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Numerical analysis of the effect of double-skin façade types on fire behaviour

Authors:

Assist.Prof. **Mehmet Akif Yıldız**, PhD. Arch.
Sakarya University, Turkey
Faculty of Arts, Design and Architecture
akifyildiz@sakarya.edu.tr
Corresponding author

Merve Ertosun Yıldız, PhD. Arch.
Sakarya University, Turkey
Faculty of Arts, Design and Architecture
merveertosun@sakarya.edu.tr

Research Paper - Subject review

Mehmet Akif Yıldız, Merve Ertosun Yıldız

Numerical analysis of the effect of double-skin façade types on fire behaviour

This study investigated the fire safety effect of double-skin façade (DSF) types that vary according to natural airflow through a numerical model. According to the cavity design, four DSF systems-multi-storey, corridor type, shaft type, and window-box type-were applied in the designed three-storey prototype office building, with the smoke spread based on fire and temperature levels analysed through simulation. Multi-storey and shaft-type DSF designs, which create a continuous cavity in the vertical direction, involve considering the chimney effect. In all the DSF designs, the office temperature did not reach the risk levels in the scenarios. By contrast, designs with a reduced cavity volume associated with the fire room caused the ambient temperature to increase.

Key words:
double-skin façade type, smoke spread, numerical model, temperature level, cavity design

Pregledni rad

Mehmet Akif Yıldız, Merve Ertosun Yıldız

Numerička analiza učinka tipova dvostrukih fasada na ponašanje u slučaju požara

U ovom je radu uz primjenu numeričkog modela istraženo ponašanje dvostrukih fasada (engl. *Double Skin Façade* - DSF) u uvjetima požara, koje se razlikuju prema prirodnome protoku zraka. Četiri sustava dvostrukih fasada u ovisnosti o tipu projektirane šupljine - višekatni, koridorski, s otvorom i kao prozorska kutija - primijenjena su u projektiranoj trokatnoj prototipskoj poslovnoj zgradi, pri čemu su širenje dima i razvijene temperature analizirani simulacijama. Za višekatne i DSF sustave s otvorom koji tvore neprekidnu šupljinu u okomitome smjeru mora se uzeti u obzir učinak dimnjaka. Kod svih analiziranih DSF sustava temperatura u prostoru ureda nije dosegnula vrijednosti rizika navedene u scenarijima. Za razliku od njih, sustavi sa smanjenim obujmom šupljeg prostora povezanog s prostorijom u kojoj je izbio požar uzrokovali su porast sobne temperature.

Ključne riječi:
dvostruka fasada, širenje dima, numerički model, razina temperature, dizajn šupljine

1. Introduction

Establishing a relationship between the built and external environments through appropriate design criteria is one of the fundamental principles of sustainability. In addition to healthy and comfortable living spaces, addressing climate change due to global problems has become a main priority in the building sector. In recent years, the construction of buildings incorporating climatic data, such as sun, wind, humidity, and air pressure, into their design, considering energy and resource conservation, has increased. Consequently, building envelope designs, wherein the relationship between climatic data and the building is first established, are differentiated because traditional designs do not respond to global needs. For the façade, the most critical component of the building envelope, double-skin façade (DSF) designs are emerging as an alternative to traditional and single-skin curtain wall systems as they allow for the controlled introduction of external environmental conditions into the interior space. DSF is preferred in energy-efficient designs because of its thermal insulation, wind pressure control, and natural ventilation, allowing windows to be opened even on upper floors.

Numerical model studies have been conducted to investigate the contribution of DSF systems to minimising heat loss through natural ventilation or shells. These studies showed that the design of a DSF cavity causes air taken from the outdoor environment to be taken indoors with different dimensions and orientations. The characteristics of the DSF cavity affect the airflow velocity through the chimney effect and change the indoor and outdoor air transfers at different rates. In addition, simulations have shown that the energy consumption efficiency of different DSF types changes during summers and winters [1–4].

The DSF, which consists of an outer layer, an inner layer, and an air cavity between these two layers, allows for the controlled passage of external air currents into the interior and solar control. Natural air drawn into the DSF cavity through the vent in the outer layer is drawn into the interior space through the ventilation gaps in the inner layer. In addition, heated and polluted air from the interior is drawn into the cavity through air vents at the top of the inner layer and discharged at the top of the outer layer by the chimney effect created by thermal differences in the cavity. The DSF cavity, which plays an important role in natural ventilation by controlling the movement of airflow, also influences the movement of smoke, flames, and other toxic gases in a fire. Therefore, natural ventilation and fire safety designs in DSF systems should be evaluated together.

Taking the necessary precautions at the design stage by addressing the fire safety risks in DSF systems, which are differentiated as the technology evolves, ensures risks are minimised during the use of the building. The main methods for monitoring fire safety requirements at the design stage are numerical modelling and full-scale test studies. Although both methods have been used in the literature, numerical modelling studies provide effective and rapid results compared to full-scale test studies, which are limited by cost, time, and design limitations. Therefore, in this study, the fire safety design of DSF systems was analysed using a dynamic fire simulator and a fire simulation model.

- The main areas of research in the literature that analyse fire risks from DSF systems through numerical models and full-scale experiments are as follows:
- Smoke propagation through the cavity to the external environment and between spaces,
- Risks of explosion and cracking of glass materials in inner and outer shells owing to high temperatures and pressures
- Classification of the effect of blinds placed in the cavity for solar control on the movement of the fire elements.

The research areas in DSF studies consist of temperature and pressure levels, flame, and smoke propagation analyses.

Computational fluid dynamics (CFD) modelling has been used to numerically analyse fire propagation influenced by a DSF cavity, where natural air movement is effective. Some studies investigated smoke propagation by varying the cavity depth between 0.2 and 2 m. Narrowing the cavity width increases the chimney effect in the cavity and the upward flow velocity [5–8]. If the cavity depth is designed at the minimum level, the smoke fills the entire cavity and spreads rapidly upward. However, as the cavity depth increases, the smoke is directed mainly toward the outer wall. If the cavity depth is designed to be 2 m or more, it becomes difficult for the smoke to reach the outer wall and causes it to be directed upward adjacent to the inner wall. However, smoke movement in a cavity is affected by the heat release rate (HRR), ventilation conditions, physical properties of the space, and cavity depth. Experimental and numerical studies on the effects of cavity width, HRR, and ventilation openings on fire development have shown that for a given cavity width, the HRR and geometry of the ventilation opening are two critical factors in the movement of smoke [9-11].

