresponding objectives are determined within the framework of the proposed fire safety measures. These objectives are defined based on information derived from a literature dataset comprising documented fire incidents, theoretical studies, numerical analyses, and experimental investigations. In addition, during this stage, the requirements stipulated by the applicable regulations are also taken into consideration, together with the information obtained from the literature dataset, to ensure that the established objectives are achieved. In the final stage, the data obtained from the previous two stages are analyzed and synthesized to determine the performance criteria required to achieve the established objectives, as well as the passive and active fire protection measures to be implemented.

The development of a design fire and its corresponding fire scenario requires the determination of appropriate input parameters, such as the heat release rate (HRR), for evaluating the target fire performance [2]. The heat release rate (HRR) is widely recognized as one of the most important parameters for characterizing potential fire hazards. Defined as the rate at which a fire releases energy, HRR largely governs the environmental consequences of a fire within an enclosed space. Once the HRR is known, it becomes possible to estimate smoke temperature, smoke layer thickness, smoke flow rate, radiative heat flux, the likelihood of flashover, and the effects on nearby combustible materials and structural components within the enclosure. Consequently, empirical correlations and fire models can be used to predict the fire behaviour throughout the building. In other words, HRR provides a basis for predicting the growth and development of a fire.

Based on the lessons learned from real fire incidents, the findings of experimental studies, and the engineering correlations reported in the literature, a well-established HRR value of 1055 kW was adopted. This value was selected from the data presented in Table 1, which provides widely accepted design values for fire growth according to the anticipated occupancy and use of the building. Accordingly, the initial heat release rate was specified as 1055 kW, while the time required to reach this value was taken as 100 s, corresponding to the fast fire growth rate for a residential occupancy, as presented in Table 2. The design fire scenario was defined based on one of the statistically most common residential fire events, namely the ignition of a sofa cushion by a smouldering cigarette in a living room, followed by flame emergence through the window opening [3]. Since the selected HRR values and fire growth characteristics have been validated through both mathematical and experimental studies reported in the literature, they were considered suitable for generating reliable computer-based fire simulation scenarios. Within this framework, the representative fire scenario was initiated by assuming the ignition of a coffee table located in the living area [4-5-6].

TABLE 1. Time required to reach an HRR of 1055 kW for different fire growth rates

Fire Growth Rate	Fire Growth Coefficient, α (kW/s²)	Time to Reach an HRR of 1055 kW, *t* (s)
Slow	0.003	600
Medium	0.012	300
Fast	0.047	150
Ultra-fast	0.188	75

TABLE.2. Fire growth rates for different occupancy types reported in the literature

Occupancy Type	Growth Rates		
Residential Buildings	Fast	Medium	Medium
Schools, Offices	Medium	Fast	Fast
Hotels, Nursing Homes	Fast	—	Fast
Shopping Centres, Entertainment Centres	Fast	Fast	Ultra-fast

In this study, the default ambient conditions provided in the PyroSim simulation software were adopted, and, as discussed above, the initial heat release rate (HRR) and fire duration for the design fire were specified as 1055 kW and 100 s, respectively, based on the generally accepted values reported in the literature (see Table 3).

TABLE 3. Ambient environmental parameters for the design fire scenario

Simulation Parameters				
Initial HRR (kW)	Ambient Temperature (°C)	Relative Humidity (%)	Wind Conditions	Simulation Duration (s)
1055	10	40	Light breeze (7.2 km/h)	100

The first stage of the study, namely the project scope definition, was established based on the premise that the geometric configuration, as the principal design criterion of building façades, plays a significant role in influencing flame movement, flame spread rate, and smoke movement during a fire [7].

Three principal façade geometries were defined, comprising a flat façade, outward-inclined façades at angles of 80° and 85°, and outward-inclined façades at angles of 95° and 100°. Each façade configuration incorporated overhangs ranging from 0 to 30 cm in length. Based on these façade geometries, 11 different design cases were developed to analyse the movement of heat, smoke, and flames over the façade surface as a function of geometric variation. The characteristics of the façade geometries are presented in Table 4.

