Placing Egress Components and Smoke Shafts in the Core Structure of Residential High-rise Buildings for Emergency Evacuation

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Received: 14 February 2021 - Accepted: 12 May 2021

Abstract

There is a growing demand for the construction of high-rise buildings in modern metropolises which calls for accurate and all-encompassing studies to ensure the safety of the residents. The present study examined the role of smoke shafts in the performance of emergency evacuation in high-rise buildings. The aim of the study was to find the optimal location of smoke shafts as well as other refuge areas and components of emergency evacuation in the core structure of high-rise buildings. This study sought to answer the question whether there is a link between the location and number of smoke shafts and the number of people evacuated. The movement of the occupants was simulated using Steering and SFPE simulators. The Fire Dynamic Simulator (FDS) was used for fire and smoke dispersion. The number and location of smoke shafts were considered as the independent variable and the evacuation time as the dependent variable. The findings indicated that including two smoke shafts in connection with the refuge area in the core of high-rise building can accelerate evacuation by up to 40% in case of fire.

Keywords: Smoke Shafts, High-rise Residential Building, Emergency Exit, Fire Dynamics Simulator (FDS)

1. Introduction

High-rise buildings are associated with several issues. Such structures are developing to accommodate people in expanding metropolises. The physical characteristics of these buildings lead to particular conditions of living and working for the occupants. Given the vertical access specifications of such buildings, arrangements for emergency evacuation must be taken into consideration as early as the design stage. Most of the emergency evacuation standards considered for buildings in the past are currently almost ineffective. Geometrical and architectural complexities of high-rise buildings in terms of various variables create challenges for the estimation and control of smoke inside the building [1, 2]. There is no refuge area in most of this type of residential buildings in Iran; they include a lot of units and no refuge area has not been considered in their design. Even in more recent constructions in some cases, the arrangements are neglected and eliminated for the profit of the beneficiaries. It has been proved that in case of fire, the rescue teams can only control and manage the situation about 10-20 percent as the rest is hardly controllable due to the catastrophic nature of such incidents [3]. Therefore, there is a need for accurate and principled design based on experiments and simulations more than before. To this end, passive systems are sustainable and effective. Active and passive systems can complement each other in controlling difficult conditions in the event of a fire. This study examined smoke extraction solutions drawing upon the past experiences of fires in high-rise buildings and using modeling and simulation. Previous studies carried out on fire control have not focused on architectural design to a vast extent. The current study examined the placing of functions in the design of the plan of high-rise buildings aiming at minimizing the effect of smoke and improving the emergency evacuation conditions. Various ways of placing the smoke shafts were studied in 5 scenarios. Finding the optimal place for the shafts is based on their effect on the movement of the occupants.

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** This article is extracted from Alireza Soltanzadeh’s Ph.D. dissertation entitled “Vertical & horizontal egress of high-rise buildings and its emergency evacuation based on behavioral culture” which is in progress under supervision of Dr. Hamed Mazaherian and the advice of Dr. Shahin Heidary. In addition, the advice of the fourth author has been used in Faculty of Architecture, Collage of Fine arts, University of Tehran.

2. Literature Review

2.1 Fire catastrophes in high-rise buildings

What has not happened in 20 years may occur in 20 seconds" [4]. Fire-related incidents in high-rise buildings inflict sizeable costs to the economy of cities and the aftermath may go beyond the city and reach regional or global scales. They also cause extensive damage to the emotional and psychological security of the urban community. The factors that contribute to such disasters must be identified in order to prevent future occurrences. Table 1 shows the most significant fires of the recent decades around the world.

Table 1

Study of significant fires in high-rise buildings around the world.

Name of the building/ use	Image	Country/ city	Year built	Height/ number of floors/ type of structure	Year of incident/ casualties	Cause of fire/ fault with the building/ consequences/ damage cost
Joelma Building/ bank and offices		Downtown São Paulo/ Brazil	Completed in 1971	25 floors, 105.5 meters/ structure: Reinforced concrete	Incident: February 1, 1974/ 179 dead and 300 injured Third highest death toll in high-rise fires [5]	• Cause: Faulty mechanical installations on the 12th floor • Faults with the building: Inner space packed with highly flammable items and furniture • Consequences: Full demolition and reconstruction, re-opened in 2008
Windsor Tower/ office building		Madrid/ Spain	1975–1979	32 floors, 106 meters/ architect: Gabinete Alas-Casariego	Incident in 2005/ no deaths, 7 firefighters were injured [6].	• Cause: Electrical fault on the 21st floor • Fault with the building: Inner space packed with highly flammable items and furniture. No sprinklers had been installed in the building [6]. • Consequences: Partial collapse, $32.5m
Beijing Television Cultural Center/ office building		Beijing/ China	The building was incomplete at the time of fire, but was reconstructed and opened in 2012 [7].	44 floors, 159 meters/ structure: Steel structure/ architecture: Rem Koolhaas and his Office for Metropolitan Architecture	Incident: February 9, 2009, 8:00 PM/ 1 dead and 7 injured	• Cause: Unauthorized New Year's fireworks near the building [9] • Fault with the building: The building was not equipped with fire extinguishing systems, and was seriously damaged in 13 minutes. Less steel was used than conventional buildings for earthquake resistance, resulting in its instability against fire. • Consequences: $588 million damage
Residential high-rise in Shanghai		Shanghai/ China	Completed in 1997	28 floors, 85 meters	November 15, 2010/ 58 killed, 70-120 reportedly injured, 36 missing	• Cause: Negligence by unlicensed welders; fire started from the scaffolding for façade repairs on the 20th floor • Problems: Contractors' illegal multi-layered subcontracting with unlicensed workers, lack of safety measures

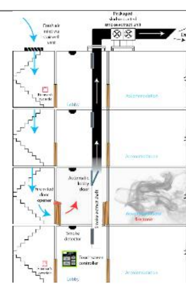
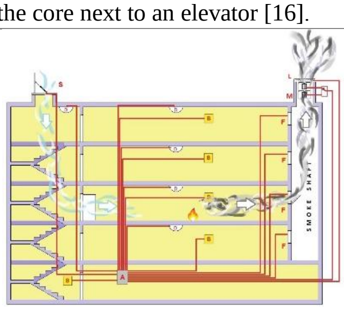
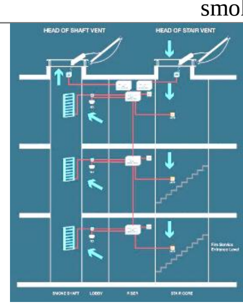
Plasco Building/ Business Building		Iran/ Tehran	1960s	17 floors, 42 meters Steel Structure	January 19 2017/ 22 killed and 235 injured	• Cause: Unknown. Contradictory reports from responsible authorities. Report of the Special Board of the National Report on the Plasco Building Incident Investigation: Electrical short-circuit and gas leakage [10] • Fault with the building: Building age over 50 years, lack of proper maintenance, possibility of sabotage • Consequences: Complete collapse during the fire • Damages: 1500 billion Tomans at the time of the fire
Grenfell Tower/ residential		West London, UK	Construction: 1972, opening: 1974	24 floors, 67.3 meters/ beam molds and shear walls	June 23, 2017/ approximately 79 killed	• Cause: Malfunctioning fridge in one of the units [11]. • Faults with the building: Old building, improper renovation, especially in the facade without fire-retardant materials. • Consequences: Partial collapse/ under reconstruction • Damages and losses: $5M [12, 13]