Glass, which forms transparent areas on façades, loses its strength and cracks at high temperatures, affecting fire development by causing smoke to be distributed from the glass surface [12]. As the temperature of the glass in the DSF cavity increases, cracking occurs according to the properties of the glass. The cracking occurring in the inner glass poses a risk for the development of a fire, whereas the cracks in the outer glass allow smoke to be discharged into the external environment [13]. Some studies tested the physical properties of glass to examine the behaviour of single glass, double glass, tempered glass, and flat glass in a fire, with the results indicating that cracking occurs at 450 °C for single glass, 600 °C for double glass, and 800 °C for tempered and double glass [14–16]. In addition, owing to the decrease in the gap width, the cracking time of the glass was shortened because of the rapid increase in the temperature in the gap. For fire safety in DSF systems, glass design should be differentiated between interior and exterior glass; moreover, using tempered glass with a thickness of 12

mm or more in the interior glass prevents the development of indoor fires.
Shading elements placed in the DSF cavity to reduce building cooling load and prevent unwanted solar gains affect the temperature levels and smoke propagation in a fire. Numerical studies that ignore the flammability properties of the shading elements show that the position and angle of the elements in the cavity affect fire development. Blinds placed at angles between 0 °and 90 °close to the inner and outer glass affected the breakage time of the inner glass and directed the spread of smoke, with the highest inner glass surface temperature varying between 283 °C and 840 °C, depending on the blind position and the slat opening angle. Without blinds, the highest interior glass surface temperatures ranged from 468 °C to 614 °C [17-19].
In the 21st century, the number of studies examining the fire safety concerns of DSF systems has increased, particularly focusing on the effects of materials in DSF systems, physical properties of the cavity, physical properties of the spaces, fire size, and fire location on fires. Accordingly, this study numerically analysed the effects of DSF types designed according to the airflow movement in the cavity of DSF systems on fire development.

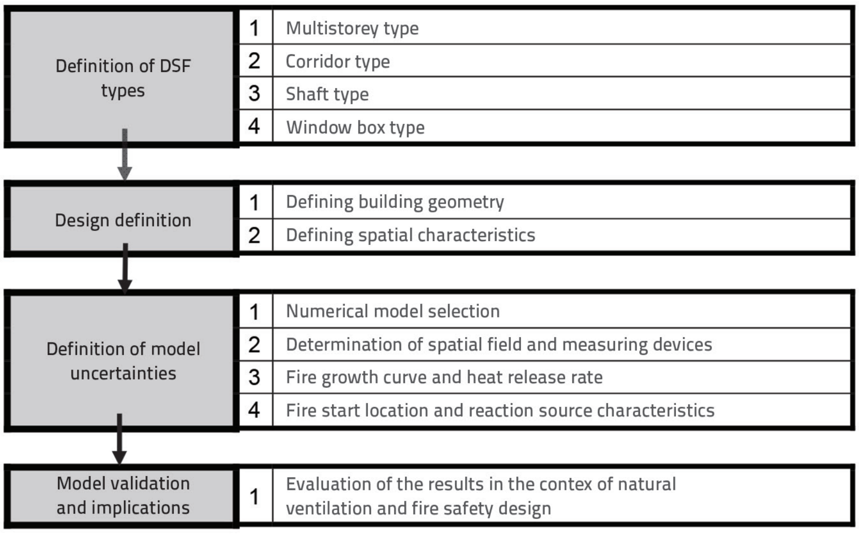


Figure 1. Stages of performance-based model

2. Material and method

Evaluating the DSF designs in the context of fire risk, the most critical risk area is the air current formed by the vertical cavity between the inner and outer shells. The upward irregular air currents formed in the vertical cavity directly affected the movement of smoke and toxic gases during the fire. In this direction, although different methods classify DSF types, smoke, temperature, and flame distribution analyses of different types of DSF according to the air cavity that most affects fire safety and comparisons according to type are conducted within the scope of the study. DSF types, widely used in the literature and for natural ventilation design depending on airflow movement in practice, are classified as multi-storey, corridor, shaft, and box window types [16]. Based on the hypothesis that these DSF designs would have different effects on natural ventilation, indoor comfort, and fire safety, simulation and numerical analyses were conducted using a performance-based fire safety approach. In this study, using data obtained from literature, the contributions of DSF types to natural ventilation design and their effects on fire safety were examined using a numerical model. Considering smoke and other toxic gases move parallel to air currents in a fire, the most appropriate fire safety design for the prepared model will also be valid for natural ventilation design. The stages of the study are shown in Figure 1.

2.1. Definition of DSF Types

Multi-storey type
In the multi-storey DSF type, the cavity between the outer and inner shells continues uninterruptedly throughout the building. The air taken into the cavity with the vents located at the ground level of the outer shell heats up, rises, and discharges from the top point of the outer shell [20, 21]. With ventilation openings designed with the desired dimensions in the inner shell, uninterrupted air flows in the cavity are taken into the interior spaces. In these systems, good performance is achieved in terms of construction and acoustics because there are only two openings in the outer shell at the ground and upper levels [22] (Figure 2).