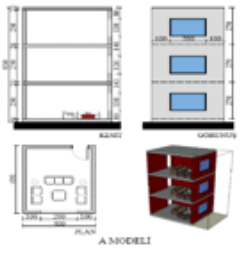
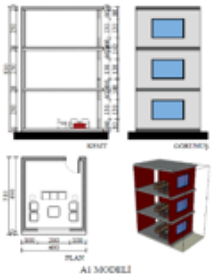
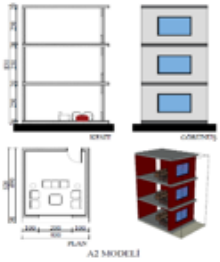
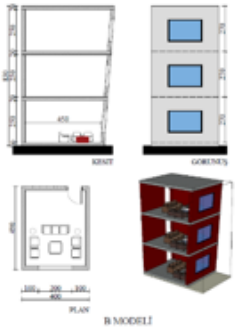
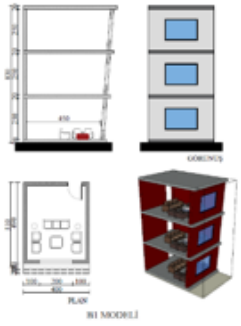
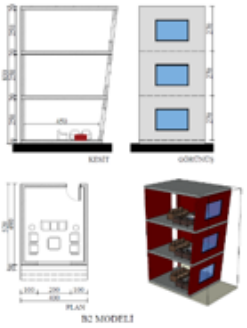
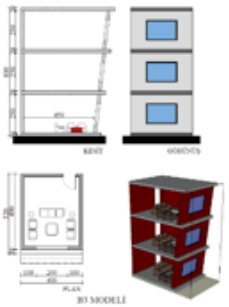
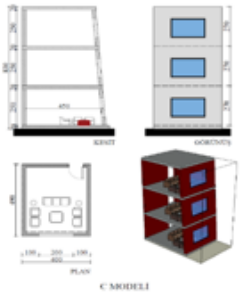
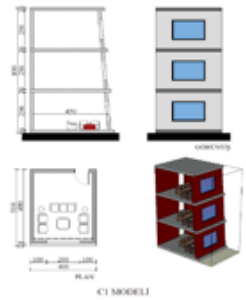
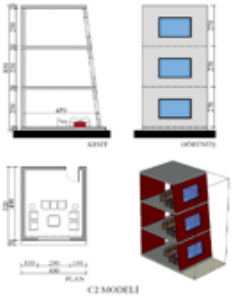
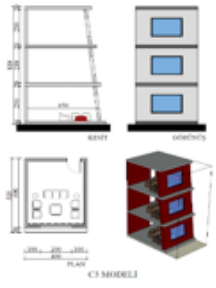
TABLE 4. Characteristics of the façade geometries

Façade Type	Façade Geometry	Overhang Length
(A)	Flat façade	None
(A1)	Flat façade with a 20 cm floor-slab overhang	20 cm
(A2)	Flat façade with a 30 cm floor-slab overhang	30 cm
(B)	85° outward-inclined façade	None
(B1)	85° outward-inclined façade with a 20 cm floor-slab overhang	20 cm
(B2)	80° outward-inclined façade	None
(B3)	80° outward-inclined façade with a 30 cm floor-slab overhang	30 cm
(C)	95° outward-inclined façade	None
(C1)	95° outward-inclined façade with a 20 cm floor-slab overhang	20 cm
(C2)	100° outward-inclined façade	None
(C3)	100° outward-inclined façade with a 30 cm floor-slab overhang	30 cm

The case studies selected to evaluate the fire safety performance of the façades were deliberately simplified to facilitate the analysis while taking into consideration the design principles that commonly promote the use of inclined façades in the built environment, such as their expression of architectural prestige and the enhancement of façade perspective through the emphasis of floor-slab overhangs.

For each case study, a three-storey building was developed based on the BS 8414 reference model, with a storey height of 2.70 m. The façade measured 4.00 m in width and 8.10 m in height, corresponding to a total façade surface area of 32.40 m². Each storey incorporated a window opening measuring 2.00 m × 1.30 m, resulting in an opening area of 2.60 m². The façade configurations corresponding to Scenarios A, B, and C are presented in Table 5.