2.2. Nature and function of smoke shaft

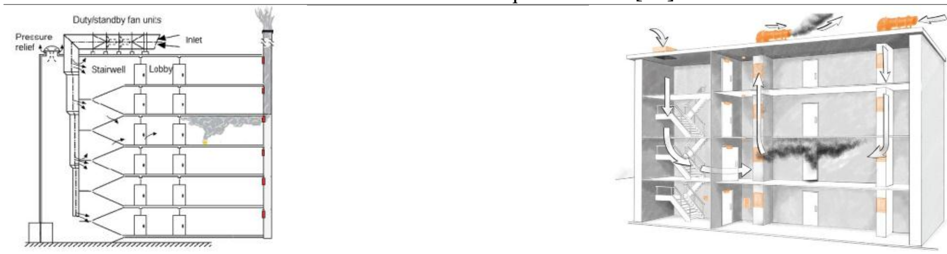
Typically, a shaft passes through all floors of the building with a damper or a similar device on each floor to control the transfer of smoke into the shaft and out of the building. Shaft systems can be designed to evacuate lobby air in order to assist firefighting operations. The regulations, especially the British building codes, iterate that firefighters must take the elevator to the floor below the fire floor, and then move the hose up the stairs. This indicates that the stairs must be protected against the smoke from the fire floor. Such conditions highlight the need to use smoke shafts connected to the staircases [14, 15]. This type of smoke shafts operate in the order of the following stages:

1- First, the smoke detector detects the smoke concentration.
2- Shaft opener opens the valve automatically.
3- The vent placed in the staircase opens to allow fresh air enter the staircase.
4- The fans placed on top of the smoke shaft on the roof start to suck out the smoke.
5- Fresh air enters the staircase and replaces the smoke.

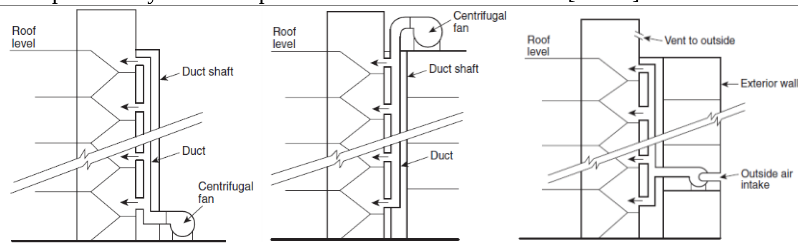
Table 2
Different types of smoke shafts.

		
An example of a smoke shaft inlet in the core next to an elevator [16].	Example of Automatic Ventilation Input (AOV)	Schematic section of the position of the smoke shaft on the floors [16, 17].
		

Different positions of smoke shafts in the building design. According to construction regulations in the UK, the dimensions of the smoke outlet duct are considered about 1.5 square meters [18].



Stair pressure system with pressurized air and smoke shaft [43-45].



Different locations of fans and smoke shaft at the top, bottom and middle of the stairs [19].

As stated in the British standard, the smoke shaft and vent must have the necessary fire resistance for 1 to 2 hours [16]. The building codes and regulations do not specify the exact dimensions and number such smoke shafts. This research attempted to use simulation and modeling for a high-rise buildings to examine the appropriate and optimal specifications for the application of such solutions.

2.3. Fire-related regulations for high-rise buildings in Iran

Rules and regulations regarding emergency evacuation and issues related to architecture and firefighting have been studied and developed at the primary layers in Iran. However, after several heartbreaking incidents, such as the Plasco building in Tehran, more precise and comprehensive regulations were added to the previous ones. The regulations specify the dimensions, sizes and components of the emergency exit to some extent. Yet, there is still a gap in the standards of high-rise buildings. Here are some of the regulations for emergency evacuation elevators stipulated in the 2017 amendment:

- Injecting positive air pressure into the elevator pit in proportion to its volume provided it can be adjusted to a minimum capacity of 0.48 cubic meters per second (1000 cubic feet per minute) for each elevator pit door.
- Buildings with more than 40 meters height difference from the ground must have at least two fire elevators with a minimum capacity of one stretcher in one of them [20].

Refuge area is one of the most important components for emergencies in high-rise buildings. It should be noted that there are several regulations in different countries for refuge areas. They may include a room or an opening and closing space or a complete floor. The following points are specified in the fire regulations of Iran regarding refuge areas:

- In buildings higher than 23 meters, placing a refuge area to hold at least 50% of the occupants per capita of 28 meters is required for one floor of each three consecutive floors at the building level. The placing of the refuge area should not be less than six square meters under any circumstances and its minimum width should not be less than two meters.
- The presence of a fire refuge area is required for any floor level that has a load of more than 50 occupants, regardless of the number of floors or the height of the floor from the ground. This area can be integrated with the fire elevator lobby as a joint area considering the special conditions of the fire elevator lobby design.
- All refuge areas on the floors must have protected access to at least one fire escape and smoke barrier in accordance with the Section 3 standards of the National Building Regulations [20].

Table 3
Smoke shafts in international building codes.

National Fire Protection Association (NFPA) [19]	Chapter 4 and 5 of NFPA 92A: Smoke Control Systems	• One of the goals of the smoke control systems is to provide a stable and smoke-free space to facilitate emergency exit through the stairs and placement in safe spaces and easy access to the exit doors. • Design parameters depend on the presence or absence of sprinklers as well as the height of retaining walls. • This standard will not be applied passively in smoke control systems using airflow. • For refuge spaces next to stairs or elevators, regulations must be in place to prevent pressure loss due to the interaction between the exhaust duct and the refuge space equipped with a smoke control system. • Recommendations on how to operate the stair fans and smoke shaft dampers • Different locations of fans on different floors of the building have been investigated.
2019 revision to CIBSE Guide E Fire safety engineering, England and Wales Approved Document B: Fire Safety the Scottish Technical Handbook Section 24 Northern Ireland Technical Booklet E5; BS 9999:20176 and BS 9991:20157 [21-27]	Part of the standards of England, Wales, Ireland and Scotland	• "smoke control" is a standalone item. Like many aspects of the design and operation of a successful building, it includes many elements, including design, product type, processes, installation, operation, and maintenance. • Smoke control is very important in tall buildings. • Smoke discharge ducts can be used both mechanically and naturally. • The problem of acoustics and sound production in such spaces is problematic.
NBS Handbook 141: design of smoke control systems for buildings [28]	National Engineering Laboratory National Bureau of Standards	• The smoke shaft is a vertical shaft that extends from the bottom to the top of the building, with openings at the top to the outside and openings to the building spaces on each floor. These openings are closed with dampers that are normally closed. • Smoke shafts are best used in open-plan buildings. • It is recommended that the smoke shafts be as far away from the stairs as possible, so as not to increase the risk of smoke near the stairway entrance when evacuating or extinguishing a fire.
Tamura, G. T., & Shaw, C. Y. (1973). Basis for the design of smoke shafts. Fire technology	Referred to NBS	• Investigation of pressure and flow patterns due to stack performance • Provide graphs of pressure and smoke movement in the smoke shaft for buildings up to twenty floors • Effect of leak parameter on smoke shaft size.

Building codes and regulations provide standards for creating desirable spaces. These standards are defined in detail for different spaces. In the combination of these spaces with each other and the interactions that have occurred, as well as the geometric, formal and functional differences of different buildings, especially tall buildings, should be examined using solutions such as simulation of the building performance. Examining smoke and fire control in high-rise buildings is largely impossible in terms of cost and safety. In these cases, simulation can be very helpful.

2.4. Literature review on smoke and fire simulation

Extensive and significant research has been done on emergency evacuation and fire protection in high-rise buildings, some of the most important and newest of which are listed in Table 4.

Table 4
Recent researches on evacuation and fire protection.