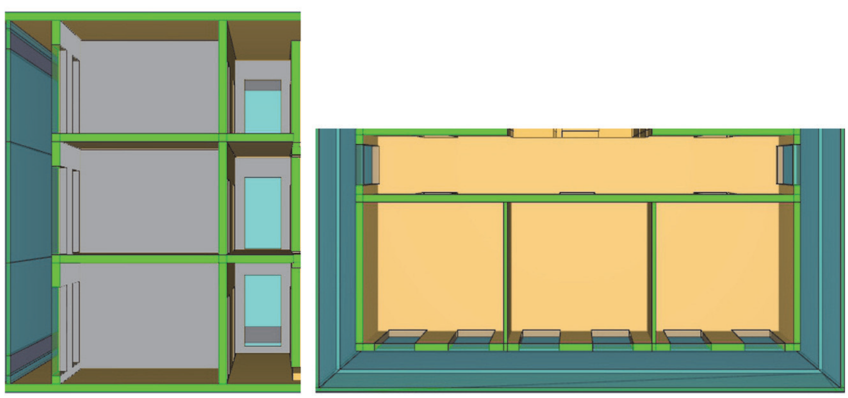


Figure 2. Multi-storey-type DSF section and plan

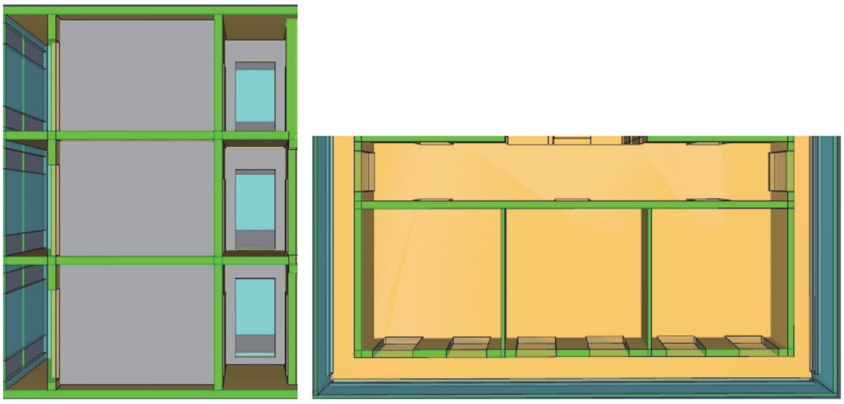


Figure 3. Corridor-type DSF system section and plan

Shaft type

Shaft-type DSF systems, which allow airflow on the floors via the chimney effect in the ventilation shaft, are based on a combination of the DSF for multi-storey and corridor types. The fresh air taken into the ventilation cavity through the openings in the outer shell at each floor level heats, rises, and transmits to the central shaft at the building height. The airflow is fast because these shafts are narrower than the vertical cavities in other systems. This situation makes it difficult to control the air in high-rise buildings [24, 25] (Figure 4).

Corridor type

In corridor-type DSF systems, the cavity is divided horizontally at each floor level, with the connection between the floors cut vertically [23]. In the outer shell, air vents are located as inlets and outlets at each floor level, ensuring each floor is ventilated independently. In these systems, fresh air is introduced into the cavity from the lower level of each floor, whereas polluted and heated air from the cavity is discharged from the upper level. Increasing the number of vents in the outer shell causes the mixing of clean and dirty air and acoustic problems [20, 22] (Figure 3).

Window-box type

In window-box-type DSF systems, each space is separated horizontally and vertically while independently establishing a relationship with the DSF cavity; in this system, the air inlet and outlet openings in the outer shell are separated [20]. Unlike the corridor and multi-storey DSF types, each space in this system provides ventilation without connections to the others. However, short horizontal and vertical distances between the grilles increase the risk of heated and polluted air being distributed between the spaces. In addition, increasing the number of grilles in the outer shell renders air circulation and noise control difficult [25] (Figure 5).

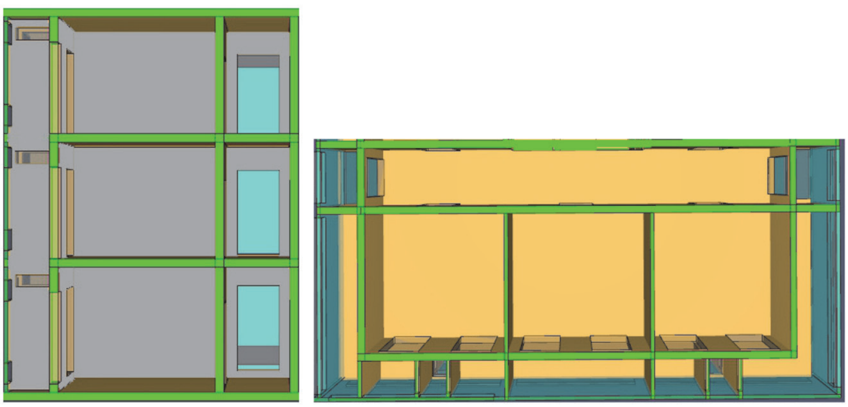


Figure 4. Shaft-type DSF system section and plan

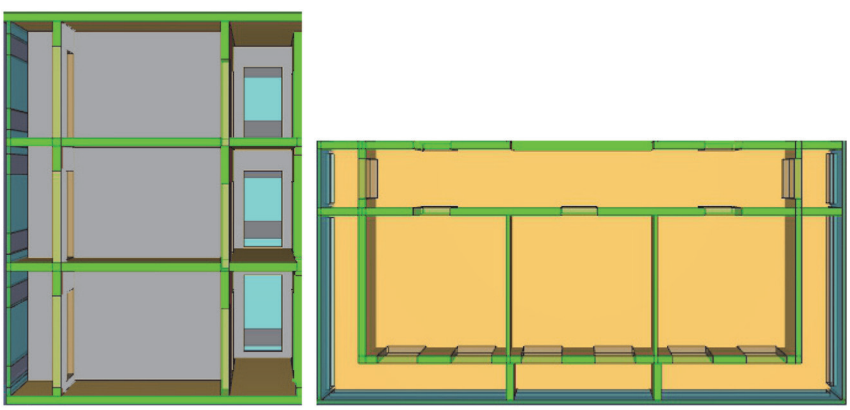
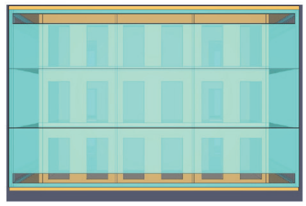
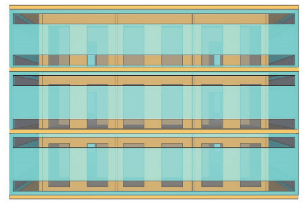
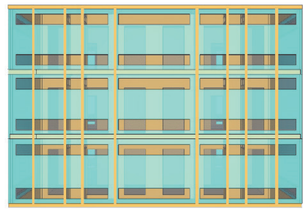
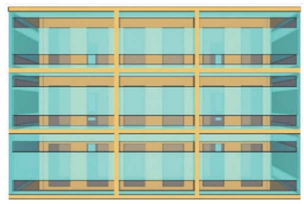


