

## Effects of Ventilation Opening Location on Fire Development and Tenability in Multi-Storey Urban Dwellings



Duy Nguyen Le 

Faculty of Fire Suppression and Rescue, University of Fire Prevention and Fighting, Hanoi 120602, Vietnam

Corresponding Author Email: [mrleduy91@gmail.com](mailto:mrleduy91@gmail.com)

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<https://doi.org/10.18280/ijss.160409>

### ABSTRACT

**Received:** 3 March 2026

**Revised:** 14 April 2026

**Accepted:** 22 April 2026

**Available online:** 30 April 2026

#### **Keywords:**

*fire development, multi-storey urban dwelling, smoke spread, stairwell, tenability, ventilation opening location*

Fire in multi-storey urban dwellings can rapidly threaten life safety because smoke, heat, and toxic gases spread through vertically connected spaces, particularly the stairwell. This study used fire dynamics simulator (FDS) to examine eight ventilation-opening scenarios in a multi-storey urban dwelling. The results showed that opening location substantially influenced both fire intensity and tenability. The simultaneous opening of the level-1 main entrance and the roof was the most adverse scenario, with a peak heat release rate (HRR) of 34.34 MW at 603.6 s and a 55.7% increase in mean HRR during 600–660 s compared with the pre-intervention period. Stairwell conditions also deteriorated markedly, with the mean temperature during 600–1200 s increasing from 403.3 °C in the baseline case to 566.7 °C. Some higher-level openings produced localized improvements in the front room; in Room 1 at level 5, the combined opening of the level-5 balcony door and the roof reduced the mean temperature from 149.9 to 95.3 °C, carbon monoxide (CO) concentration from 2,333 to 398 ppm, and fractional effective dose (FED) from 128.41 to 42.54. However, improvement in the rear rooms was limited; in Room 2 at level 2, the same scenario reduced FED only from 1.91 to 1.31. Overall, ventilation opening strategies in this building type should be understood as a trade-off, in which any localized benefit in the target space must be weighed against simultaneous fire intensification and deterioration along the stairwell.

## 1. INTRODUCTION

Multi-storey urban dwellings present a high risk to life safety in the event of fire because smoke, heat, and toxic gases can spread rapidly under conditions of restricted external access. According to the annual report of the Fire Prevention, Firefighting and Rescue Police, from 15 December 2024 to 14 December 2025, 3,151 fires occurred nationwide, causing 90 deaths and 98 injuries; of these, fires in single-family dwellings accounted for 36.12% of all incidents, while fires in mixed-use residential buildings accounted for 6.00% [1]. Several particularly severe recent fires in urban residential areas also showed that, when fire develops in multi-storey buildings with limited access, smoke and toxic gases can quickly render conditions unsurvivable and lead to catastrophic loss of life [2]. These findings indicate that fire safety in multi-storey urban dwellings remains an important research issue in terms of both fire development and tenability.

In this building type, the stairwell serves not only as the main vertical circulation route but also as a highly sensitive pathway for the spread of smoke, heat, and toxic gases under different ventilation conditions. Previous studies showed that opening location and ventilation state could significantly influence smoke movement, thermal conditions, and hazard distribution in stairwells and other vertically connected spaces [3-13]. However, most existing studies mainly examined

whether openings were open or closed, or considered only a single opening configuration, and often focused on smoke movement or stairwell conditions rather than simultaneously assessing the broader consequences of opening location in multi-storey buildings.

Recent simulation-based studies have extended fire-risk assessment beyond static hazard identification by combining multi-criteria assessment methods with evacuation and smoke-spread modelling. Li et al. [14] assessed fire risk in employee dormitory buildings using the Ordinal Priority Approach and PyroSim, showing that visibility, ventilation conditions, and fire-fighting facilities are important factors affecting evacuation safety and available safe evacuation time. He et al. [15] combined DEMATEL and PyroSim to evaluate fire risk in multi-functional teaching buildings, highlighting the influence of wind speed and wind direction on smoke propagation, particularly in stairwells. These studies support the use of scenario-based simulation for evaluating fire hazards and life-safety conditions in multi-storey buildings. Nevertheless, they mainly address fire-risk assessment, evacuation safety, or smoke-control performance at the building scale, rather than the operational consequences of where ventilation openings are introduced during fire intervention.

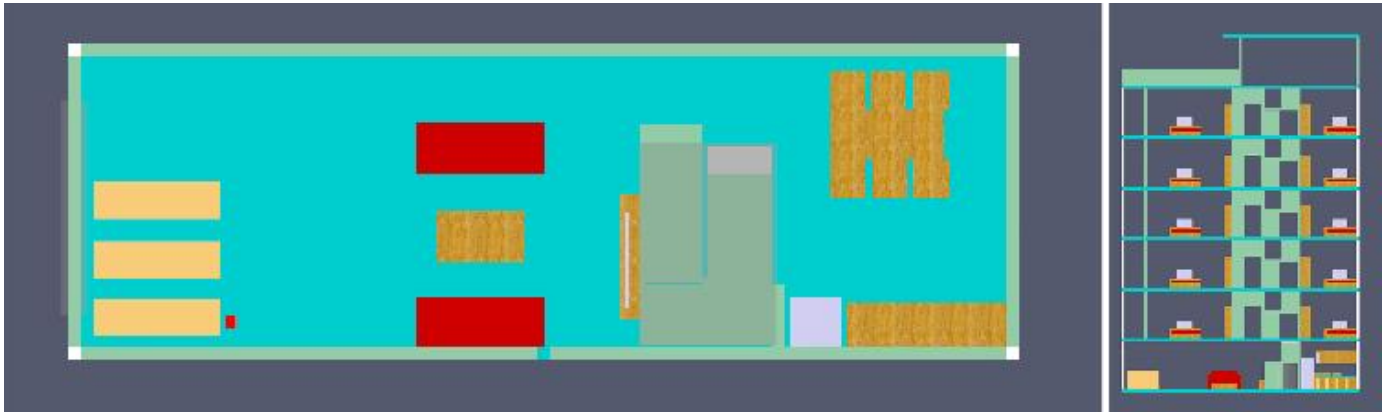
Therefore, quantitative evaluations are still lacking that simultaneously examine three aspects under different opening