References	Model / Case Study	Evaluations	Evacuation / Fire Simulation Model	References	Model / Case Study	Evaluations	Evacuation / Fire Simulation Model
Vigne, G., Węgrzyński, W., et al. (2020, September). [29]	large-volume enclosures	Shows the importance of considering fires with multiple sources due to the faster smoke production	Fire Dynamic Simulator (FDS)	**Bae, S., Shin, H. J., & Ryou, H. S. (2014, October). [33]**	High-rise building	The strength of the stack effect is estimated using the movement of a neutral plane in a stairwell over	(USCOP) Unsteady Smoke Control Program

		compared with single fires.				time.	
Bae, S., Ko, G. H., Lee, C. W., & Ryou, H. S. (2013, June). [30]	Ultra-high-rise building	Smoke control system, energy transfer.	CAU_ESCAP network-based program	**Yan, G., Wang, M., Yu, L., Duan, R., & Xia, P. (2020, August). [34]**	Vertical shafts	natural ventilation	Fire Dynamics Simulator (FDS)
Ronchi, E., Alvear, D., et al. (2010, July). [31]	Road Tunnels	Fire modelling using FDS and STEPS to evaluate ducts in underground tunnel.	FDS+EVAC, STEPS, PATHFINDER	**Zhang, P., Wang, K., & Wang, S. (2011). [35]**	High-rise building	Controlling high-rise building fire smoke.	Fire Dynamics Simulator
Gershon, R. R., Qureshi, K. A., Rubin, M. S., & Raveis, V. H. (2007). [32]	High-rise building Analysis (World Trade Center)	Various factors at the individual, identified that affected evacuation.	Questionaries' and interviews	**Fridolf, K., Nilsson, et al (2018). [36]**	Human Behavior	Walking Speed in Smoke	advanced technique adopted so-called fractional effective dose (FED) concept

Most of the cited studies have been conducted by scholars in areas such as mechanical engineering (fluid mechanics or energy conversion), environmental engineering, civil engineering, computer science, and building safety. Architects have made a small contribution to this field, while they have the most pivotal role in the formation of a building. The lack of research by architects in such areas prevents the results of such research from being applied to buildings. This study attempts to probe into emergency evacuation with an architectural approach. The output of such research works is a guide for designers to find new solutions to solve problems of plan design and spatial relationships in various types of buildings.

3. Methodology

3.1. Review of smoke and fire simulator models

There are several models for computer simulation of fire flow. These models include theoretical, experimental, physical and quasi-experimental models. Among these, theoretical models have problems in validation [37]. There are different mathematical models for simulating the movement of people: continuous model, fine network, continuous model based on guiding behavior, fine network and hybrid mode, continuous model based on social forces model. Among the models mentioned in this research, the movement of people has been simulated based on agent based modeling. There are several methods for simulating the flow of smoke and fire as well as toxic gases: (1) Gaussian model; (2) box model; (3) Lagrangian puff models; (4) analytical models; and (5) computational fluid dynamics models [38]. In this research, fire and smoke simulator dynamics have been used.

Table 5
The types of smoke and fire simulators are listed in

Fire Dynamic Simulation Tools			
PyroSim - Thunderhead Engineering	ASPIRE Smoke Detection Simulation - Xtralis	BlenderFDS - Emanuele Gissi	CYPE-Building Services - CYPE
WizFDS - Mateusz Fliszkiewicz			
Calculation Tools			
PROPTI - T. Hehnen, L. Arnold, P. Lauer, A. Vinayak, C. Trettin	FDS MESH Size Calculator - S. Benkorichi	FDS+Evac tools - R. Lovreglio	ParFDS - S. Link
Mult Mesh - S. Benkorichi	FIM, Fire Integral Model - Ilya Karkin	FDS Docker Images - Robert Weiße, Brandschutz Consult Ingenieurgesellschaft mbH Leipzig	FDS2FTMI - Julio Cesar Silva

3.2. Building Characteristics

Pyrpsim was used to simulate the flow of smoke and fire. This software is based on the fire dynamic simulator (FDS), which is a program written in Fortran language. FDS is a fire simulator developed at the National Institute of Standards and Technology (NIST). In this research, a 60-story high-rise building with a central core for access between floors was used. The dimensions and type of plan were fixed in all floors as a rectangle of 42 by 54 meters. The plan of the rectangular tower stretched in the east-west direction. There were two refuge floors for this tower on the 20th and 40th floors. A podium with a height of 20 meters and dimensions of 80 x 65 meters was placed at the ground floor of this 60-storey tower. Moreover, several rooms were designed inside the core for temporary accommodation of the disabled and more vulnerable occupants.

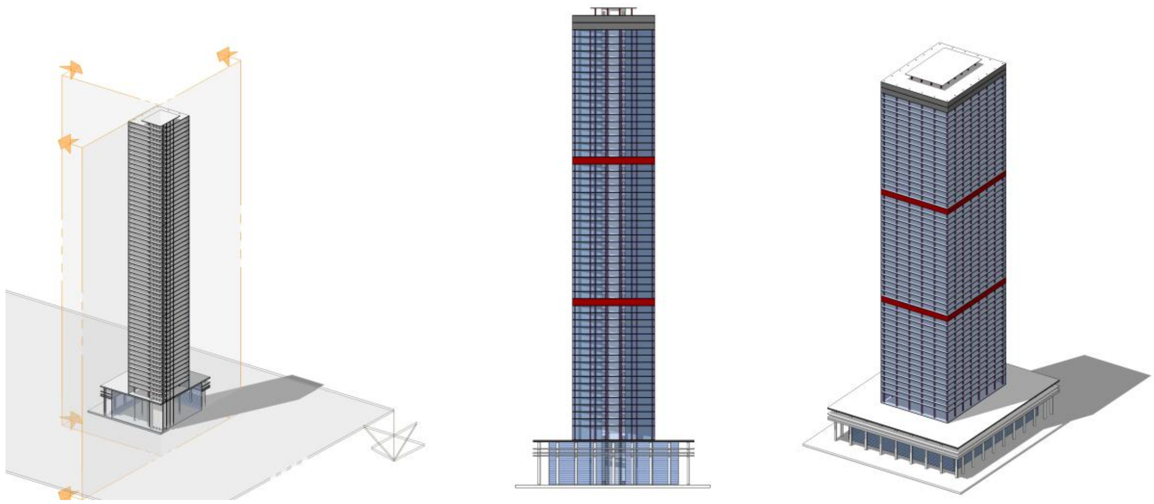
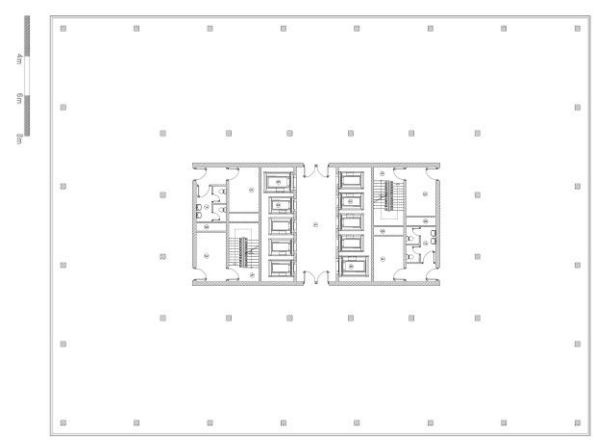
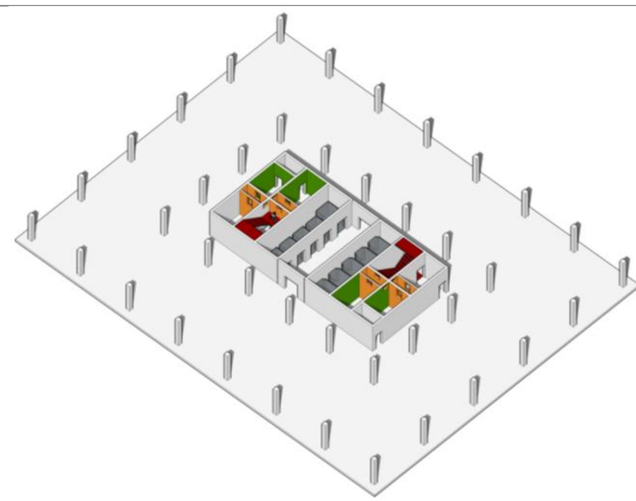


Fig 1. Perspective of the 60-storey tower. (Refuge floors marked in red)

The central core of the tower consisted of two parts connected via a corridor. This corridor can be protected by sliding doors in the event of emergency.