Figure 5. Window-box type DSF system section and plan

2.2. Design definitions

The 14 × 9 m prototype building had a total floor area of 126 m^2, three floors, and a total height of 9 m. Owing to the need for effective control of natural lighting and ventilation, office units are accessible by the corridor along the central axis of the building (planned as an office). A double-shell façade surrounding the entire building was designed with a cavity width of 1 m. While the outer shell has air inlets and outlets at different locations according to the type of double-shell façade, the ventilation gaps in the inner shell were planned to be 90 × 110 cm, with two in each office unit. To investigate the high-risk level for fire development, air inlets and outlets, ventilation gaps, and doors of the spaces were assumed to be open in all scenarios. Considering the four types of double-shell façade types are aimed at examining the effect of fire development, the physical properties of the prototype building constitute constant values of the design. If all design features are constant, the fire scenarios

Table 1. Model scenarios

Scenario	Façade type	Air inlet location	Air outlet location	Image
1	Multi-storey	Ground floor lower level	Last floor top level	
2	Corridor	Lower level on each floor	Top level on each floor	
3	Shaft	Lower level on each floor	Top level on each floor and ceiling level on shaft sections	
4	Window box	Lower level on each floor	Top level on each floor	

consisting of multiple stories, corridors, shafts, window boxes, and double-shell types are listed in the table below (Table 1).

2.3. Definition of model uncertainties

In fire modelling, several uncertainties, including the definition of the numerical calculation method, software, and necessary primary resources, must be selected in accordance with the design for the implementation of the scenarios and the precision of the results.

2.3.1. Numerical model selection

Various fire models have been used to predict fire events. Algebraic models are the simplest mathematical equations used to predict the values of variables as functions of space and time. Zone models are more complex, simplifying a system's behaviour by approximating that a given volume or region is homogeneous, uniform, or well mixed. The most complex models are CFD models, also known as field models [26].

In a CFD model, partial differential equations (Navier–Stokes equations) of thermodynamic and aerodynamic variables are solved at multiple points in the compartments [27]. The CFD model for indoor fires was used for performance-based fire modelling in this study, as it is suitable for low-velocity, thermally driven flows with an emphasis on smoke and heat transfer from fires.

Fire Dynamic Simulator (FDS), an open-source software used to simulate a model based on the CFD calculation method, is a fire modelling software. FDS manages and solves input parameters and equations via text files and writes user-defined output data to the files. At the same time, Smokeview is the program that reads FDS output files and helps with graphics and animations. As FDS is text-file-oriented, various third-party programs have been developed to create text files containing the input parameters required by FDS. This study used the PyroSim simulation program, which includes FDS and Smokeview functions and allows for geometric editing and drawing boundaries. The PyroSim simulation program is a user interface that solves CFD equations in the background and contains open-source FDS software.

Many studies have conducted evaluations to verify the validity of fire simulation programs by comparing the actual fire test results with those obtained from simulation programs. FDS provides reasonable temperature and flow predictions when gas temperature comparison, fuel pyrolysis, and combustion rate are modelled appropriately. In addition, FDS results for the atrium and large areas are consistent with experimental results; thus, FDS can be used for rapid design control [28–31].

2.3.2. Determination of spatial fields and measuring devices

To prepare the three-dimensional model in the PyroSim program, 308,000 cell meshes, each 0.2 × 0.2 × 0.2 m in size, were placed to determine the limitations. Selecting an appropriate cell mesh structure and dimensions is critical to model resolution and the accuracy of the output values. Slices were placed in the X2 direction to measure the temperature, smoke movement, and velocity, with thermocouples placed to measure the temperature values at the floor levels of the offices and the DSF cavity (Figure 6).

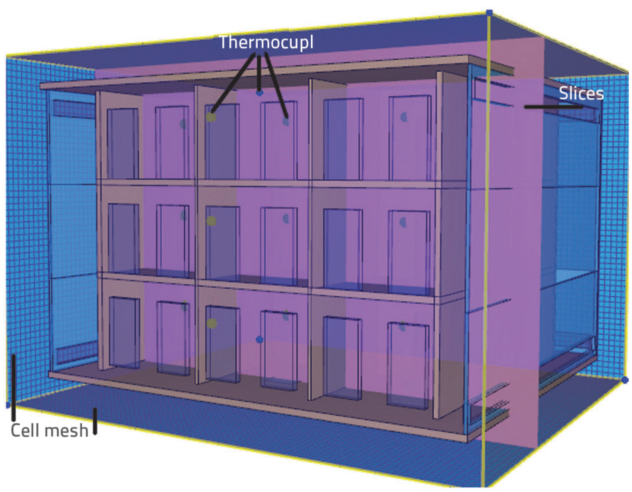


Figure 6. Thermocouple, mesh, and slice view in computer model

2.3.3. Design fire features

HRR and fire growth rate for any item were expressed by a curve proportional to the square of time. The curve is defined as the maximum HRR and time required to reach a given HRR value. For fire design, a simplified equation was used to input the fire growth into the numerical model:

$$Q = \alpha t^p \tag{1}$$

where
Q - Heat release rate Btu/s [kW]
α - Fire growth coefficient Btu/s³ [kW/s²]
t - Time from ignition [s]
p - Positive exponent.

According to the NFPA 92 B Smoke Management Systems in Malls, Atria, and Large Areas standard, the fire growth rate is classified as slow, medium, fast, or ultrafast; the reference HRR for designs is 1055 kW. Accordingly, the fire growth curves are shown in Figure 7 for slow, medium, fast, and ultrafast growth rates to reach a reference HRR of 1055 kW [32]. Using NFPA 92, the reference HRR was selected as 1055 kW, the fire growth rate was selected as fast, and the fire growth coefficient to be transferred to the numerical modelling program according to the equation was calculated as 0.047 kW/s².