locations in multi-storey urban dwellings: whole-building fire development, tenability conditions along the stairwell axis, and localized improvement or deterioration in target spaces within the building. This gap is particularly important because one opening action may produce local benefits in one room while simultaneously worsening conditions along the main access route. On this basis, this study used fire dynamics simulator (FDS 6.9.1) to examine eight scenarios in a representative multi-storey urban dwelling, including one baseline case and seven ventilation-opening configurations at different locations. The aim of the study was to clarify how the location and combination of ventilation openings alter the trade-off among fire intensification, stairwell conditions, and localized effects in target spaces under a common intervention applied at 600 s.

## 2. MATERIALS AND METHODS

### 2.1 Building model and simulation conditions

Fire simulations were conducted for a representative multi-storey urban dwelling of tube-house form, a common building type in high-density residential areas. The building had overall dimensions of  $15.0 \times 5.0$  m and consisted of six occupied storeys with a roof level above. The height to the top of the roof parapet was 22.2 m. Each typical storey had a clear height of 3.0 m, a floor slab thickness of 0.2 m, and a main wall thickness of 0.2 m. Figure 1 presents the floor plan and vertical section of the building model, while the main geometric dimensions and representative openings are summarized in Table 1.



**Figure 1.** Floor plan and vertical section of the building model

**Table 1.** Main simulation parameters

Parameter	Value
Building type	Multi-storey urban dwelling (tube-house form)
Building dimensions	$15.0 \times 5.0$ m
Number of storeys	6 storeys and roof level
Clear storey height	3.0 m
Slab / wall thickness	0.20 / 0.20 m
Simulation software	FDS
Simulation duration	1200 s
Number of meshes	8
Total number of cells	551,831
Grid size	0.10 m in the fire region; 0.20 m in the remaining regions
Device output interval	$\approx 1.2$ s
Initial ambient temperature	20 °C
Ambient pressure	101,325 Pa
Initial relative humidity	41%
Fire source location	$(x, y, z) = (3.575, -4.40, 0.075)$ m
Fire source dimensions	$0.15 \times 0.20 \times 0.15$ m
Burner HRRPUA	49.4 kW/m <sup>2</sup>
Burner TMP_FRONT	805 °C
Combustion reaction	SFPE POLYURETHANE_GM37 fuel
CO yield / soot yield	0.024 / 0.113
Heat of combustion	17.9 MJ/kg
Radiative fraction	0.514
Ventilation intervention time	600 s
Scenarios	S0–S7

Notes: FDS = fire dynamics simulator; HRRPUA = heat release rate per unit area; TMP\_FRONT = front surface temperature of burner

From level 2 to level 6, each storey contained three main spaces: Room 1 (front room), the central stairwell, and Room 2 (rear room). Room 1, representing the front room, measured approximately  $5.4 \times 4.6$  m and was connected to a front balcony measuring  $1.2 \times 4.6$  m. It could exchange air with the

outdoor environment through door gaps and other small openings. Room 2 measured approximately  $3.5 \times 4.6$  m and represented rear rooms located deeper inside the building, without direct natural ventilation to the outside. The stairwell measured approximately  $3.9 \times 4.7$  m, extended continuously

through all storeys, and served as the principal vertical pathway for the spread of smoke, heat, and combustion gases.

All simulations were performed using FDS for a total simulation time of 1,200 s for each scenario [16, 17]. The computational domain was divided into eight meshes, with a total of 551,831 cells. A cell size of 0.10 m was used in the fire compartment and the area in front of level 1, where finer resolution was required to capture fire development and airflow exchange through the main openings, whereas a cell size of 0.20 m was used in the remaining regions. Output data from measuring devices were recorded at intervals of approximately 1.2 s.

The mesh system was selected on the basis of the characteristic fire diameter criterion,  $D^*/\delta_x$ , as recommended in the FDS User's Guide, where  $D^* = (\dot{Q}/\rho_\infty c_p T_\infty \sqrt{g})^{2/5}$  and  $\delta_x$  is the nominal cell size [16]. For the representative heat (HRR) release rates considered in this study, ranging from 18.19 MW in the baseline scenario to 34.34 MW in the most adverse scenario, the corresponding  $D^*$  values were approximately 3.07-3.96 m. Accordingly, in the fine-mesh region with  $\delta_x = 0.10$  m, the  $D^*/\delta_x$  ratio was approximately 30.7-39.6, indicating sufficient resolution to represent the fire source, the initial plume, and exchange flow through the main openings. In the remaining regions, where a 0.20 m cell size was used, the corresponding  $D^*/\delta_x$  ratio was approximately 15.4-19.8, which remained suitable for analysing smoke spread and for comparing whole-building responses across scenarios. This mesh treatment is consistent with previous simulation studies of smoke flow in stairwells, in which the mesh system was assessed through grid-independence checks or mesh-sensitivity analysis before the main analysis was conducted [4, 8]. Because the same mesh arrangement was used for all eight cases, the effect of numerical discretization was kept consistent across scenarios, thereby allowing controlled comparisons of HRR, temperature, visibility, carbon monoxide (CO), and fractional effective dose (FED) under different ventilation-opening configurations.