High-rise floor plan.



Isometric of one of the floors, the orange color represents the space intended for the smoke outlet duct. The green color is considered for the safe space, the red for the emergency stairs and the gray for the evacuation elevators

Figure 3 shows the location of the smoke outlet ducts. These ducts can be used for both stairwells and safe rooms. The specifications of the spaces designed for simulation are given in the following tables.

Table 6
Egress components characteristics.

Dimensions of emergency staircases	*Number of staircases*	*Dimensions of doors*	*Height of floors*	*Corridor width*
6*3 meters	2	1.20m *2.10m	3 m	4.4 m

	Number of smoke shafts	*Dimensions of ducts*	*Number of refuge rooms*	*Number of elevator cabins*	*Area of refuge rooms*
Scenario1	_	2*1.3 m	4	10	69 m^2
Scenario2	2	2* 2.25 m	4	12	69 m^2
Scenario3	2	2*1.3 m	2	10	27 m^2
Scenario4	2	2*1.3 m	4	14	115 m^2
Scenario5	4	2*1.3 m	4	10	51 m^2

The model was analyzed in two phases. In the first phase, the effects of smoke were analyzed in Thunderhead Engineering PyroSim 2018-3-1210 after determining different scenarios and the smoke-related data output was imported into Thunderhead Engineering Pathfinder 2018-4-1210 for application on people. In Pathfinder, the scenarios were first simulated using steering method and then analyzed using SFPE method. The results of the two simulations were compared. In the SFPE method, the walking speed of occupants is determined by the density of their presence inside a room as well as by the flow of movement and their passage through the door [39]. In order to simulate the smoke flow in PyroSim, meshing and a border layer must be created when the geometry is done. The dimensions and size of the meshes depend on the fire characteristics which are obtained using the following equation. The obtained value of D divided by 20 gives us the correct mesh dimensions [40].

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty C_\rho T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \qquad (1)$$

Jeanne was the first to work on the relationship between visibility and speed of movement in the 1970s [41]. The variable of visibility in smoke and its effect on occupants' speed of movement has been examined in this study. Ronchi's article iterates that given the walking speed of people with different amount of visibility and the relationship between their distance and proximity to the place of fire, their walking speed can be estimated in three ways. In the first method, a constant speed is attributed to all occupants in the simulation and the only factor is the amount of smoke that affects the visibility and the walking speed of all of the people. In the second method, occupants are divided into three groups: those who walk normally, those who are slow, and those who have physical problems and are very slow at the event of emergency. In the third method, the walking speed of each person is considered randomly. In the following formula, the depth of visibility needs be specified in each part of the walking plan of the occupants and the normal walking speed, which is randomly selected, is entered. Finally, the coefficient that should function as the decelerator is obtained [42].

$$W = \min (W_{Smoke\ -free};\ \max (0.2;\ W_{smoke\text{-}free} - 0.34*(3-v))) \qquad (2)$$

The following diagram shows the different intervals of occupants' walking speed and their visibility in the third method

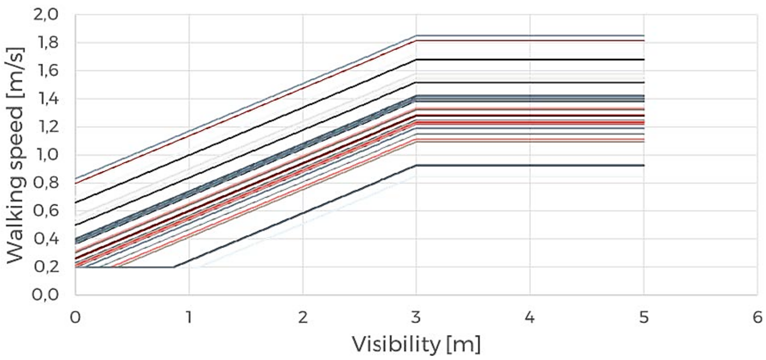


Fig. 2. The relationship between the depth of vision of individuals and their movement speed in the method of considering random velocities for all individuals [42].

The obtained numbers are applied on the speed of people using PyroSim by simulating the fire and obtaining the visibility in different parts of the floor plan and the central core plan, in order to calculate the evacuation time and find the escape routes. Meanwhile, by placing smoke shafts in different places and with different numbers, the role of such solutions in changing the total evacuation time can be evaluated.

The variables analyzed in the simulation include:

- The effect of smoke on occupants' walking speed
- The effect of smoke on occupants' visibility
- The place of smoke shafts

Simulation defaults:

- Walking pre-time of occupants (detection time and reaction time) according to different physical types of the occupants of the building: Women (20 to 50 age group), women (50 to 80 age group) - men (20 to 50 age group), men (50 to 80 age group)
- People with disabilities or special physical conditions

The stack phenomenon and performance of HVACs have not been considered in this study. In addition, the transfer of smoke from the facade is not considered. Stairs, corridors and other open spaces are considered.

Fire & Boundary Conditions/ Property	Value
Fire Position	38nd Floor
Fire Size	5 MW
Wind Velocity	0 m/s

The study area for analyzing occupant's visibility range is shown in the figure below.