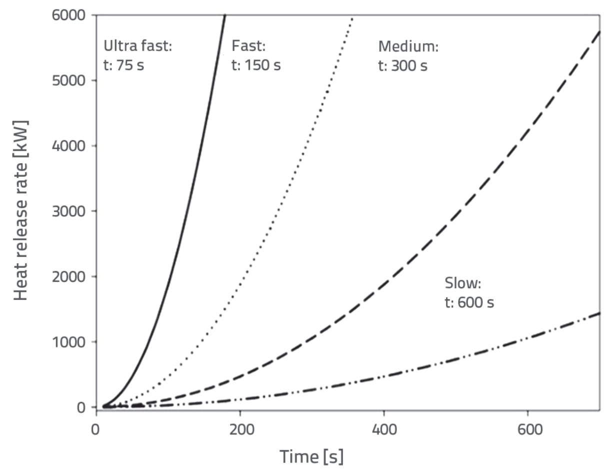


Figure 7. Fire growth rate to reference HRR for designs [33]

In an office located on the centre axis of the ground floor, a material with a surface area of 1 m² on the floor, the primary material of which was polyurethane foam, was selected as the fire source. The fire reaction source is polyurethane GM27 (flexible polyurethane foam), which consists of 1.00 carbon, 1.7 hydrogen, 0.3 oxygen, and 0.08 nitrogen atoms [26]. The effect of climatic elements such as location and prevailing wind was not considered in the design. The properties of the design fire, whose ambient temperature before ignition was determined at a constant 10 °C, are given in Table 2.

Table 2. Design model features

Feature	Value
Reaction type	Polyurethane GM27
Fire growth	Fast
Smoke production	0.198 g/g
CO production	0.042 g/g
Heat release rate (HRR)	1055 kW
Fire growth coefficient	0.047 kW/s²
Simulation duration	150 s
Ambient temperature	10 °C

The change in HRR for 150 s with a fire growth coefficient of 0.047 according to Equation 1 and Figure 7 for a t^2 fire is shown in Figure 8 to verify the model.

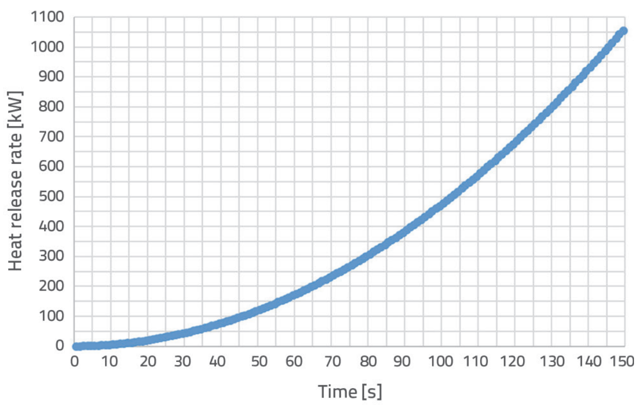


Figure 8. HRR curve for model

2.3. Model findings

The smoke and temperature analyses for the four scenarios are presented in Table 1.

Scenario 1: Multi-storey DSF model

The smoke layer levels at different times for Scenario 1, which had a DSF cavity that continued horizontally and vertically on the four sides of the building, are listed in Table 3. As the smoke density in the fire room increases, the smoke passes from the doorway to the corridor and spreads upward through the stairwell. The smoke started to disperse to the top-floor office room on the axis of the fire room at 60 s and to the top-floor offices at 70 s. Subsequently, the spread accelerated on the façade of the room where the fire started; this room was covered with smoke at the end of the fire period. Considering smoke discharges to the external environment through air outlets located at the upper level of the outer shell, which continue along the four façades, the spread of smoke is limited to the façade where the fire occurred. However, the staircase area in the interior, which has a continuous vertical cavity, caused smoke to spread throughout the interior spaces.

Considering pressure increases as temperature increases and the chimney effect increases depending on the pressure, the temperature in the cavity and the chimney effect are directly proportional. In this direction, as the temperature increased at the upper-floor level of the cavity, the upward airflow increased in the cavity. The office and cavity temperatures are shown in Figure 9, with the highest ambient temperature of 271.67 °C recorded. In the offices, the highest temperature was 38.79 °C at the top floor of the fire room, while the cavity temperature at the fire room level reached 123.59 °C at the ground floor level and 69.41 °C at the last floor level.

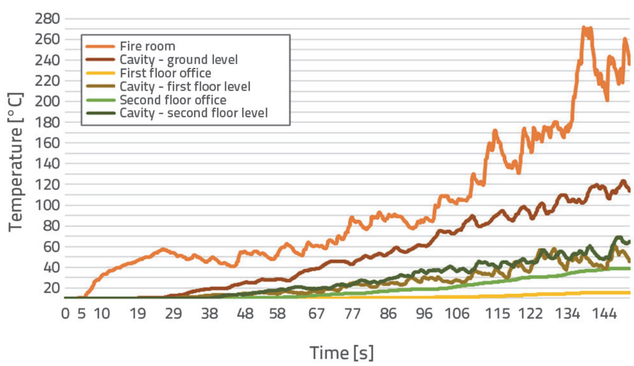


Figure 9. Temperature values measured by thermocouples for Scenario 1

Table 3. Smoke view in Scenario 1

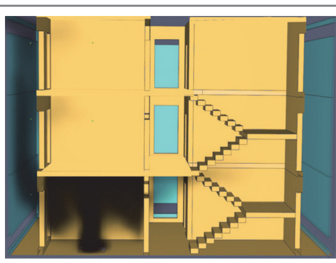
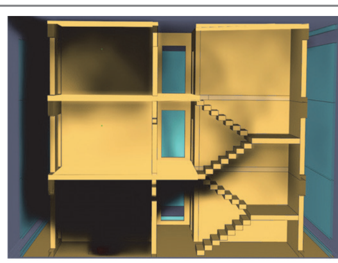
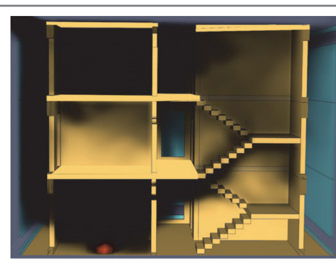
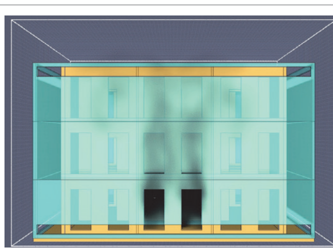
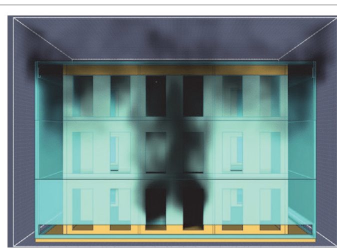
	40 s	80 s	120 s
Section			
Façade			

