The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-4/W4-2022
17th 3D GeoInfo Conference, 19–21 October 2022, Sydney, Australia

# 3D BASED SMOKE FIRE EMISSION AND EMERGENCY EVACUATION SIMULATION IN HIGH-RISE BUILDINGS

M.Taleai[1,2*], M. Mokhtari[1], S. Zlatanova[2]

[1] GIS Department, Faculty of Geomatics, K.N.Toosi Univ. of Technology, Iran – taleai@kntu.ac.ir, majid.mkhtrr13@gmail.com
[2] GRID, School of Built Environment, A.D.A., UNSW, Australia – (m.taleai, s.zlatanova)@unsw.edu.au

**Commission IV, WG IV/9**

**KEY WORDS:** Evacuation, Simulation, BIM, 3D-GIS, High-rise Building, Emergency, Fire.

**ABSTRACT:**

High-rise buildings, with high number of population, have always been among the concerns discussed in urban crisis management. One of the crucial aspects of high-rise buildings is having a proper and timely action plan for evacuation in the case of emergencies such as fires. The spread and progression of fire smoke in high-rise buildings are affected by the architectural design of the building, and having a three-dimensional (3D) model of high-rise buildings can play key role in damage reduction in such cases. This paper, first presents a method for 3D smoke emission based on utilizing 2D cadastral data to generate a 3D model of the buildings. Then, in step of smoke fire emission simulation, the influence of different smoke movement paths such as the entrance/exit doors, windows, smoke barrier, stairs, and elevators, are examined in different scenarios. Next, the emergency evacuation of occupancies with different behavioral and physical characteristics is simulated. The results indicate that 2D cadastral data of apartments can be employed as a suitable source to create 3D models of high-rise buildings, and allows to examine the emergency evacuation of residents by including the smoke simulation spread in the building.

## 1. INTRODUCTION & BACKGROUND

The expansion of population and the tendency of people to live in cities has led to the use and attention of high-rise buildings more than ever. Such structures have always been among the concerns and issues discussed in the codification of guidelines related to urban beauty, urban planning, urban management, urban crisis management, etc.

High-rise buildings can have different uses such as residential, commercial, workplace, or multi-use as a complex building, with a high number of residents and population density. One of the crucial aspects of high-rise buildings is having a proper and timely action plan to tackle emergencies including fires, earthquakes, and terrorist attacks (Sagun et al 2013, Aleksandrov et al 2021b). Three-dimensional (3D) models of high-rise buildings fires play a key role in crisis management and damage reduction in such cases.

Fire smoke is one of the main reasons for fatalities in building fires. The presence of toxic gases and their high emission rate cause people to have difficulty seeing and walking, experience dizziness and confusion, and there is a possibility of suffocation and death. In high-rise buildings, the spread and progression of fire and smoke behave in a complex and unpredictable manner and progresses rapidly. Its movement and diffusion in different parts of the building are affected by the architectural design of the building. Ways of transferring smoke from one floor to another can be air conditioners, ducts, elevators, stairwells, and even common windows to the shared areas such as patios. Therefore, determining these ways and cutting off access and spreading smoke to other floors is very important.

Various models and software have been proposed to simulate the spread of fire and smoke emissions in buildings, including the Cellular Automata (CA) Model (Mutthulakshmi et al., 2020), Consolidated Model of Fire and Smoke Transport (CFAST) (Peacock et al., 2015), Large Eddy Simulation (LES) (Chen et al., 2018), the SMARTFIRE Model ( Ewer et al., 2010), and Fire Dynamics Simulator (FDS) (Gawad & Ghulman 2015). The last three are numerical models which use Computational Fluid Dynamics (CFD) model. He et al., (2015) have investigated the spread of smoke in elevator shafts using numerical methods based on CFD. Lo et al. (2002) have used CFD numerical methods to evaluate the airflow status and spread of smoke in the building, by introducing a floor as a shelter and also the effect of floating force on the speed and movement of smoke. COSMO (Black, 2009a, 2009b, 2010 and 2011) and CONTAM (Walton and Dols 2008) are two computer programs that study smoke movement, determine airflow and investigate air pressure tests. Also, CUsmoke model considered smoke simulation in a high-rise building by three statuses for Heat Release Rate (HRR): constant, linear, and nonlinear changes that came to the attention of researchers (Wang et al., 2013b; Li et al., 2016; Wang, 2008).