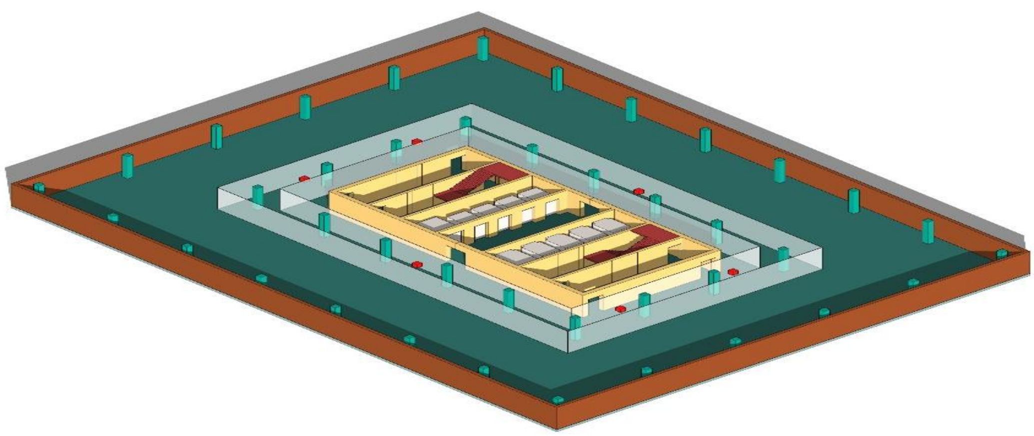


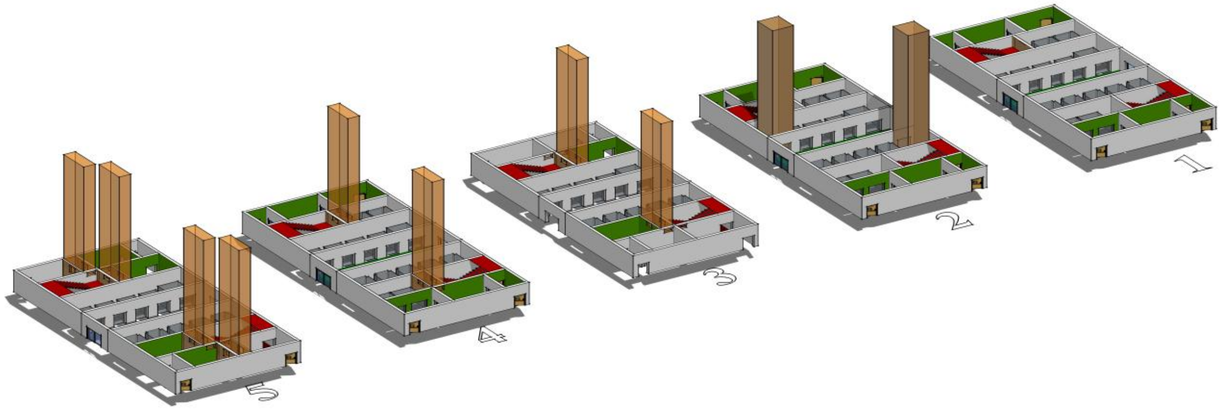
Fig. 3. At the red spots marked in the image, the visibility in meters is checked at different intervals of the simulation. The hypothetical white transparent screens also show the range of decision and movement to access emergency egress components.

4. Simulation and analysis

4.1. Simulation scenarios

The place of the smoke shafts has been determined in the central core of the building.

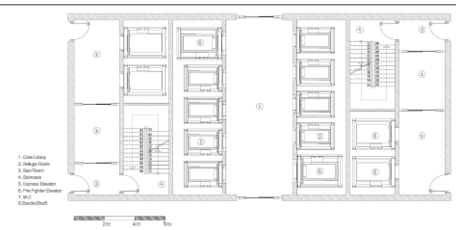
Table 7
Diagram of different scenarios.



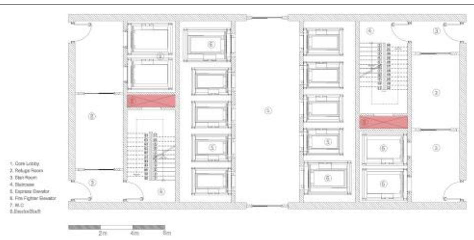
The intended cylinders in orange are smoke shafts. Spaces marked in green are refuge rooms and red indicates stairs.

Core plan in five scenarios

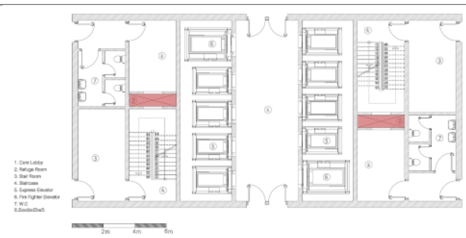
Scenario 2



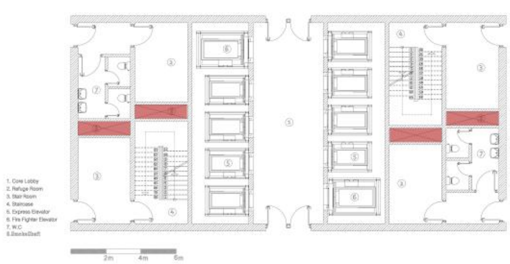
Scenario 1



Scenario 4



Scenario 3



Scenario 5

Table 8
Simulation Parameters.

Air discharge fan specifications	Combustible material	Fire area / fire heat dissipation rate	Number of meshes	Ceiling sprinkler	Simulation time
Dimensions about 1.2 * 1.7 meters / at a speed of 30 meters per second	ethanol	1.5*1.5m / 1000 kW per square meter	From 100 to 500 thousand quadrilateral networks	It has not been considered.	300s

4.2 Scenario 1: Examining the central core without considering the smoke shaft

The simulation in this scenario was carried out from the 38th floor where the fire starts to the 60th floor in 300 seconds. Due to the proximity of the fire to the right wing of the central core of the tower, the staircase located on that side practically spreads the fire to the upper floors. Within 300 seconds, considering the fire characteristics listed in Table 7, the fire reaches the 49th floor. It should be noted that in these simulations, the spread of fire through the facade of the building is overlooked.

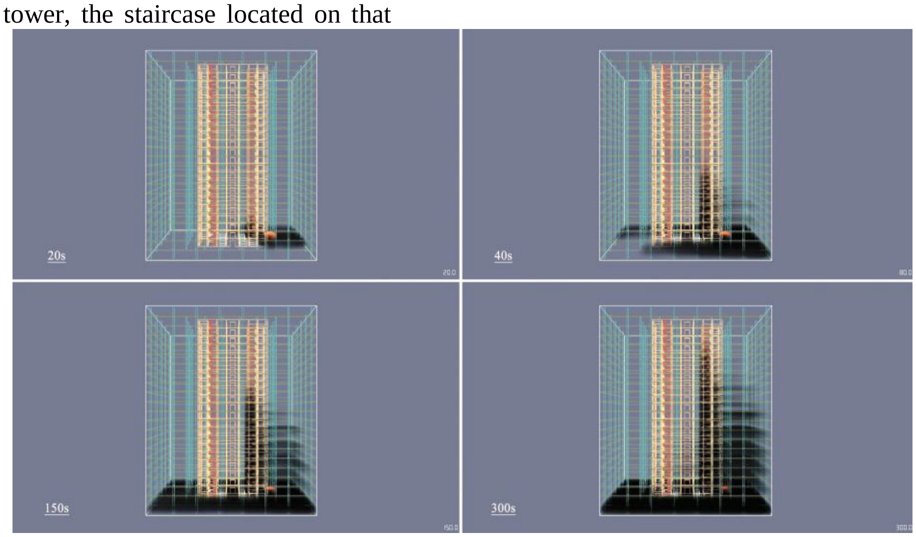


Fig. 4. Smoke emission from the 38th to the 60th floor in 300 seconds.

This scenario consists of two parts. The first part was mentioned above, and the second part is examining the events that took place on the fire floor. This section was carried out considering only the floor where the fire was, namely the 38th floor. In this scenario, smoke emission was studied without considering the shaft.

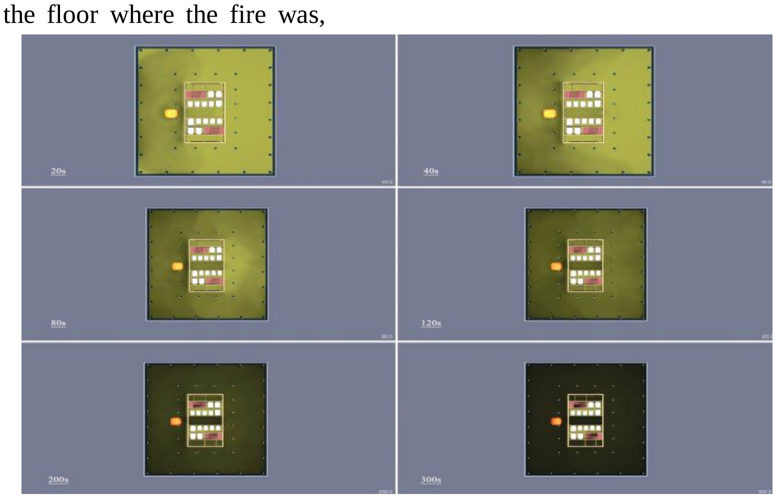


Fig. 5. Smoke emission in the first scenario.