## 2.2 Fire source and materials

The fire source was located near the main entrance on level 1, representing the vehicle parking area commonly found on the ground floor of urban dwellings in Vietnam. The fire was initiated by a localized burner positioned near the front façade and then allowed to interact with combustible materials and fuel items arranged within the level-1 space. In the model, the fire load on level 1 was simplified by retaining the main combustible groups most likely to govern fire development in a typical parking/storage area, including wood and polyurethane-based materials (plastics and upholstered items), rather than reproducing every individual object in detail. This approach allowed a reasonable representation of the heat source and fire environment on level 1 while maintaining model feasibility [16, 17]. The burner was assigned the reaction SFPE POLYURETHANE\_GM37, with the main parameters including the CO yield, soot yield, heat of combustion, and radiative fraction, as summarized in Table 1; the remaining principal materials were specified directly in the FDS input file and are summarized in Table 2 [16, 18, 19]. The use of a prescribed burner or surface with a specified heat release rate per unit area (HRRPUA) is also consistent with the modelling principles of FDS, in which the associated materials primarily provide the thermal properties required for heat transfer and fire spread calculations [16]. This configuration was considered representative of typical ground-floor parking/storage conditions in multi-storey urban dwellings in Vietnam, where motorcycles, including electric motorcycles, combustible household items, plastic components, and light storage materials are commonly concentrated near the main entrance and may rapidly interact with the front opening and internal stairwell once a fire occurs [3, 4, 11, 12]. Given the increasing number of fires involving electric motorcycles in this building type in Vietnam, this study referred to previous studies on Li-ion battery fires and electric vehicle fires to inform the selection of HRR and thermal hazard parameters for the initiating burner [18, 19].

**Table 2.** Main materials and locations of measurement devices

Item	Main Parameters
Pine wood	$c = 1.35$ kJ/kg·K; $k = 1$ W/m·K; $\rho = 400$ kg/m <sup>3</sup> ; MLRPUA = 0.0035 kg/m <sup>2</sup> ·s; T_ign = 290 °C
Concrete	$c = 1$ kJ/kg·K; $k = 1.65$ W/m·K; $\rho = 2300$ kg/m <sup>3</sup>
Plaster mortar	$c = 1.7$ kJ/kg·K; $k = 0.2$ W/m·K; $\rho = 800$ kg/m <sup>3</sup>
Brick	$c = 0.80$ kJ/kg·K; $k = 0.85$ W/m·K; $\rho = 1965$ kg/m <sup>3</sup>
Polyurethane (PU)	$c = 1.25$ kJ/kg·K; $k = 0.1$ W/m·K; $\rho = 28$ kg/m <sup>3</sup> ; MLRPUA = 0.0035 kg/m <sup>2</sup> ·s; T_ign = 390 °C
Devices in the stairwell	$x = 11.0$ m; $y = -4.3$ m; $z = 3.9, 7.1, 10.3, 13.5, 16.7, 19.9$ m
Devices in Room 1	$x = 3.710$ m; $y = -3.34 / -3.14$ m; $z = 4.808, 8.008, 11.208, 14.408, 17.608$ m
Devices in Room 2	$x = 13.3$ m; $y = -3.34 / -3.14$ m; $z = 4.808, 8.008, 11.208, 14.408, 17.608$ m
Monitored variables	Temperature, visibility, CO concentration, FED

Notes:  $c$  = specific heat;  $k$  = thermal conductivity;  $\rho$  = density; MLRPUA = mass loss rate per unit area; T\_ign = ignition temperature; CO = carbon monoxide; FED = fractional effective dose. Coordinates  $x$ ,  $y$ , and  $z$  are given in m.

## 2.3 Scenario design

Eight scenarios were constructed on the same baseline model. The only difference among the scenarios was the location and combination of ventilation openings applied at 600 s. Scenario S0 was the baseline case, in which the initial ventilation conditions were maintained throughout the simulation. Scenario S1 involved opening the main entrance on level 1, representing access and ventilation from the lower part of the building. Scenario S2 involved opening the roof access door, representing smoke release or top-down access.

Scenario S3 involved the simultaneous opening of the level-1 main entrance and the roof access door. Scenario S4 involved opening the balcony door of Room 1 at level 5 while keeping the door connecting this room to the stairwell closed. Scenario S5 involved the simultaneous opening of the level-5 balcony door of Room 1 and the roof access door. Scenario S6 involved opening the level-5 balcony door of Room 1 together with the door connecting Room 1 to the stairwell at the same level. Scenario S7 involved the simultaneous opening of the roof access door, the balcony door of Room 1 at level 6, and the door connecting Room 1 to the stairwell at the same level.

Scenarios S4–S6 were designed to represent opening actions focused on an upper target floor that was not the highest occupied level of the building. This selection allowed the effects of localized opening actions to be evaluated under conditions in which the opened space was not directly connected to the roof zone. Accordingly, level 5 was selected as a representative upper target floor below the roof. By contrast, S7 was designed to represent a coordinated opening configuration at the highest occupied level near the roof, with level 6 used as a roof-adjacent target floor that is operationally relevant when access or smoke venting actions are undertaken near the top of the building. Therefore, S7 should not be interpreted as a fully equivalent case for direct comparison with S4–S6. In addition to opening combination itself, floor elevation may also alter smoke movement, hot-gas accumulation, and flow development within the building.