Evacuation of people in the building must be done with proper and timely plan observing safety regulations (Ronchi and Nilsson, 2013). The quality, efficiency, and effectiveness of the evacuation strategy are based on the number of people who have reached the safe area in good health. Understanding the behaviours and reactions of people in emergencies helps to set the appropriate strategy for evacuation, optimal and intelligent design of the building, and increase the safety of the structure (Aleksandrov et al., 2018). People with different gender, ages, physical ability, and social and psychological characteristics are more likely to act in different ways under the same circumstances that affect a person's decisions and actions.

Almeida et al., (2013) used an Agent-based system for emergency evacuation after a fire to model the fire (smoke, temperature, pressure, visibility, etc.) and geometric information about the building by utilizing FDS and PyroSim. In this model,

* Corresponding author

for intelligent agents, BDI[1] characteristics including age, gender, experience, stress, and task (role of the agent in evacuation) are considered to examine the health status, movement, speed, field of view, and location of individuals. Esteves (2009) and Aguiar (2010) presented a graphical representation of the evacuation process in the Modp 3D viewer environment for 3D environments under the OpenGL programming interface. Wu and Huang, (2015) simulated the movement and dynamics of individuals during evacuation and examined the total evacuation time of a high-rise building using a Volume Control model under seven scenarios. The evacuation of a 28-storey high-rise building with 440 occupants was implemented in CFAST (Smoke and Toxic Emission Simulation software) and Building EXODUS (Evacuation Simulation software) with a specific attention to the staircases (Xing and Tang, 2012). Yang et al., (2013) utilized Discrete Design Method (DDM) based on the integrated model between fire spread and human movement to simulate emergency evacuation after the fire occurred using FDS&Evac software. Patterson and Johnson (2018) examined the evacuation process of two large concert halls under several population scenarios by using the Unity game engine. Zheng et al. (2017) have presented the Floor Field (FF) model to study the movement and evacuation of people in fire and smoke emission conditions, in both static and dynamic modes.

Trained firefighters and computer simulations can increase the preparedness of individuals and rescue personnel. The high cost and resourses required for prforming real evacuations as well as the complexity in collecting and accessing empirical data on accidents are factors that make realisic training and evacuation difficult. Therefore, computer evacuation simulations to study and evaluate demographic behaviour is largely investigated.

This article presents a method for 3D smoke emission and evacuation that uses on 2D cadastral data to generate a 3D model of a building. In the fire simulation, the primary purpose was to influence the smoke movement paths to other points such as the entrance/exit doors, windows, smoke barrier, stairs, and elevators, which are examined in different scenarios. This study selected a real high-rise building to set specific fire scenarios, create an FDS fire model, analyze the direction and characteristics of smoke emission in different fire scenarios, and simulate the emergency evacuation of occupancies with different behavioral and physical characteristics.

## 2. CONSIDERATIONS AND METHODOLOGY

Fire heat affects the body in several ways but the temperature and duration of time when a person is exposed to heat are considered the most effective parameters. People must not enter areas where the temperature is above 49 degrees Celsius unless protected by special equipment. Smoke reduces vision and irritates the eyes and lungs which in many cases it will be difficult for people to identify obstacles and ways out. Furthermore, the duration of exposure to the toxic gases of fire will be deadly.

3D building models can be generated with different methods according to the production goal and costs ahead: data like 2D raster data (satellite imagery), 2D vector data (Wu et al., 2020), LiDAR data (Fichtner et al., 2018; Nikoohemat et al., 2021). Often 2D spatial data available in databases (such as Oracle, Geodatabase, and SDE[2]) are used to generate 3D models in 3D formats (such as OBJ, FBX, KML, and COLLADA) or semantically rich 3D models such as CityGML and building information modeling formats (such as IFC and RVT) (Liu et al., 2021). Furthermore, different levels of detail (LoDs) in CityGML or levels of development (LoDs) in BIM can be applied.

The fundamental issue for high rise buildings is the unavailability of suitable 3D data sources. When 3D models are lacking, researchers are looking for other data sources, tools and techniques to make it possible to provide 3D models with the necessary details for simulating the spread of fire smoke. For example, Ding et al. (2017) proposed a manner for constructing geometric and topological models called EABNOF3 Yin et al. (2008) utilized two-dimensional architectural plans in the Autodesk Revit environment. Barki et al. (2015) produced a BIM model for skyscrapers by combining two-dimensional maps and images from indoor scans with digital cameras. Emamgholian et al. (2021; 2018; 2017) utilized two-dimensional cadastral data to make a 3D model of a large complex high-rise building in Tehran, and proposed a 3D proximity analysis to model the easement rights. Hosseini and Taleai (2021) reviewed recent researches on integration of BIM and GIS which amied to better management of spatial information and better decision-making to solve issues related to different urban ploblems. Mokhtari and Taleai (2020) utilized 2D cadastral maps to produce a 3D model of building with adequate details and then investigate smoke emission in the building.