4.3 Scenario 2: Examining the core considering two smoke shafts in the corridor and two refuge areas

In this scenario, the effectiveness of the smoke shaft and its performance inside the corridor was studied considering the occurrence of fire inside the central core corridor. For this purpose, the fire was first simulated in conditions where no smoke shaft is placed inside the corridor. Then, it was repeated with the addition of two smoke shafts and finally, the effectiveness of the shaft was evaluated on one floor above the fire floor.

4.3.1. Occurrence of fire inside the corridor without placing smoke shafts

There are only elevators in the core corridor of the tower and the smoke shafts have been disregarded. The following results show the amount of smoke emitted in the floor space in the period of 300 seconds.

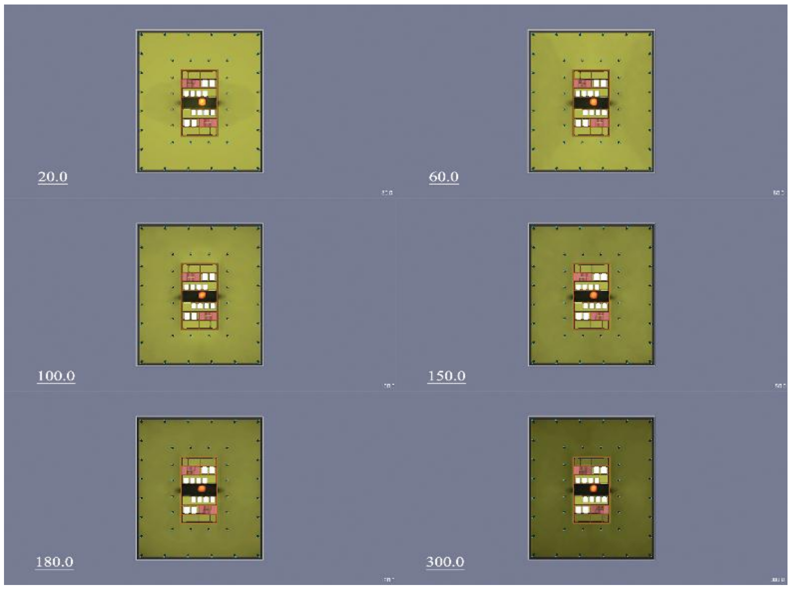


Fig. 6. Smoke emission in the second part of the first scenario in the fire floor.

4.3.2.Occurrence of fire inside the corridor with placement of smoke shafts

In this scenario, the effectiveness of the shaft was compared to the previous scenario with the addition of two smoke shafts in the vicinity of the elevators and the vents inside the corridor. The comparison of the results of temperature changes in the two scenarios is shown in the figure below.

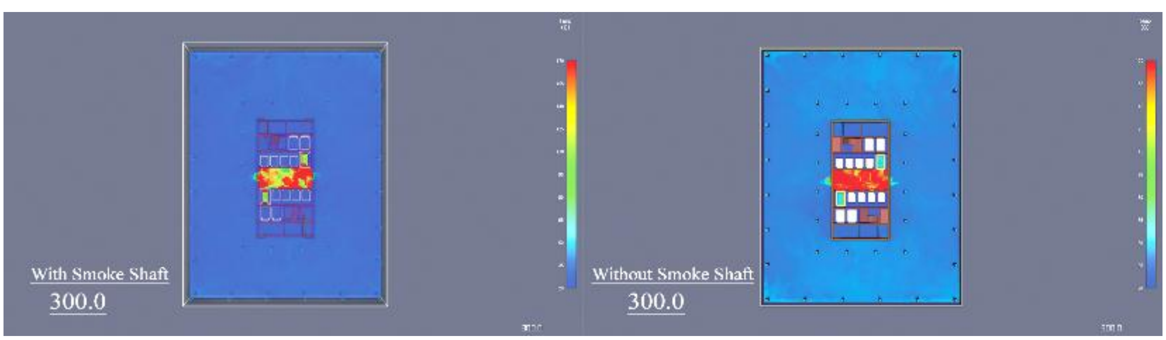


Fig. 7. On the right side, the temperature of the whole fire without placing smoke shafts is shown and on the left side, the same values are displayed with the placement of smoke shafts.

With the addition of the smoke shafts, the floor temperature remained within the standard range of 25-30 degrees at the event of fire. In cases like this, in scenarios where fire occurs inside the corridor of the central core, the possibility of evacuation is troubled and thus the central core should have access to fire escape and evacuation elevators on every side in order to prevent blocked access when the fire is at the core. One of the best ways to prevent this blockage is to use two cores in the corners of the high-rise building plan.

4.4.Scenario 3: Examining the core with the placement of two smoke shafts by the staircase and a refuge area

In this scenario, two smoke shafts were placed on the two sides of the core adjacent to the staircase with a neighboring refuge area. The range of temperature change after about 300 seconds from the beginning of the simulation is shown in the figure below.

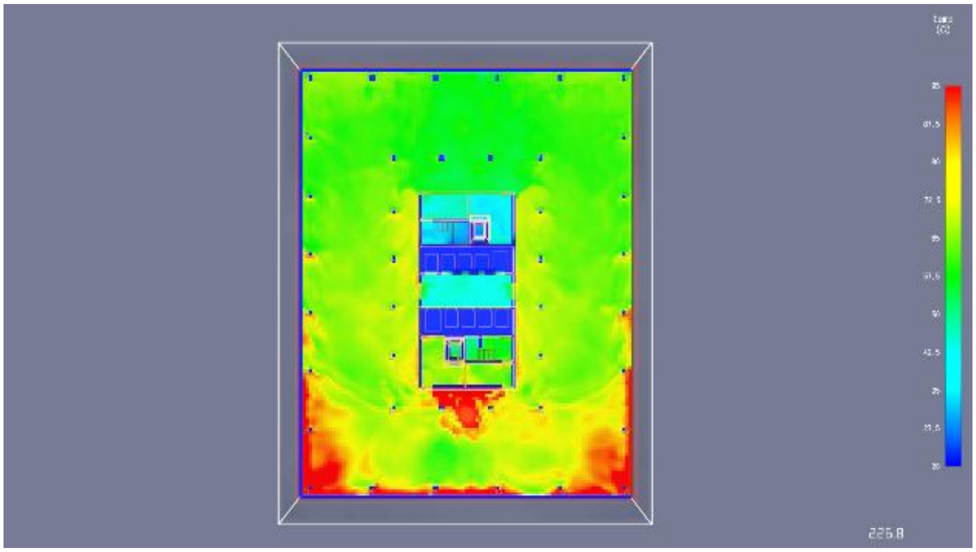


Fig. 8. Range of temperature changes in the plan of the fire floor after about 300 seconds.

The figure shows that the temperature of the area around the fire rises to 90 degrees Celsius after about 300 seconds. Due to the proximity of the fire site to one side of the core, it is possible to use the other wing to evacuate or take shelter in a refuge area. In the refuge area of the northern part of the plan, the temperature remains around 30 to 35 degrees, which shows the difference of about 15 degrees with the refuge area and the staircase of the southern part.

4.5 Scenario 4: Examining the core without placing two smoke shafts by the staircase and two refuge areas

This scenario differs from the previous scenario in the number of refuge areas and two separate but interconnected refuge areas were placed, which can hold more occupants until the firefighter team arrives.