This scenario structure made it possible to isolate the effects of ventilation opening at a low level, at the roof, at a specific upper floor, and under vertically coordinated opening configurations. At the start of the simulation, doors within the building were assumed to be closed, and background air exchange occurred only through door gaps and small openings defined in the baseline model.

A common intervention time of 600 s was selected for all scenarios to represent firefighting and rescue activities that altered the ventilation regime after the fire had already developed substantially. Applying the same intervention time to all scenarios made this study a time-controlled comparison, in which the differences among cases primarily reflected the effects of opening location and opening combinations under the same pre-intervention fire condition. Therefore, the results should not be interpreted as independent of opening time, but rather as applying to the specific condition in which the fire had developed to the selected intervention time of 600 s.

## 2.4 Instrumentation and monitored variables

The model was instrumented with measurement devices to simultaneously monitor conditions in the stairwell, in the rooms, and across the building as a whole. Device clusters along the stairwell were positioned at elevations representing intermediate landings between storeys and the roof level. Within each cluster, the monitored variables included temperature, visibility, CO concentration, and FED.

In the rooms, device clusters were positioned at the central area of each room, representing the bed location. The device system was established for both Room 1 and Room 2 from level 2 to level 6. The detailed positions of the device clusters in the stairwell and in the rooms are presented in Table 2. At all measurement locations, the devices were installed at a height of approximately 1.6 m above the floor, representing the human breathing zone.

The main analysis focused on five variables: HRR, temperature, CO concentration, visibility, and FED. HRR was used to characterize fire development intensity, whereas the other variables were used to assess tenability conditions in the stairwell and in the rooms [17].

In this study, tenability was interpreted on the basis of a combined assessment of temperature, visibility, CO concentration, and FED at the breathing zone. FED was used as the central indicator of cumulative tenability impairment following the ISO 13571 approach; FED values  $\geq 1$  were taken to indicate that conditions in the space had become unacceptable for access or continued occupancy. Visibility

was used as a practical indicator of orientation and access in a smoke-filled environment; in this study, a reduction in visibility below 10 m was taken to indicate that access conditions were no longer acceptable. Temperature and CO concentration were used as complementary indicators to clarify the severity of local conditions. Therefore, the assessment in this study was not based on a single variable, but on the combined interpretation of tenability indicators within the same space and during the same stage of fire development [20–22].

## 2.5 Data processing and comparison strategy

To ensure a consistent assessment of the effects of ventilation opening location, the data were analysed over three time intervals: 540–600 s (pre-intervention), 600–660 s (immediate response after opening), and 600–1200 s (sustained effect). Time-averaged values over these intervals were used primarily to compare trends and the magnitude of sustained effects across scenarios. However, in the context of tenability assessment, average values were not treated as the sole basis for judging whether a space was acceptable or adverse. The interpretation also considered unfavorable periods, peak excursions, and threshold exceedances of key indicators, particularly at locations relevant to access and rescue operations. Therefore, a scenario with more favorable average values did not necessarily mean that the space had become acceptable if severe visibility loss or marked increases in FED, temperature, and CO still occurred during critical periods. This approach was directly linked to the assumption that all scenarios used the same intervention time of 600 s, thereby enabling a controlled comparison at a common time point. Accordingly, the observed differences among scenarios should be understood primarily as the effects of the location and combination of ventilation openings under the same pre-intervention fire condition, rather than as comparisons across different intervention times.

In this study, comparisons were not made by directly contrasting all scenarios against one another, but by grouping scenarios to answer specific analytical questions. First, scenarios S1–S3 were used to clarify the effects of opening location under the main access directions, including lower-level access (S1), top-down access (S2), and coordinated low-high opening (S3), on fire development and tenability conditions in the principal areas of the building. Second, scenarios S4–S6 were used to show that even when different opening strategies were all directed toward the same target space, namely Room 1 on level 5, they could still produce substantially different consequences both for that space itself and for the stairwell. Third, scenario S7 was used as a representative case of a coordinated opening configuration at the highest floor near the roof, in order to show that, in addition to the influence of opening combinations, floor elevation itself could alter smoke movement, hot gas accumulation, and flow development within the building.

On the basis of this comparison strategy, the results were interpreted across three interconnected dimensions. The first dimension was whole-building fire development, assessed through HRR. The second dimension was tenability along the stairwell axis, assessed through temperature, CO concentration, visibility, and FED. The third dimension was the localized effect within target spaces inside the building, in which the effectiveness of each opening configuration was evaluated simultaneously in terms of improvement in the room

requiring access and the adverse effects generated in the stairwell or adjacent spaces.

### 3. RESULTS AND DISCUSSION

#### 3.1 Effects of ventilation opening location on fire development intensity

In the baseline scenario (S0), the fire developed under ventilation-limited conditions, with a peak HRR of 18.19 MW at 1194.0 s. The mean HRR during 600–660 s increased by only 1.8% relative to the pre-intervention period, indicating that, without any change in opening conditions, fire growth remained slower and the peak occurred later.

Within the S1–S3 group, changes in the vertical arrangement of openings markedly affected fire intensity. Opening only the main entrance on level 1 (S1) increased the peak HRR to 25.28 MW at 603.6 s, while the mean HRR during 600–660 s rose by 47.9%. Opening only the roof access door (S2) produced a lower peak of 21.69 MW at 603.6 s, with a mean increase of 29.8%. The stronger response in S1 than in S2 indicates that a low-level opening at level 1 enhanced air supply to the fire more effectively than an upper opening acting primarily as an exhaust path. The most adverse case was S3, in which the level-1 main entrance and the roof access door were opened simultaneously. In this scenario, the peak HRR reached 34.34 MW at 603.6 s, and the mean HRR during 600–660 s increased by 55.7%, indicating that the low–high opening combination established a clear air supply path from below and an exhaust path above, resulting in the strongest fire intensification.