Figure 1 illustrates the steps of the practical approach applied in this paper. The first step is the Hig-rise 3D modelling. The process is completed in City Egine and the final product is a 3D model at LoD4. ArcGIS was utilized for data preparation, creating 3D building model in CityEngine after assigning CGA[4] rules to features and layers.

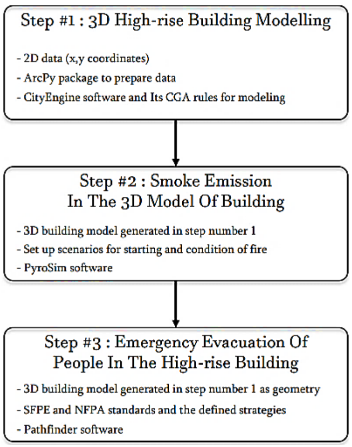



**Figure 1.** Main processing steps

Next, the smoke emission in the building is simulated in PyroSim under seven scenarios which aims to evaluate the effects of ducts, skylights or windows to the shared areas, and smoke-proof stairwells (or fire doors) in the smoke propagation towards various tall building components.

Then, emergency evacuation of building's occupants is computed in Pathfinder, based on the preferred strategy from the before step and in both Steering and SFPE modes. Besides, five categories of persons are considered in terms of age, gender, and physical ability, including evacuation of disabled persons through the elevators in a safe manner and other persons via staircases.

[1] Belief-Desire-Intention (BDI)
[2] Spatial Database Engine
[3] Extrusion Approach Based on Non-Overlapping Footprints
[4] Computer Generated Architecture


https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-139-2022 | © Author(s) 2022. CC BY 4.0 License.

## 3. THE CASE STUDEY BIULDING

The case study is a 17-storey building located in the Shemiranat district of Tehran (Figure 2), including 13 floors and 3 underground floors. This building complex consists of three separate towers that are located next to each other with total area of 6454 square meters, includes the prayer hall, meeting hall, gym, 373 parking lots, 300 residential warehouses, 300 residential units (apartments), 2 commercial units, more than 30 ducts, and 6 elevators.

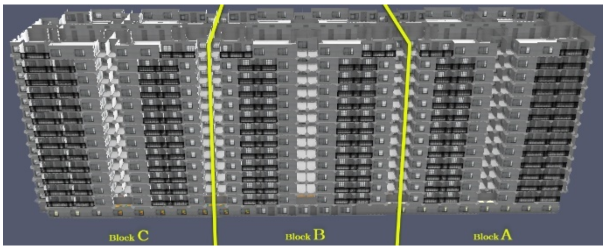



**Figure 2.** Case Study: a high-rise building in Tehran

It should be noted that in the 3D building modelling step, the entire building with its 17 floors has been created. However, in the next two steps (modelling the spread of smoke and simulating the evacuation of occupants) the focus is just on 13 floors of the middle tower block B, with an area of 914 square meters and includes two elevators, two stairs, 8 residential apartments on each floor and 11 ducts.

## 4. STEP 1: 3D HIGH RISE BUILDING MODELLING

In the first step, i.e. preparing 2D data, ArcGIS and ArcPy framework were used, which resulted in the formation of a 2D plan of each floor (Figure 3). Then a 3D model was made using CGA rules in CityEngine software. Finally, the 3D model of the building will be available at LOD 4 (Figure 4).