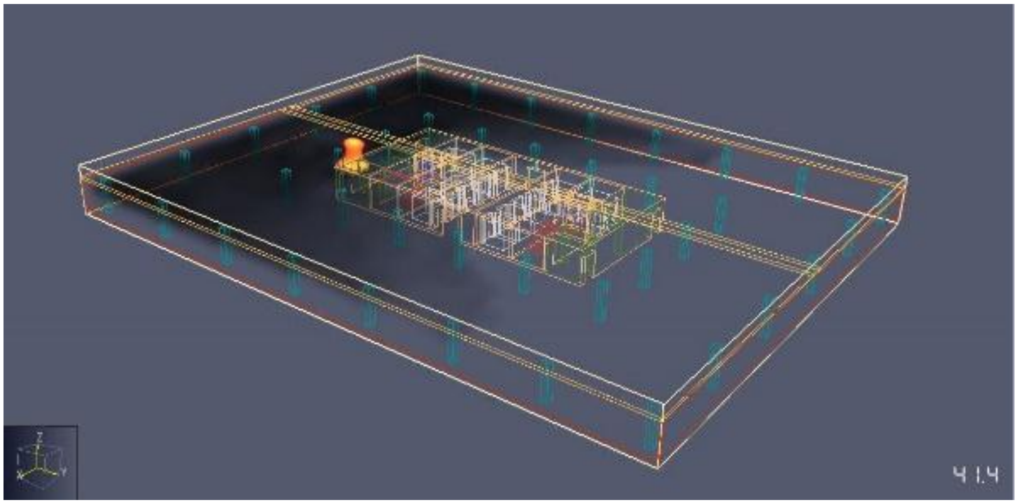


Fig. 9. Smoke emission pattern on the fire floor after about 41 seconds.

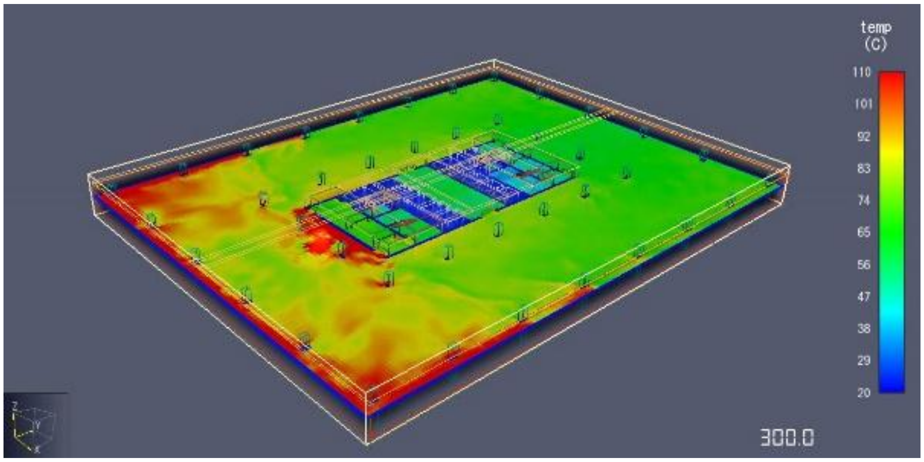


Fig.10. Range of temperature changes in the plan of the fire floor after about 300 seconds.

4.6 Scenario 5: Examining the central core with the placement of four smoke shafts by the stairs and two refuge areas.

In this scenario, the spread of smoke flow in the fire floor and two floors above were simulated for 5 minutes with the placement of two smoke shafts on both sides of the central core and two separate refuge areas on both sides of the central core of the high-rise building. One of the important issues to be addressed in such architectural arrangements is that for a given number of floors, particular exits should be considered for smoke evacuation. Simulations showed that the bottom-to-top outright smoke shaft cannot be efficient without having interval evacuation in this high-rise building.

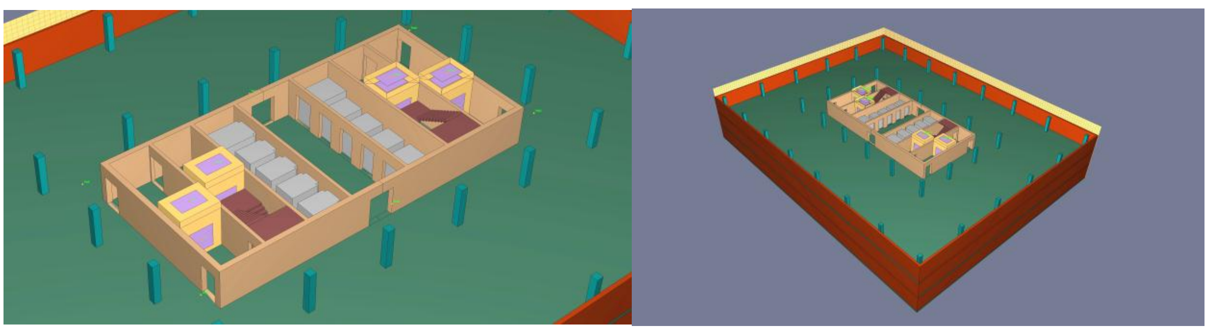


Fig.11. Smoke shafts on both sides of the central core corridor are marked in purple. The smoke shaft is on the side of the staircase and on both sides of the refuge rooms of smoke vents.

Placing smoke shafts on both sides of the core seems to be very efficient in this simulation. In this way, if fire occurs anywhere, a series of shafts will carry out the smoke extraction.

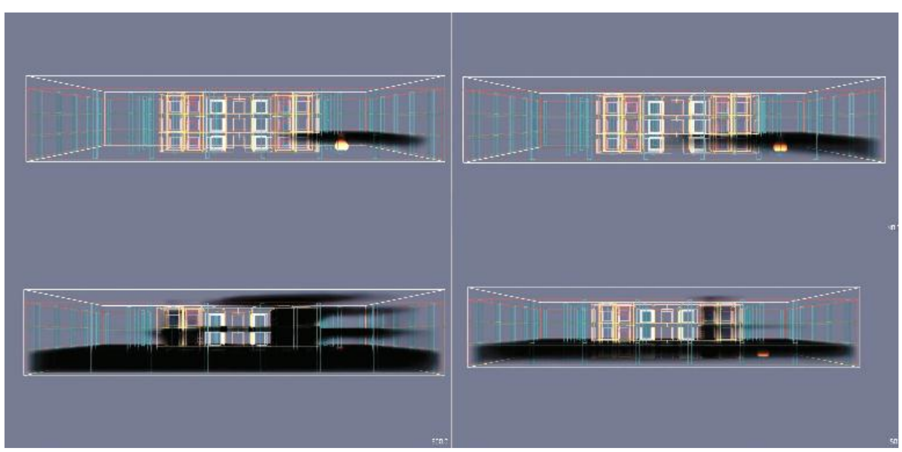


Fig. 12. Emission of smoke in the three fire floors of the tower at 20, 40, 150, 300 seconds after beginning the simulation.

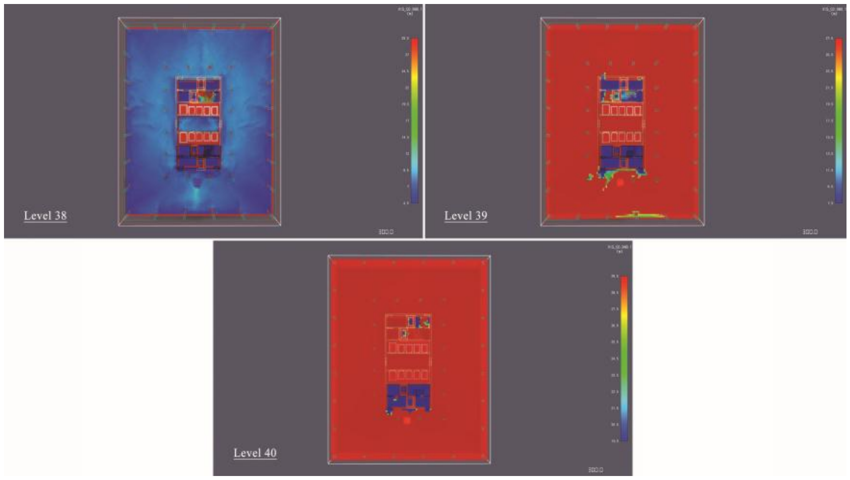


Fig. 13. In floors 38, 39 and 40, the visibility range is specified 5 minutes after beginning the simulation.