The S4–S6 group shows that even when the opening actions were directed toward the same target space at level 5, different opening configurations produced markedly different HRR responses. Opening only the balcony door of Room 1 on level 5 (S4) had little effect on overall fire intensity: the peak HRR reached only 19.56 MW at 1131.6 s, and the mean HRR during 600–660 s increased by 7.0%. When the level-5 balcony door was combined with the roof access door (S5), the peak HRR increased to 23.56 MW at 610.8 s and the mean increase reached 35.8%. When the level-5 balcony door was combined with the internal door connecting Room 1 to the stairwell (S6), the peak HRR reached 22.01 MW at 1149.6 s and the mean increase was 25.2%. These results indicate that, for the same target space at level 5, opening only to the outside produced only a minor effect, combining the opening with the roof led to a stronger increase in fire intensity, and connecting the room to the stairwell produced an intermediate response.

Scenario S7 was used as a representative case of coordinated opening at the uppermost floor near the roof to show that, in addition to opening combination, floor elevation itself could also influence fire development. In this scenario, the peak HRR reached 24.12 MW at 609.6 s, and the mean HRR during 600–660 s increased by 36.3%. This increase was greater than that in S6 and close to that in S5, suggesting that shifting the opening zone to the uppermost floor near the roof altered smoke transport paths and flow conditions in a manner more favourable to air exchange, thereby producing a stronger fire response immediately after intervention.

Overall, fire development intensity depended not simply on whether openings were introduced, but more strongly on their vertical arrangement, the opening strategy applied to a given target space, and the floor elevation at which the opening

action occurred. Among the investigated scenarios, the coordinated low–high opening configuration (S3) produced the strongest fire intensification, whereas opening only the level-5 balcony door (S4) produced the smallest change in HRR. Within the scope of this study, however, HRR was not interpreted as an endpoint in itself, but as the first dimension of the trade-off associated with ventilation opening location. Changes in HRR therefore need to be interpreted together with the results for stairwell tenability and localized effects in the target spaces presented in the following sections.

#### 3.2 Effects of ventilation opening location on conditions in the stairwell

If Section 3.1 showed how ventilation opening location altered fire intensification, this section addresses the second dimension of the same problem: the cost imposed on the building's main access route, namely the stairwell.

Based on the selected tenability criteria, the results show that the stairwell lost tenable conditions very early in all scenarios. At the position between levels 1 and 2, FED exceeded 1 after approximately 180 s, while visibility fell below 10 m after only about 20 s. This indicates that, within the present model, the stairwell no longer maintained acceptable access conditions before ventilation openings were introduced. The ventilation-opening scenarios were therefore assessed in terms of whether they improved, maintained, or further worsened conditions in this space.

Within the S1–S3 group, changes in the vertical arrangement of openings worsened stairwell conditions in different ways. Considering the stairwell as a whole over 600–1200 s, the mean temperature increased from 403.3 °C in S0 to 478.2 °C in S1, 534.9 °C in S2, and 566.7 °C in S3. The distribution by elevation showed that this effect was not uniform. In the lower part of the stairwell, the position between levels 1 and 2 increased from 635.5 °C in S0 to 817.7 °C in S1 and 853.6 °C in S3, indicating that configurations involving opening the main entrance on level 1 were particularly unfavorable for the lower half of the stairwell. By contrast, in the upper part of the stairwell, the position between levels 5 and 6 increased from 267.2 °C in S0 to 395.2 °C in S2 and 401.2 °C in S3, indicating that configurations involving roof opening or coordinated low-high opening had a stronger effect on the upper half of the stairwell. At the same time, throughout 600–1200 s, mean visibility at stairwell locations remained only about 0.06–0.07 m, while mean FED remained very high, at approximately 170.8–203.1. These results show that, after intervention, locations along the stairwell axis remained highly unfavorable, with visibility far below the 10 m threshold and FED far above the threshold of 1. This is consistent with the very early threshold exceedances noted above.

The S4–S6 group further shows that even when opening actions were directed toward the same target space at level 5, different configurations still produced different levels of impact on the stairwell. Among these cases, S4 caused the least additional deterioration: the mean stairwell temperature over 600–1200 s was 402.7 °C, almost identical to S0. At the position between levels 1 and 2, the mean temperature in S4 was 634.4 °C, again nearly unchanged from S0; at the position between levels 5 and 6, the corresponding value was 268.1 °C. By contrast, when the level-5 balcony opening was combined with the roof opening (S5), the mean stairwell temperature increased to 541.0 °C; when the level-5 balcony opening was

combined with the internal door connecting to the stairwell (S6), it increased to 468.6 °C. In the upper part of the stairwell, the temperature at the position between levels 5 and 6 reached 397.8 °C in S5 and 313.0 °C in S6, both clearly higher than in S4. These results indicate that, although all three scenarios targeted the same space at level 5, opening only to the outside produced almost no additional deterioration in the stairwell, whereas combining the opening with the roof or with the stairwell connection made stairwell conditions more adverse, particularly at upper levels.