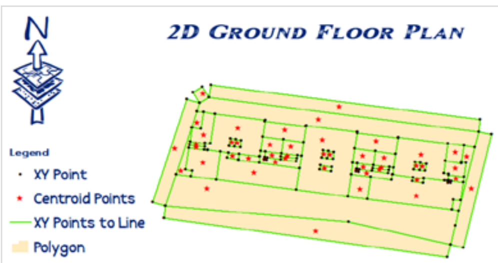



**Figure 3.** Ground floor 2D plan with bounding points, bounding lines, polygon center points and polygons (ArcMap)

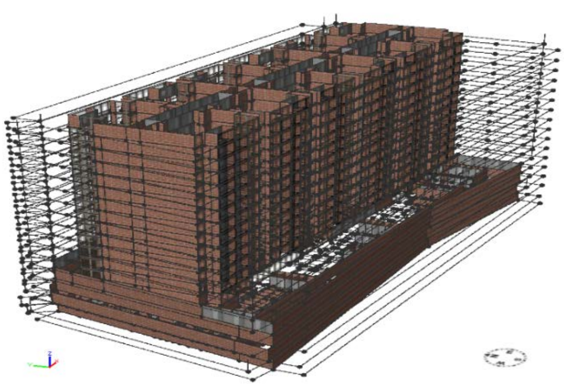


**Figure 4.** The 3D building model rendered in CityEngine

## 5. STEP 2: SMOKE SIMULATION IN THE 3D MODEL

Seven scenarios were simulated by PyroSim to investigate the situation of smoke spread in high-rise buildings. Generally, the purpose of these scenarios is to investigate the role of ducts, windows, and fire doors on the arrival time and concentration of smoke to the corridors, stairs, adjacent units, and upper floors at the high-rise buildings. Furthermore, due to the separation joint in the building and between the blocks, it is assumed that smoke and fire will not be transmitted to the adjacent block. Figure 5 exhibits the building structure model in the FDS.

**Figure 5.** The 3D model at LOD4 in FDS.

The settings of the smoke emission scenarios are presented in Table 1.

| *No.* | *Block* | *Floor* | *Doors* | *Firestops (smoke barriers)* | *Ducts* | *Skylights* |
|---|---|---|---|---|---|---|
| *1* | A | 1 | open | close | open | open |
| *2* | A | 1 | open | close | open | close |
| *3* | C | 4 | open | close | close | open |
| *4* | B | 4 | open | open | close | close |
| *5* | B | 4 | open | open | close | open |
| *6* | B | 4 | close | majority open | close | close |
| *7* | B | 4 | close | close | close | close |

**Table 1.** Details of smoke simulation scenarios with their central emission location

To be able to perform a smoke simulation, the 3D model was voxelised. Methods for voxelisations are discussed in Aleksandrov et al 2021a. The grid dimensions were determined for each block to create 172,800 voxels. The influential parameter in choosing the grid size is the expression of $D^*/_{\delta x}$ (acceptable values for this ratio are in the range of 4 to 16), where $D^*$ is the characteristic diameter of the fire and $\delta x$ is the nominal size of each voxel.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty\, c_p\, T_\infty \sqrt{g}}\right)^{\frac{2}{5}}, \tag{1}$$

where $\dot{Q}$ is the rate of heat release, $\rho_\infty$ is the gas density at ambient temperature, $c_p$ is the specific heat capacity of air, $T_\infty$ the ambient temperature, and g the acceleration of gravity. In this simulation, $\dot{Q}$=960 (kW), $\rho_\infty$=1.204 (kg/m), $c_p$=1.005 (kJ.kg$^{-1}$.K$^{-1}$), $T_\infty$=293 (K), and $g$=9.81 (m/s$^2$) was considered, which resulted in the value of $D^* = 0.943$ and $\delta x = 0.167$, and the ratio $D^*/_{\delta x} = 5.647$.

To begin the fire and create smoke in a building, an object (such as a sofa) is considered as a burning object. Afterward, a burning surface with dimensions of $0.6 \times 0.8 \times 0.25\, m^3$ was defined and the value of $500\, {kW}/_{m^2}$ was set as a parameter of the Heat Release Rate Per Unit Area (HRRPUA). This value corresponds to an object made of wood, plastic, and cellulose, like a sofa (Hietaniemi and Mikkola, 2010).

A general discussion on the method for measuring smoke from burning materials, specific extinction coefficient of flame generated smoke, and studies the human behavior and tenability in fire smoke is available in the SFPE fire protection handbook (Dinenno, 2008). The implementation steps of a scenario with its FDS modeling is described in details as follow.

### 5.1 Smoke productions and properties calculation

At scenario No.6, a fire broke out in Unit B2. Smoke detectors set up near to the entrance/exit doors provide information on the effect of putting open the fire doors or windows to the shared patios on the movement of the detected fire and its related smoke inside and outside the building.

After 60 seconds and 180 seconds of receiving the alarm, windows to the shared patio and the entrance/exit doors of the unit B2 are opened, respectively. As result, the smoke moves towards the corridor and stairs and finally enters other floors (Figure 6) via the windows and fire doors, which were kept open. For instance, windows to the shared patios of unit B2 on floors 1, 2, 3, 5, 6, 7, 11, and 12; Entrance/exit door of unit B2 in floors 7, 9 and 11; The entrance/exit door of unit B4 located on floors 6, 8 and 10.