TABLE 5. Façade configurations corresponding to the design scenarios

Scenario A	Type A	Type A1	Type A2	
				
Scenario B	Type B	Type B1	Type B2	Type B3
				
Scenario C	Type C	Type C1	Type C2	Type C3
				

METHODOLOGICAL FRAMEWORK

The systematic methodology, illustrated in Figure 3, was developed based on the premise that each fire follows its own unique evolution. Briefly, the methodology establishes the principal inputs of the proposed framework by first defining the scope of fire safety for each design, followed by the establishment of the research objectives and goals, and subsequently the definition of the performance criteria.

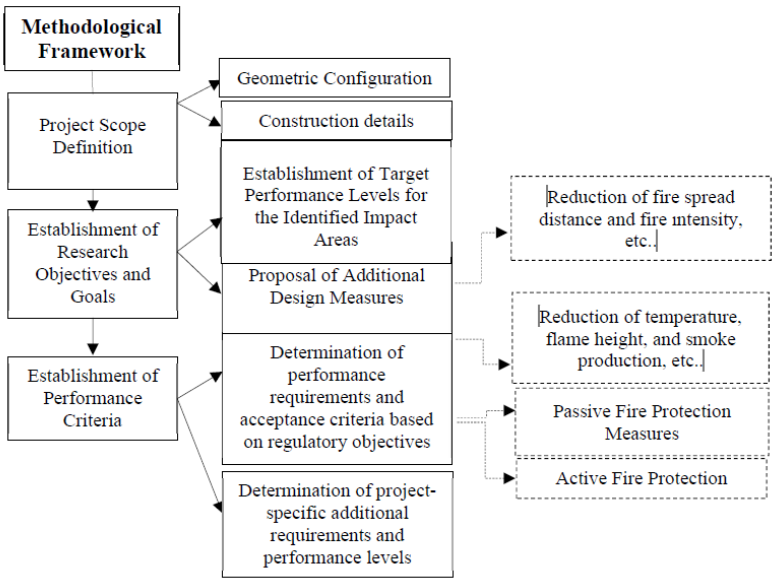


FIGURE 3. Flowchart of the proposed methodological framework.

Within this framework, if ensuring the fire safety of a building façade is defined as the design problem, it becomes possible to analyse the factors that contribute to flame movement, flame spread rate, smoke movement, fire intensity, fire temperature, and fire growth, as well as the potential for vertical fire spread between storeys and horizontal fire spread to adjacent buildings at the urban scale. Consequently, the corresponding impact areas can be identified [8].

Considering that geometric configuration and, subsequently, construction details play key roles in this process, the project scope definition is established accordingly. This enables the determination of objectives aimed at reducing parameters such as temperature, flame spread, and fire intensity within the identified impact areas, or alternatively, at implementing passive and active fire protection measures. Within this framework, the performance criteria can be established by taking into account the requirements specified in applicable regulations and standards, together with project-specific considerations, such as additional client requirements or statutory obligations. Accordingly, the accurate definition of these parameters constitutes a fundamental stage of the proposed methodology [9-10].

The proposed methodology can be applied to next-generation designs that adopt a performance-based fire safety approach and is expected to become one of the principal alternatives to the traditional prescriptive approach, which provides fire safety solutions within predefined regulatory limits.

VALIDATION OF THE PROPOSED METHOD – ANALYSIS OF THE EFFECTS OF FAÇADE GEOMETRY UNDER FIRE CONDITIONS

Accordingly, this study focuses on the premise that appropriate façade design can mitigate the risk of fire spread by preventing a fire originating within a building from propagating to adjacent structures and causing large-scale environmental or urban disasters. In this context, façade design is considered a passive fire protection measure capable of reducing the risk of fire spread. Therefore, the reduction of the distance associated with the upward external flame spread from an open window or opening along the building façade (leapfrog effect) [11], together with the reduction of temperature and smoke, was established as the primary performance criteria.

Following the transformation of the outputs obtained from the analytical model into a numerical dataset, the Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST) and first released as an open-source software package in 2000, was used for the evaluation and interpretation of the results. Smokeview, the visualization interface of FDS, was employed to present the simulation results visually [12-13].

The computational domain was defined as 6.50 m × 4.90 m × 8.10 m. A uniform computational mesh with cell dimensions of 0.20 m × 0.20 m × 0.20 m was adopted throughout the model. For the cases incorporating floor-slab overhangs on inclined façades, the mesh size was locally refined to 0.10 m × 0.10 m × 0.10 m to obtain more detailed results in the regions affected by the façade geometry.