Table 4. Smoke view in Scenario 2

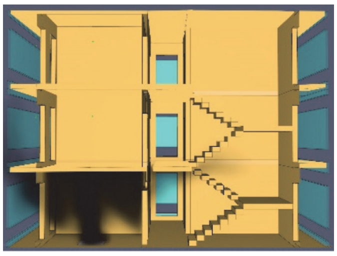
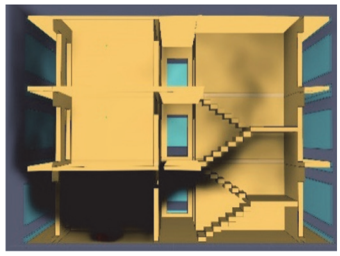
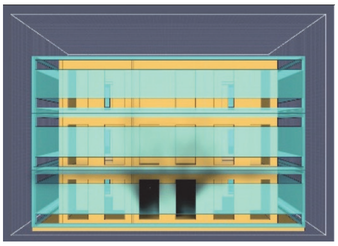
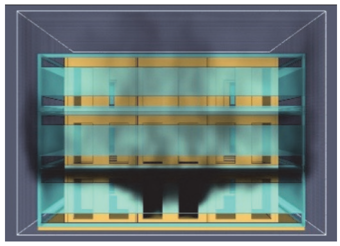
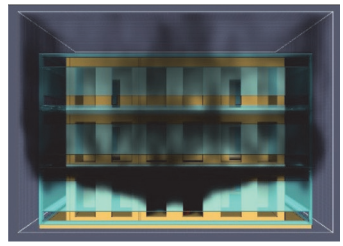
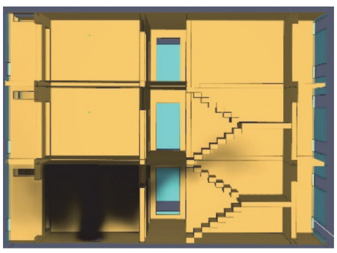
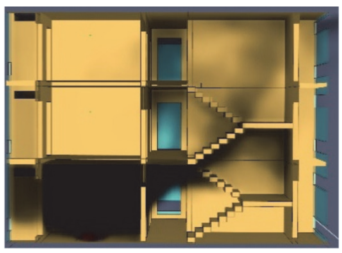
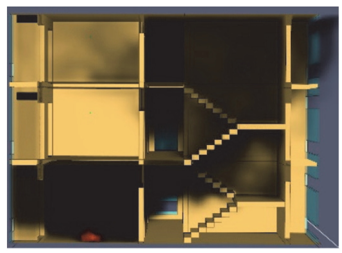
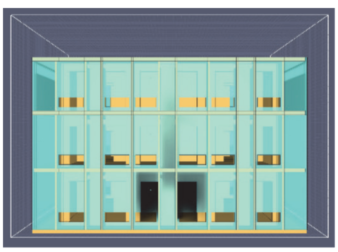
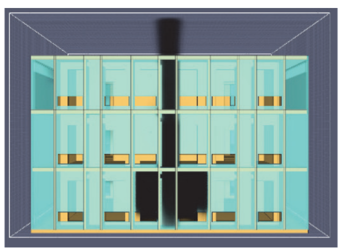
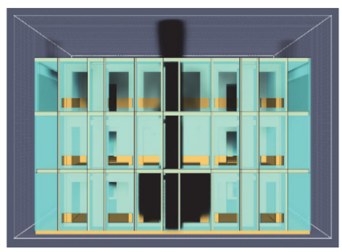
	40 s	80 s	120 s
Section			
Façade			

Table 5. Smoke view in Scenario 3

	40 s	80 s	120 s
Section			
Façade			

Scenario 2: Corridor-type DSF model

Table 4 shows the smoke layer levels at different times for Scenario 2 with a corridor-type DSF system, which causes uninterrupted cavities horizontally along the storey levels in the building. The smoke passing from the fire room to the cavity first reached outside the building at the outer shell air outlet, owing to the interruption of the cavity at floor level. As the smoke density in the cavity increased, horizontal spread occurred along the cavity, with the spread limited to the façade adjacent to the fire owing to the air outlets. Owing to the limitation of smoke spreading along the façade, smoke spread in the interior occurred at a low density in the stairwell.

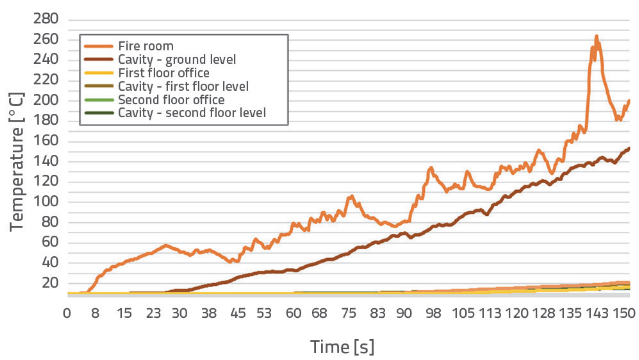


Figure 10. Temperature values measured by thermocouples for Scenario 2

Table 6. Smoke view in Scenario 4

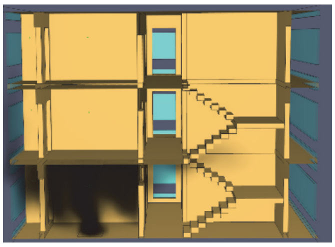
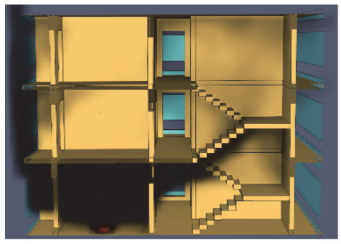
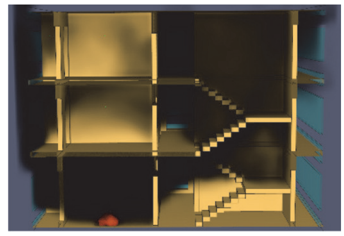
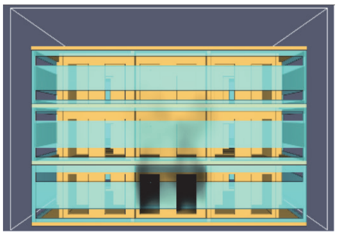
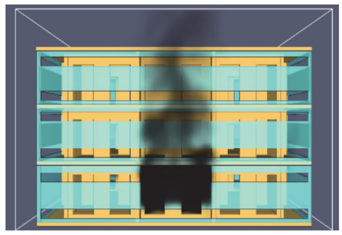
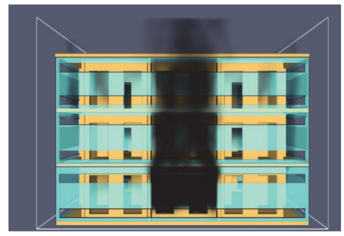
	40 s	80 s	120 s
Section			
Façade			