Scenario S7 was used as a case at the uppermost floor near the roof to clarify the additional influence of floor elevation. In this scenario, the mean stairwell temperature over 600–1200 s reached 543.4 °C, close to S5 and clearly higher than S6. At the position between levels 5 and 6, the mean temperature reached 401.0 °C, higher than S6 and nearly equal to S3. At the same time, mean visibility in this area remained only about 0.06 m, while mean FED also remained very high. When S7 is considered alongside S6 as an indicative comparison, it can be seen that shifting the coordinated opening zone from level 5 to the uppermost floor near the roof was associated with a clear change in smoke movement and hot-gas accumulation in the upper part of the stairwell. This difference suggests that, in addition to opening combination, floor elevation is itself a factor capable of altering airflow organization within the building.

Overall, the results in this section show that the stairwell was the space most adversely affected by ventilation-opening strategy, both in terms of tenability and the ability to maintain acceptable access conditions. Within the S1-S3 group, the vertical arrangement of openings determined different degrees of deterioration in the lower and upper halves of the stairwell, with the low-high configuration being the most adverse. Within the S4-S6 group, even when all strategies targeted the same space at level 5, they produced very different levels of additional deterioration in the stairwell, with S4 having the smallest effect. Finally, S7 shows that, beyond opening combination, floor elevation also substantially affects smoke travel paths, hot-gas accumulation, and tenability along the stairwell axis.

### 3.3 Effects of ventilation opening location on conditions in internal spaces

After clarifying fire intensification at the whole-building scale and the associated trade-off along the stairwell axis, this section addresses the third dimension of the same problem: the extent of localized improvement actually achieved in the target spaces within the building.

First, scenarios S4-S6 were used to show that even when all opening actions were directed toward the same target space, namely Room 1 on level 5, different opening strategies could still produce markedly different levels of localized improvement, while also leading to different degrees of adverse impact on the stairwell. Scenario S7 was then used as a case at the uppermost floor near the roof to clarify that, in addition to the influence of opening combination, floor elevation itself could alter smoke movement, hot-gas accumulation, and flow development, thereby changing the local effectiveness of the opening strategy. Accordingly, the results in this section are intended not only to identify which spaces benefited from opening, but also to show how changes in opening strategy or target-floor elevation could lead to different consequences.

Based on the selected tenability criteria, the front rooms lost acceptable access conditions very early, clearly earlier than the rear rooms. In Room 1 on level 5, visibility dropped below 10 m after approximately 87.6 s in all scenarios, while FED exceeded 1 after about 308.4–316.8 s. In Room 1 on level 6, visibility fell below 10 m after about 96.0–104.4 s and FED exceeded 1 after 333.6–340.8 s. By contrast, in Room 2 on level 2, visibility fell below 10 m after about 138.0 s, whereas FED exceeded 1 much later, at approximately 777.6–830.4 s. These results indicate that front rooms located closer to the vertical smoke path were affected earlier, whereas rear rooms also lost visibility relatively early but accumulated toxic exposure more slowly.

Within the S4-S6 group, different opening strategies directed toward the same target space, Room 1 on level 5, produced markedly different consequences for that room itself. Notably, even in the most favourable case, S5, acceptable access conditions were not restored: mean visibility during 600–1200 s reached only 0.25 m, far below the 10 m threshold, while mean FED remained as high as 42.54, well above the threshold of 1. Thus, according to the selected tenability criteria, S5 still left Room 1 on level 5 far from acceptable access conditions. However, compared with S0, this configuration still produced the clearest relative local improvement in the target room: mean temperature decreased from 149.9 °C to 95.3 °C, CO decreased from 2,333 ppm to 398 ppm, FED decreased from 128.41 to 42.54, and mean visibility increased from 0.04 m to 0.25 m. This indicates that opening the level-5 balcony door together with the roof access door could substantially reduce thermal and toxic exposure in the target room, but the result should be interpreted as a relative improvement rather than a restoration of acceptable access conditions. By contrast, S4 and S6 produced only partial improvement in CO, FED, and visibility, while sharply increasing temperature in the target room itself; in S4, mean temperature increased to 278.2 °C, and in S6 it increased to 282.6 °C, while FED remained 44.90 and 48.57, respectively. This comparison shows that even when the same target space at level 5 was considered, opening only to the outside, combining the opening with the roof, or connecting the room to the stairwell produced very different levels of improvement in tenability indicators, and not every strategy yielded benefits commensurate with the associated trade-off.

Local effectiveness in the front rooms also varied markedly with elevation. Under the same S5 configuration, Room 1 on level 2 showed major improvement, with mean temperature reduced to 21.9 °C, visibility increased to 18.38 m, CO reduced to 9.6 ppm, and FED reduced to 0.02; these values indicate that the space was almost restored to acceptable access conditions after intervention. However, in Room 1 on level 3, although S5 still reduced temperature from 148.2 °C to 76.3 °C, CO from 2,320 ppm to 584 ppm, and FED from 99.34 to 24.75, mean visibility reached only 0.48 m and FED remained far above the threshold of 1. At this level, the improvement therefore remained only relative. In Room 1 on level 5, as noted above, S5 again produced a relatively clear improvement, but the tenability indicators still remained highly adverse, particularly because visibility was far below 10 m and FED remained well above 1. These results show that even under the same opening configuration, local benefits in the front rooms were not uniform with elevation; the degree of improvement clearly diminished as the room location shifted upward.

Scenario S7 was used to clarify the additional influence of

floor elevation under a coordinated opening configuration near the roof. In Room 1 on level 6, S7 changed local conditions more clearly than configurations applied at lower levels: mean CO decreased to 1,294 ppm and mean FED decreased to 35.21, both substantially lower than in S0, while mean visibility increased from 0.04 m to 0.08 m. However, mean temperature also increased sharply to 222.9 °C, and FED still remained at 35.21. This indicates that even when local benefits in toxic exposure and cumulative dose were observed, the room still remained far from acceptable access conditions. When S7 is read alongside S6 as an indicative comparison, shifting the opening zone from level 5 to the uppermost floor near the roof was associated with a clear change in local improvement and in flow organization within the building. This confirms that, in addition to opening combination, floor elevation is itself a factor capable of substantially altering the effectiveness of ventilation opening strategies in target rooms.