The potential effects of façade geometry on flame spread, smoke movement, and temperature during a fire were evaluated through 11 predefined scenarios. Each scenario was simulated for 100 s using PyroSim, the graphical user interface that enables performance-based fire simulations with FDS. Consequently, an individual dataset was generated for each scenario. The temporal development of smoke movement and temperature distribution was visualized using Smokeview, as illustrated in Figure 4.

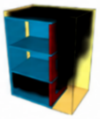
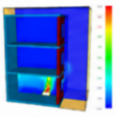
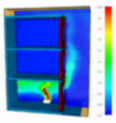
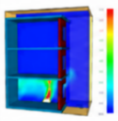
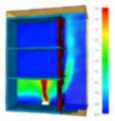
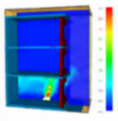
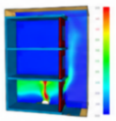
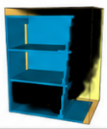
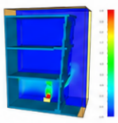
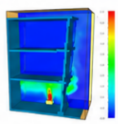
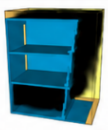
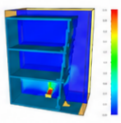
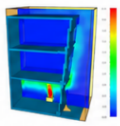
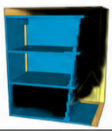
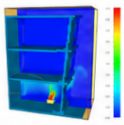
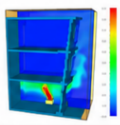
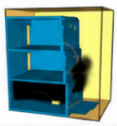
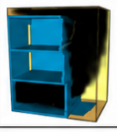
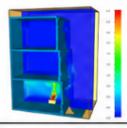
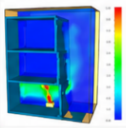
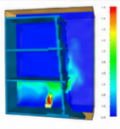
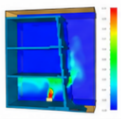
SCENARIO	SMOKE EXHAUST HEIGHT		TEMPERATURE CHANGE		MAXIMUM TEMPERATURE / TIME		MAXIMUM HRR / TIME	
	10 Seconds	25 Seconds	10 Seconds	25 Seconds	Time	Temperature	Time	HRR
A 90° Without Overhang					65 sec.	115°C	86 sec.	340 kW
A1 90° 20 cm. Overhang					100 sec.	105°C	80 sec.	300 kW
A2 90° 30 cm. Overhang					60 sec.	85°C	95 sec.	300 kW
B1 85° 20 cm. Overhang					100 sec.	95°C	89 sec.	370 kW
B2 80° Without Overhang					90 sec.	125°C	82 sec.	350 kW
B3 80° 30 cm. Overhang					85 sec.	85°C	90 sec.	360 kW
C 95° Without Overhang					60 sec.	95°C	90 sec.	310 kW
C1 95° 20 cm. Overhang					75 sec.	85°C	78 sec.	350 kW

FIGURE 4. Temporal evolution of smoke spread and temperature distribution

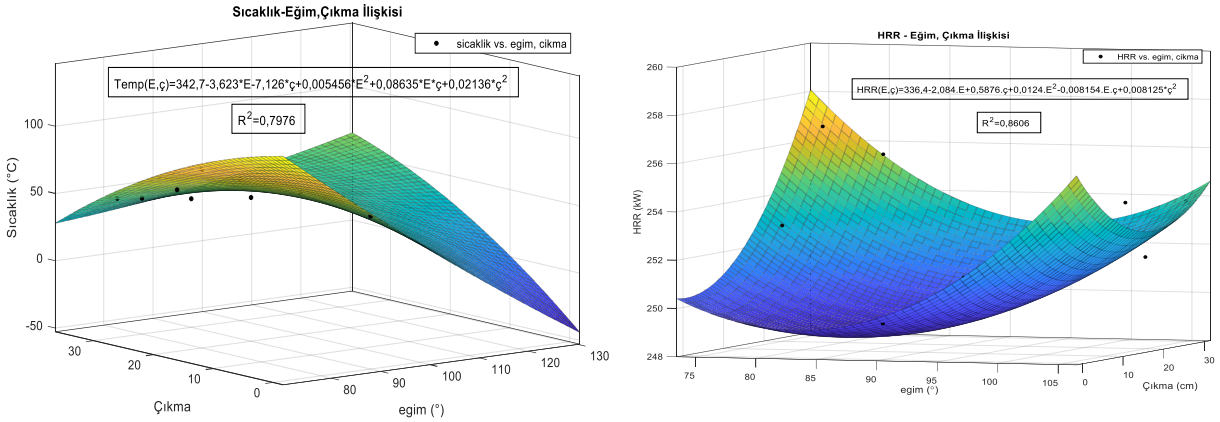
Using the *Plot Time History Results* function available in the PyroSim interface, numerical datasets corresponding to each simulation scenario were obtained. Subsequently, all HRR and temperature datasets were imported into MATLAB (Matrix Laboratory) to enable a more detailed evaluation of the effects of façade overhangs and inclination on temperature and HRR. Furthermore, for each scenario, the relationships between façade overhang, façade inclination, temperature, and HRR were investigated using the mean and median values calculated in MATLAB.