Figure 10 shows the ambient, office, and cavity temperatures in scenario 2. With the horizontal breakers ensuring that the flames did not reach the upper points of the cavity, the temperature levels at the upper points and offices were reduced. The highest ambient temperature was 264.39 °C, and the highest temperature in the cavity was 153.76 °C at the floor level. As the smoke and flames did not reach the upper floors through the cavity and spread horizontally, the temperature level in the offices next to the fire room was 21.17 °C. Temperature levels did not increase in the offices on the other floors.

Scenario 3: Shaft-type DSF model

The smoke layer levels at different times of the shaft-type system, which allows the contaminated air in the spaces to discharge through the shaft designed in the DSF cavity, are listed in Table 5. In this design, smoke passing from the fire room to the DSF cavity passes to the shaft through the ventilation gaps on the shaft and moves rapidly upward owing to the chimney effect. Smoke extracted from the building through the air outlets at the upper point of the shaft did not spread on the façade. However, smoke spreads from the fireroom door to the corridor and stairwell, causing movement inside the building.

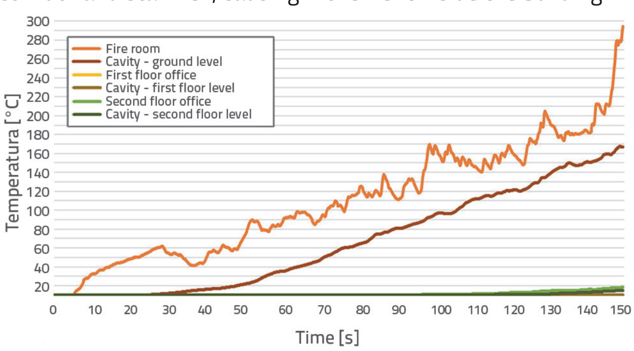


Figure 11. Temperature values measured by thermocouples for Scenario 3

Figure 11 shows the temperature levels in the ambient environment, office, and cavity for Scenario 3. Owing to the slabs at the storey levels and the shaft that holds the smoke and flame with pressure differences, the temperature levels remained low, except at the fire room and DSF ground floor level. The highest temperature was 294.62 °C in the fire room and 167.39 °C in the DSF ground floor level adjacent to the fire room. In the office spaces, the highest temperature level was 18.22 °C in the office on the second floor.

Scenario 4: Window-box type DSF model

The smoke layer level of the window-box-type scenario, in which the DSF cavity was planned separately for each space, is presented in Table 6. Considering the cavity was limited vertically by the upper-floor slab and horizontally by the walls in each space, smoke passing from the fire room to the cavity did not spread onto the façade. Air inlets and outlets designed for each limited cavity area provide smoke extraction from the cavity. Considering the ground-floor air outlets of the exterior shell and the first-floor air inlet were in close proximity, the smoke extracted from the external environment passed back into the building through the first-floor air inlet. This situation caused smoke to spread to the first-floor office, even at a low intensity. In this scenario, the stairwell spread smoke to the upper floors.

Owing to the horizontal and vertical confinement of the DSF cavities in the spaces, the temperature levels increased only at the fire room and cavity ground-floor levels. The highest temperature was 329.69 in the fire room and 180.67 in the DSF cavity adjacent to the fire room at the ground floor level. In the office spaces, the temperature was measured as 19.22 on the first floor and 16.18 on the second floor. The higher temperature at the first-floor level was due to the fire components coming out of the outer shell ground-floor air outlet to pass back to the first floor with the air inlet (Figure 12).

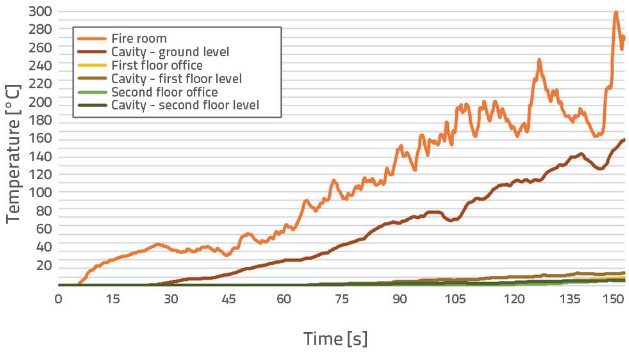


Figure 12. Temperature values measured by thermocouples for Scenario 4

Verification model

The time-dependent HRR values obtained from the PyroSim program as a result of scenarios of the model consisting of four different DSF types were arranged using Microsoft Excel. The graph obtained from Equation 1 is shown in Figure 8, while the HRR values obtained from the four scenarios are shown in Figure 13. Accordingly, the HRR time graph obtained from the mathematical calculations and the HRR values obtained from the model results draw a curve close to each other, depending on time, thus confirming that the mathematical calculations and numerical model are compatible.

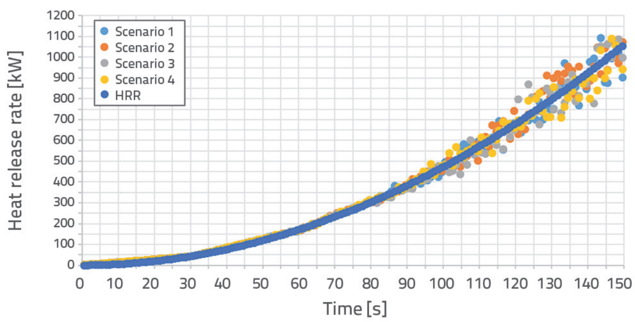


Figure 13. HRR graph of numerical model and mathematical calculations

3. Discussion

The numerical model study examined the effects of varying DSF systems according to the natural ventilation design on fire safety, smoke propagation, extraction strategies, and temperature levels in the spaces. In all scenarios, the smoke descending from the ceiling level of the fire room moved primarily into the cavity owing to the airflow effect. The height of the cavity, the position of the horizontal and vertical breakers, and air inlets and outlets affected the smoke movement in the cavity and inside the building.