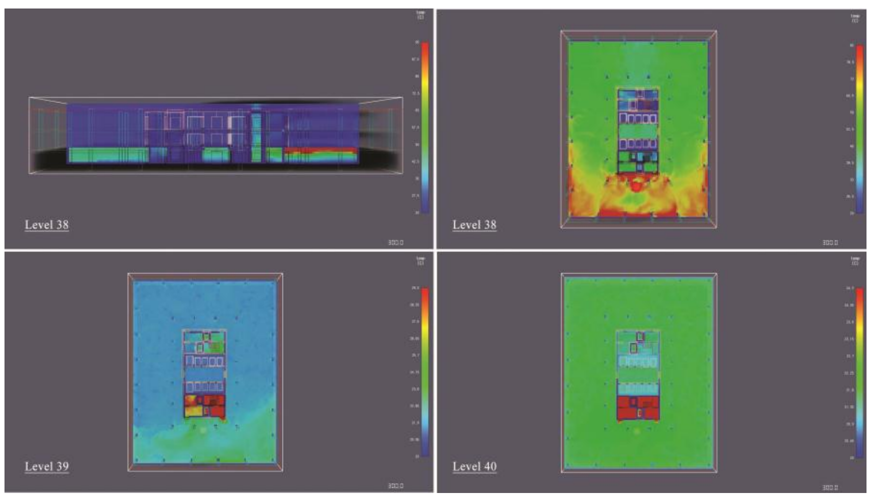


Fig. 14. Emission of smoke in the three fire floors of the tower at 20, 40, 150, 300 seconds after beginning the simulation.

In this simulated situation, the role of evacuation elevators and corridors is vital. They can be of help in case of local fires in the work area and the corridor can play the role of a safe space. According to ASHRAE handbook, the exhaust duct needs to be installed far away from the entrance of the stairs, but this study showed that installing the exhaust duct close to the stairs and a safe space will be capable of preventing smoke from spreading into the top floors.

4.7. Studying the effect of smoke shafts on occupant evacuation

In this section, the effect of smoke in limiting the visibility as well as temperature changes in different parts and creating the tendency towards difference occupant escape ways were studied according to the results obtained from the simulation of smoke flow in the five scenarios. First, the data on visibility range, which has been already determined on different parts of the plan were obtained from FDS simulator. Then they were converted into time coefficients through equation number one to calculate the deceleration of occupants' walking speed. Evacuation simulations were carried out for the five different scenarios based on SFPE and STEERING algorithms. The evacuation scenario was as follows: the occupants are first transferred to the safe floor and stop there for 30 seconds and then they are transferred to the lobby through the egress components. The total simulation time was set at 300 seconds. The most important goal in the beginning is to evacuate occupants at the fire floor to the refuge area to control the danger.

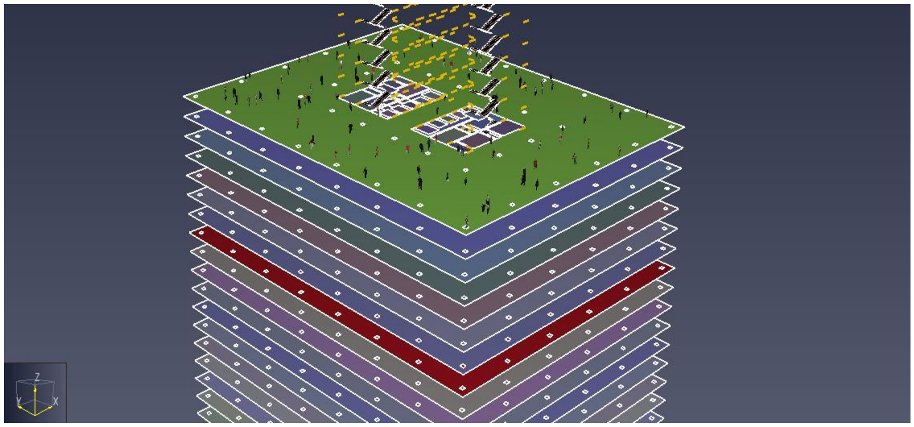


Fig. 15. The fire floor is marked in green with 100 people, the refuge floor is marked in red.

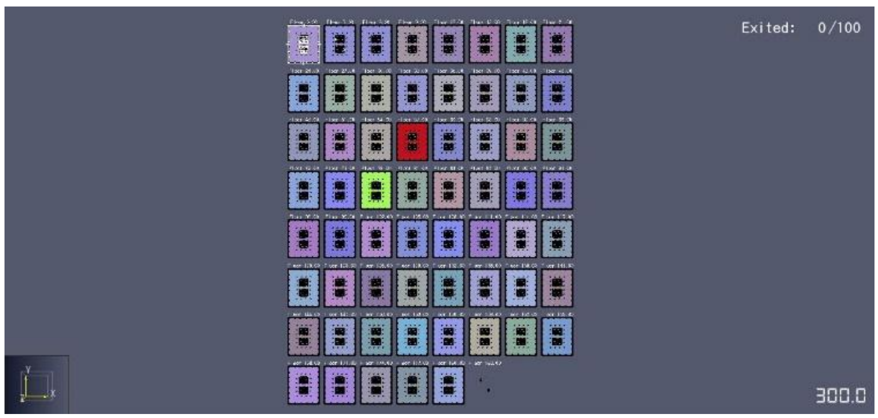


Fig. 16. Examining the movement of occupants and their position; fire floor and refuge floor are marked in green and red.

5. Data Analysis

The analysis and the comparison of different scenarios are detailed in the table below. This table shows the output of occupants' movement analysis. The goal was to find the optimal scenario in which more occupants can be evacuated or moved to the lower floors of the building at a given time.

Table 9
Analysis of the results of the effectiveness of smoke shafts on the number of evacuated occupants in the building.

Number of floors involved in evacuation during the simulation	The number of people considered in the fire floor	Simulation Duration	
12 Floors			**First Scenario**
11 Floors			**Second Scenario**
11 Floors	100	300	**Third Scenario**
8 Floors			**Fourth Scenario**
6 Floors			**Fifth Scenario**

6. Conclusion

In this study, the effectiveness of smoke shafts in controlling the air inside high-rise buildings was examined at the event of a fire. In this regard, five different scenarios were designed to evaluate the efficiency and effectiveness of such installations considering the design criteria for emergency egress components in high-rise buildings. The data specific to changes in temperature and visibility range were obtained via FDS simulator and the visibility range was converted into a decelerating coefficient using the designed formula and was applied to the occupants' walking speed at the fire floor. The results showed that the smoke shaft and particularly its placement in the vicinity of refuge rooms and staircases were substantially significant in reducing floor temperature and increasing visibility. Furthermore, according to the simulations, the number of evacuated occupants increased by 40% compared to the scenario without a shaft. Apart from the placement of smoke shafts, future studies could examine the details of the number of floors that can be considered for smoke shafts. Moreover, the feasibility of smartization of the analysis of designed plans could be studied using smart optimization algorithms to find optimal solutions for emergency exit.

Table 10
Nomenclature

FDS	
Q	Heat Release Rate (kW)
$\boldsymbol{p_\infty}$	Density (Kg/m^3)
$\boldsymbol{c_p}$	Specific Heat (kJ / kg-K)
$\mathbf{T_\infty}$	Ambient Temperature (k)
Gravity (g)	9.81 (m / s^2)

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