For the rear rooms, the ventilation-opening configurations did not produce clear or consistent improvement in tenability conditions. The most favourable case remained Room 2 on level 2 under S5, but the improvement was limited: mean temperature decreased only from 93.0 °C to 91.0 °C, CO from 1,387 ppm to 1,214 ppm, and FED from 1.91 to 1.31, while mean visibility remained only about 0.06 m. At higher rear-room levels, the differences among scenarios were even smaller. In Room 2 on level 5, mean FED ranged from 0.96 to

1.28; in Room 2 on level 6, it ranged from 0.67 to 0.96. However, mean visibility in the rear rooms remained only about 0.06-0.07 m in all scenarios, still far below the 10 m threshold. These findings indicate that for spaces located deep within the building, without direct air exchange to the outside, the investigated opening configurations were insufficient to produce a meaningful change in tenability conditions. Some cases showed slight reductions in temperature or FED, but these improvements were not robust; mean visibility remained only about 0.06-0.07 m, and FED at many positions remained close to or above 1.

Physically, this pattern was governed mainly by buoyancy and elevation-dependent pressure differences arising from density differences between hot gases inside the building and the ambient air, thereby establishing a dominant vertical flow field along the stairwell axis.

Once openings were introduced, the flow system was reorganized according to mass conservation, in which paths with larger pressure differences and lower flow resistance preferentially served as air-supply or exhaust routes. As a result, the investigated opening actions mainly altered airflow and smoke distribution in the stairwell and in spaces close to the openings, whereas the rear rooms, located deeper in plan, without direct air exchange to the outside and outside the dominant flow paths, benefited much less.

**Table 3.** Qualitative comparison of the effects of ventilation-opening scenarios

Scenario	Fire Intensification	Stairwell Impact	Front-Room Effect	Rear-Room Effect	Overall Interpretation
S0	Baseline	Baseline	Baseline	Baseline	Reference case
S1	Strong increase	Highly adverse, especially lower stairwell	No clear local benefit; tenability remained poor	Minor, unstable changes	Lower opening intensified fire and worsened stairwell access
S2	Marked increase	Clearly adverse, stronger in the upper stairwell	Some local improvement in lower-to-mid front rooms	No clear improvement	Upper opening produced some local benefit, but at the cost of stairwell deterioration
S3	Greatest increase	Most adverse	Tenability remained highly unfavorable	No clear improvement	Most adverse configuration; clearly established low-level air supply and high-level exhaust
S4	Very small increase	Minimal additional deterioration	Limited local change; no clear major benefit	No clear improvement	Smallest increase in fire intensity and least additional stairwell penalty
S5	Moderate to strong increase	Clearly adverse	Clearest local improvement in some front rooms, especially Room 1 on level 5	Very limited improvement; visibility remained very low and FED remained adverse at many locations	Produced the clearest local benefit, but with a marked stairwell trade-off
S6	Moderate increase	Intermediate adverse effect	Limited local improvement; some indicators improved, but temperature increased	No clear improvement	Opening the room to the stairwell did not provide local benefits commensurate with the trade-off
S7	Moderate to strong increase	Clearly adverse, especially in the upper stairwell	Noticeable local changes were observed, but visibility and FED remained highly unfavorable	No clear improvement	Representative coordinated opening near the roof; not directly equivalent to S4-S6

Notes: CO = carbon monoxide; FED = fractional effective dose; tenability was interpreted using temperature, visibility, CO, and FED. Scenario S7 represents a coordinated opening configuration at the uppermost occupied floor near the roof and is not fully equivalent to S4-S6 for direct one-to-one comparison.

Overall, the results in this section highlight three main points. First, within the S4-S6 group, even when all strategies were directed toward the same target space at level 5, different opening configurations still produced very different levels of

localized improvement in temperature, CO, visibility, and FED. Second, for front rooms, openings at higher elevations or configurations involving roof opening could produce clearer relative improvement, but these improvements were

not uniform with elevation and did not imply restoration of acceptable access conditions at higher levels. Third, when the target space shifted from an upper floor that was not the highest to the uppermost floor near the roof, as in S7, the results showed that, in addition to opening combination, floor elevation itself could substantially alter smoke movement, hot-gas accumulation, and the local effectiveness of the opening strategy. Therefore, conditions in interior spaces should be interpreted not only in terms of the degree of improvement achieved in the target room, but also in terms of the robustness of that improvement across tenability indicators and the trade-off it imposes on the remaining spaces, particularly the stairwell.

From both technical and operational perspectives, the results show that ventilation opening in multi-storey urban dwellings should not be regarded as an inherently beneficial measure, but rather as an intervention that must be selected according to the target space and the level of trade-off considered acceptable in the remaining spaces. First, opening configurations arranged along a low-high axis or directly connected to the stairwell, particularly the S3-type configuration, should be regarded as adverse under the fire-development conditions examined here, because they both intensified the fire and markedly degraded conditions along the main access route. Second, opening configurations at higher elevations should be considered only when the priority is to achieve localized improvement in a specific front room, and even then, the resulting benefit should be understood as a relative improvement rather than a rapid restoration of acceptable access conditions throughout the building. Finally, for rear rooms without direct air exchange with the outdoor environment, the opening configurations examined in this study produced little meaningful improvement; therefore, ventilation opening alone should not be expected to resolve tenability conditions in these spaces. The main practical implication of this study therefore lies not in identifying a universally “best” opening configuration, but in showing that the choice of opening location must be tied to a specific priority among limiting fire intensification, reducing deterioration in the stairwell, and achieving meaningful localized improvement in the space requiring access.