Overall, the results indicate that the HRR varies according to the façade geometry, with fire intensity increasing as the façade inclination angle increases. In contrast, the temperature distribution was found to vary with both façade geometry and overhang length, with temperature decreasing as the inclination angle increased. Evaluation of the simulation data further revealed that the HRR increases in inverse proportion to the façade inclination and in direct proportion to the overhang length, whereas temperature increases in direct proportion to the façade inclination and in inverse proportion to the overhang length. Based on these observations, the mean and median values of the 1,001 data points obtained from each simulation scenario were calculated using MATLAB (Table 6).

TABLE 6. Characteristics of the façade geometries

Scenerio	Façade Inclination (°)	Overhang (cm)	HRR		Temperature	
			Mean	Median	Mean	Median
A	90	0	250,6	249,5	60,84	55,7
A1	90	20	251,5	250,8	54,03	52,07
A2	90	30	250,9	250,6	42,77	43,86
B	85	20	254,1	252,8	67,29	64,78
B1	85	30	261,3	256,6	50,61	50,82
B2	80	20	251,8	250,5	79,62	81,13
B3	80	30	259,1	255,5	48,24	46,78
C	95	20	251,7	251,3	51,86	49,24
C1	95	30	255,2	253,7	52,13	54,55
C2	100	20	251,9	251,8	46,18	45,34
C3	100	30	255,7	253,8	45,82	49,53

Regression analysis of these data was performed in Microsoft Excel to evaluate the relationships between façade overhang, façade inclination, temperature, and HRR based on regression statistics. The results indicated that, to improve the accuracy of the relationship, the formulation between the independent and dependent variables should be extended to a second-order polynomial model. Accordingly, the same datasets were reanalysed in MATLAB to obtain a second-order polynomial formulation. As a result, a mathematical model describing the relationship between temperature, façade inclination, and overhang was developed, with a coefficient of determination (R^2) of 79.76% (Figure 5a). The same procedure described above was also applied to determine the relationship between HRR and façade inclination and overhang. As a result, a mathematical model describing the relationship between HRR, façade inclination, and overhang was developed, with a coefficient of determination (R^2) of 86.06% (Figure 5b).



(a) **(b)**

FIGURE 5. Relationships between façade inclination/overhang and (a) temperature and (b) HRR.

An example illustrating how the obtained graphs and equations can be applied is presented below using the diagram shown in Figure 6.

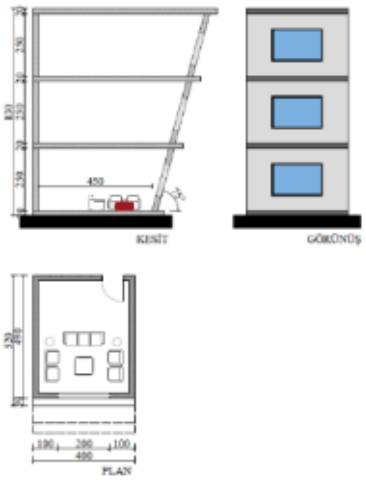


FIGURE 6. Example case selected for the validation scenario.