In the multi-storey DSF cavity type, owing to the chimney effect caused by the high height of the cavity, the smoke passed into the cavity and moved rapidly upward, and smoke extraction started from the upper-floor air outlet. However, as the rate of heat released in the fire increased, the density and movement speed of the smoke increased, and the smoke spread from the cavity to the last floor of the office and from the fire room door to the stairwell through the hall. In the corridor-type DSF cavity, as the cavity height was only one storey high, there was no chimney effect in the cavity. The smoke passing into the cavity begins discharging from the air outlet at floor level. However, owing to the inadequacy of smoke extraction from the air outlet and the inability of the cavity to spread upward, the smoke propagation time from the fire room door cavity to the building was shorter than that for the multi-storey DSF type. As the cavity did not continue uninterruptedly between the floors, no smoke filled the offices on the upper floors of the fire rooms. In a shaft-type DSF system, where heated and polluted air reaching the cavity discharges through the shafts, smoke passing into the cavity reaches the shaft through ventilation openings. The smoke moving upward rapidly owing to the high chimney effect occurring in the thin and long shafts is thrown out of the building from the top of the shaft. However, with no direct air outlet in the DSF cavity and insufficient ventilation opening in the shaft, the transmission rate and density of smoke from the fire room to the corridor were higher than those in the other DSF types. In the window-box-type DSF, while the smoke moves similarly to the corridor-type DSF system, the intensity of the passage of smoke from the fire room to the corridor increases owing to the limited horizontal and vertical movement areas of the smoke in the cavity and the insufficient natural air outlet.

In developing a fire along the façade, the scenarios showed that the DSF systems differed. In the multi-storey DSF type, smoke spreads upward along the fire room level, hitting the upper shell level before spreading horizontally at the last floor level at the façade. In the corridor DSF type, smoke spread horizontally from the fire room to the first-floor slab, with smoke passage to the ground-floor level limited to the façade. In the shaft-type DSF system, smoke passing from the fire room to the cavity passes to the shaft, with smoke passage to the fire room limited by the ground-floor façade level and shaft. In the window-box-type DSF, smoke spreads at the ground floor façade level owing to the horizontal and vertical divisions of the façade cavity. Owing to the short distance between the air inlets and outlets in the outer shell, smoke re-enters the DSF cavity from the external environment and spreads along the upper floor levels of the fire room on the façade.

Analysing the ambient temperature during the simulation according to the DSF type, the temperature level was highest in the window-box-type model and lowest in the corridor-type model. In the multi-storey DSF model, the ambient temperature was 271.67 °C at 138 s and 264.39 °C at 141 s in the corridor-type model. In the shaft-type model, the highest temperature of 294.62 °C was reached at 150 s, while in the window-box-type model, the highest temperature of 329.69 °C was reached at 148 s (Figure 12).

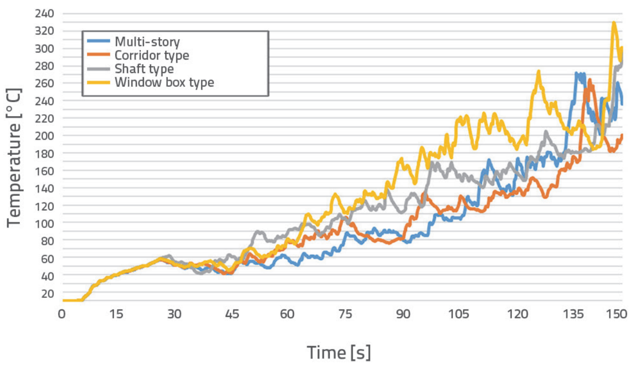


Figure 14. Time-dependent ambient temperature changes in different DSF models

4. Conclusion

We examined the effect of DSF types varying according to different cavity designs on fire development and conducted a numerical analysis of smoke and temperature change. The simulation results showed that the effects of the DSF type on fire development and their effects on natural ventilation differ. In the multi-storey-type model, airflow and smoke movement were rapid throughout the building owing to the increased height of the cavity. In contrast, in the shaft-type model, the shaft height was high, while the width and length of the shaft were narrow, indicating that the chimney effect was at its highest level. In the other models, as the height of the cavity was only one storey, smoke and airflow movement slowed, and the smoke inside the building occurred irregularly. These scenarios revealed that an appropriate cavity design contributes to the extraction of smoke from the outer shell air outlets.

The cavity, air inlet, and outlet designs in the DSF types affected the temperature levels in the fire, and a reduction in the cavity volume associated with the fire room caused an increase in the ambient temperature. The temperature levels in the offices were below 60 °C, the threshold value human skin can withstand. The temperature was higher than that of the other cavity types owing to the spread of flames to the offices on the upper floors in the cavities that continued uninterrupted vertically.

This study analysed the effect of the DSF types defined by Oesterle on fire development; however, other design parameters affecting fire development were not included. Thus, considering all design and environmental conditions as the same helped reveal the effects of the four different DSF types on the temperature levels and smoke propagation. Owing to the inclusion of design parameters such as cavity dimensions, location, and dimensional characteristics of ventilation openings, dimensional characteristics of the spaces, natural and mechanical exhaust systems, and the design of fire dampers where necessary, smoke can be extracted through the cavity. Incorporating these design parameters in the model provides new evaluation opportunities for future studies.

Fire safety in buildings can be addressed at the design stage, and risk factors in the use phase can be minimised by taking necessary precautions. Using performance-based numerical modelling approaches to monitor fire safety design decisions before a building is constructed and identify deficiencies provides advantages for implementing early security measures. Consequently, the effects of DSF types with different cavities and ventilation designs on fire safety were investigated using the performance-based numerical model presented in this study, with the results indicating that the different types affect the movement of fire elements and temperature levels inside the building. Within the scope of the study, a high fire safety risk level was ensured with a design that covers situations in which all design components are considered fixed, gaps such as windows, doors, and staircases are open, and fire occurs on the ground floor. In this direction, only the effect of the DSF type on fire development was examined; other fire safety design requirements can be fulfilled by including other design elements in future numerical modelling studies.

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