Taken together with the results in Sections 3.1 and 3.2, these findings indicate that the influence of ventilation opening location in this building type should be understood as a three-dimensional trade-off among fire intensification, deterioration of conditions along the main access route, and the actual localized benefit achieved in the target space.

Table 3 summarizes the qualitative comparison of the effects of the ventilation-opening scenarios across fire intensification, stairwell conditions, and local effects in internal spaces.

#### 4. CONCLUSIONS

Overall, the results indicate that ventilation opening location in multi-storey urban dwellings should be understood as a trade-off rather than as an inherently beneficial measure. Within the scope of the present model, these findings were derived for the same representative building configuration, the same fire source location, and the same ventilation intervention time of 600 s; they should therefore be interpreted primarily as time-dependent assessments.

The main findings of this study are as follows:

The S1-S3 group showed that the relative arrangement of openings along the main access directions markedly affected both fire development intensity and conditions along the stairwell axis. Within this group, the coordinated low-high opening configuration (S3) was the most adverse case, as it both produced the strongest fire intensification immediately after intervention and caused more severe deterioration in stairwell conditions than the cases involving only lower-level or only upper-level opening. It should therefore not be regarded as a favorable configuration when maintaining vertical access is the primary objective.

The S4-S6 group showed that even when all opening actions were directed toward the same target space, namely Room 1 on level 5, different opening strategies could still produce markedly different consequences both for that room and for the stairwell. Within this group, S5 produced the clearest local improvement in the target room in terms of temperature, CO, FED, and visibility; however, this benefit was still insufficient to restore acceptable access conditions and was accompanied by a more pronounced deterioration of stairwell conditions.

In the stairwell, configurations involving direct opening connections to the stairwell clearly worsened environmental conditions, whereas the configuration involving only the level-5 balcony opening caused almost no additional deterioration in this space. These results indicate that opening strategies directly connected to the stairwell axis, or that enhance vertical air exchange, may substantially increase the trade-off imposed on the building’s main access route.

For the front rooms, ventilation opening could produce localized improvement in some spaces at lower levels. However, at higher levels, visibility generally remained far below 10 m and FED remained at highly adverse levels. This indicates that opening configurations at higher elevations can only be regarded as options for localized improvement in specific target spaces, rather than as a general means of rapidly restoring acceptable access conditions throughout the building.

For the rear rooms, no ventilation-opening configuration produced clear and consistent improvement in tenability conditions. In general, the changes were small, while visibility remained very low and FED at many locations remained close to or above the adverse threshold. These findings suggest that, for spaces located deep within the building, ventilation opening alone is unlikely to be sufficiently effective unless combined with additional supporting measures.

Scenario S7 showed that, in addition to opening combination, floor elevation itself can substantially affect smoke travel paths, hot-gas accumulation, and flow development within the building. When the coordinated opening configuration was shifted from an upper target floor that was not the highest to the uppermost floor near the roof, both the local effectiveness in the target room and the degree of adverse impact in the upper part of the stairwell changed markedly.

From an application perspective, these results suggest that decisions on ventilation opening in this building type should be framed as a problem of operational prioritization: avoiding configurations that strongly intensify the fire and worsen stairwell conditions, accepting trade-offs only when the objective is localized improvement in a specific space, and not assuming that ventilation opening alone will substantially improve conditions in rear rooms.

This study was conducted for one representative building configuration, with a common ventilation intervention time of

600 s and a specific fire source representation. The results should therefore be interpreted as time-dependent findings, applying primarily to conditions in which the fire has already developed to the selected 600 s intervention point. The conclusions should not be directly extended to situations involving earlier ventilation opening or later fire decay stages. Factors such as firefighting water application and door-opening behaviour associated with occupant evacuation were not considered. Future studies should extend the analysis to multiple intervention times and a wider range of scenarios in order to evaluate more fully the robustness of the findings and the trade-offs associated with each ventilation-opening configuration under realistic conditions.

## ACKNOWLEDGMENT

The author gratefully acknowledges Thunderhead Engineering for providing access to the PyroSim software used in this study. The author also sincerely acknowledges the support of the agencies, organizations, and individuals who provided data, professional input, and valuable comments that contributed to the refinement of the simulation method and the analysis of the results.

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## NOMENCLATURE

$c$	specific heat, kJ/kg·K
$c_p$	specific heat at constant pressure, kJ/kg·K
$D^*$	characteristic fire diameter, m
$g$	gravitational acceleration, m/s <sup>2</sup>
$k$	thermal conductivity, W/m·K

$T$	temperature, °C
$T_\infty$	ambient temperature, K
$T_{ign}$	ignition temperature, °C
TMP_FRONT	front surface temperature of burner, °C

## Greek symbols

$\delta_x$	nominal cell size, m
$\rho$	density, kg/m <sup>3</sup>
$\rho_\infty$	ambient air density, kg/m <sup>3</sup>

## Abbreviations

CO	carbon monoxide, ppm
FDS	fire dynamics simulator
FED	fractional effective dose
HRR	heat release rate, MW
HRRPUA	heat release rate per unit area, kW/m <sup>2</sup>
MLRPUA	mass loss rate per unit area, kg/m <sup>2</sup> ·s