The representative case was defined using a façade inclined outward at 75° with a 30 cm overhang. By substituting the corresponding façade parameters into the first equation, which describes the relationship between temperature, façade inclination, and overhang, the predicted mean temperature beneath the second-floor window after 100 s of fire exposure was calculated as follows:

Temp(E,c)=342.7-3.623E-7.126\c+0.005456E^2+0.08635E\c+0.02136\c^2

$$\text{Temp}(75,30) = 342.7 - 3.623(75) - 7.126(30) + 0.005456(75)^2 + 0.08635(75)(30) + 0.02136(30)^2 = 101.3965°\text{C}$$

Similarly, the second equation, which defines the relationship between HRR, façade inclination, and overhang, was used to estimate the mean fire intensity after 100 s by substituting the façade parameters into the equation:

HRR(E,c)=336.4-2.084E+0.5876\c+0.0124E^2-0.008154E\c+0.008125\c^2

$$\text{HRR}(75,30) = 336.4 - 2.084(75) + 0.5876(30) + 0.0124(75)^2 - 0.008154(75)(30) + 0.008125(30)^2 = 256.444\ \text{kW}$$

A visual inspection of the graphs, together with an analysis of the mean and median values of the 1,001 temperature–time data points and 1,001 HRR–time data points obtained for the validation scenario from the PyroSim simulation in MATLAB, showed that the mean HRR value predicted by the developed equation was in almost complete agreement with the simulation results. In contrast, the predicted temperature value was found to be higher than the mean temperature obtained from the simulation. This discrepancy was attributed to the relatively lower predictive accuracy of the equation describing the relationship between temperature, façade inclination, and overhang.

CONCLUSIONS AND RECOMMENDATIONS

According to the evaluation of smoke spread among inward-inclined, outward-inclined, and flat façades, the inward-inclined C2 façade provided the most effective solution. In other words, a reduction in smoke spread was observed as the façade inclination angle increased. However, when overhangs were introduced, the A2 façade, consisting of a flat surface with a 30 cm overhang, exhibited both smoke detachment from the façade surface and lower smoke spread than the other façade configurations. While the overhang acted as a smoke deflector on the flat façade, it caused the smoke to recirculate above the overhang and move back towards the façade surface on both inward- and outward-inclined façades. Therefore, it was concluded that, within the scope of this study, the use of overhangs on inclined façades was not an effective design solution.

The temperature–time curves obtained for all case studies showed that horizontal projections acted as flame deflectors. Among the façades without overhangs and those with outward inclinations, the highest temperature values were recorded for the B2 façade configuration, and the measured temperatures increased as the façade angle decreased.

Accordingly, it was concluded that temperature increased with decreasing façade inclination angle, indicating an inverse relationship between temperature and façade inclination.

The highest HRR values, one of the most important indicators of fire severity and fire safety performance, were recorded approximately between 80 and 90 s for Scenarios A and B, whereas the maximum HRR values for Scenario C occurred between 65 and 85 s. Accordingly, increasing the inward inclination of the façade caused the peak fire intensity to occur within a shorter period, although the difference was not substantial compared with the other scenarios. Since this behaviour may accelerate the transition to the flashover stage, it is considered appropriate to exercise greater caution in implementing measures aimed at reducing fire intensity in buildings incorporating inward-inclined façades. The heat release rate also decreased with increasing façade inclination angle for the different façade configurations investigated. Although increasing the overhang dimension resulted in a slight increase in HRR, the effect was not significant. Therefore, it was concluded that additional investigations using larger and more varied overhang dimensions are required to better evaluate the influence of overhang size on HRR.

It was determined that a horizontal projection must exceed 20 cm to effectively alter the trajectory of the smoke plume. Furthermore, projections exceeding 30 cm were found to be more effective in reducing heat transfer along the façade surface. It was therefore concluded that combining horizontal projections with inclined façade surfaces may provide an effective design strategy for minimising vertical fire spread.

Since the façades considered in this study were assumed to be constructed from reinforced concrete, the effects of fire on façade materials were not included within the scope of the investigation. Therefore, the influence of both adhesively bonded and mechanically fixed cladding systems should also be taken into consideration during the design process.

A comparison of the effects of different façade configurations on flame and smoke spread during fire demonstrated that systems incorporating outward-inclined façades present a greater fire hazard than the other façade configurations examined. Furthermore, because overhang elements on both inward- and outward-inclined façades tended to redirect smoke back towards the façade surface, it is anticipated that designing such façades without discontinuous overhang elements would provide a more effective solution.

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