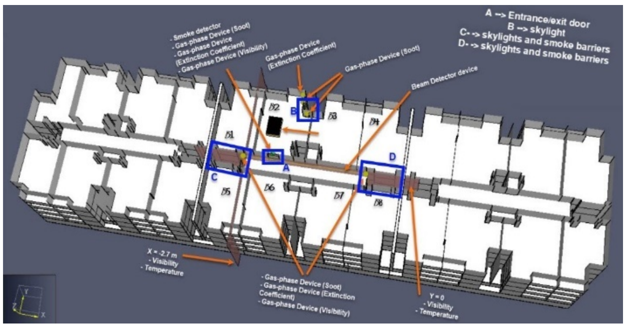



**Figure 6.** Scenario No.6: The generated model in PyroSim with layers, sensors, and burning object in unit B2

### 5.2 FDS visualization results

In scenario No.6, all the windows and doors at the shared areas, are considered close, and the smoke barriers are open except for a few. The explosion and disintegration from the windows of shared patios of unit B2 located on the 4th floor of the building caused a massive volume of smoke move to the upper floors. Furthermore, keeping open the fire door of the mentioned unit results in rapid spread of smoke on the other floors via the stairs. Figures 7 and 8 show the visual results of the fire simulation. Also, in Figures 9 and 10 demonstrate the values sensed by sensors embedded in different parts of the building during the total evacuation time.

Figure 10 above represents the measured smoke as follows: (A) Fire door at 3rd floor; (B) Fire door at 4th floor; (C) Fire door at 5th floor; (D) Fire door at 12th floor; (E) Shared patio at 4th floor; (F) Shared patio at 5th floor; (G) Shared patio at 12th floor; (H) near to the door of Unit B2, 4th floor; (I) Door Visibility sensor located near the 3rd floor smoke barrier; (J) Door Visibility sensor located near the 5th floor smoke barrier; (K) Door Visibility sensor located near the 12th floor smoke barrier; And (L) the Beam Detector linear sensor used in the 12th floor hallway.

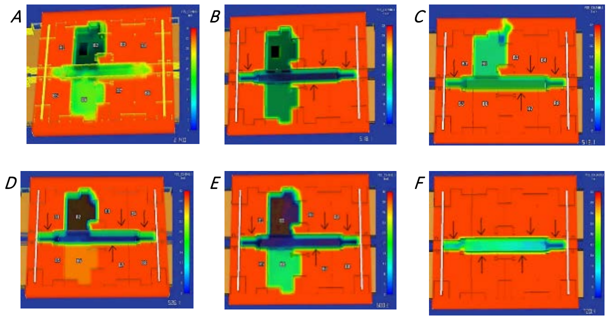


**Figure 7.** Smoke emission in: (A) main floor of fire (4th floor) after 214s; (B) 4th floor after 518s; (C) 12th floor after 518s; (D) upstairs of 5th floor after 526s; (E) 6th floor after 600s; (F) 2nd floor after 720s.

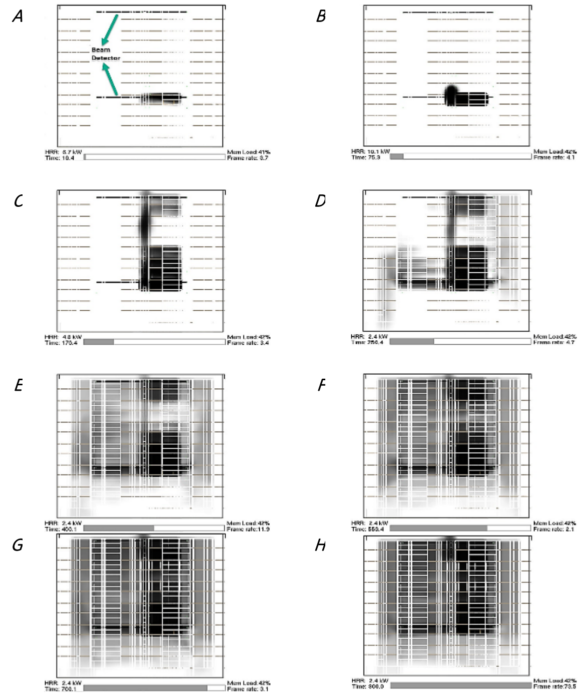


**Figure 8.** Smoke emission status on various floors at seconds: (A) 10 and hrr=6.7$^{kW}$; (B) 75 and hrr=10.1$^{kW}$; (C) 170 and hrr= 4.8 $^{kW}$; (D) 250 and hrr =2.4$^{kW}$; (E) 400 and hrr=2.4$^{kW}$; (F) 550 and hrr=2.4$^{kW}$; (G) 700 and hrr=2.4$^{kW}$; (H) 800 and hrr=2.4$^{kW}$.

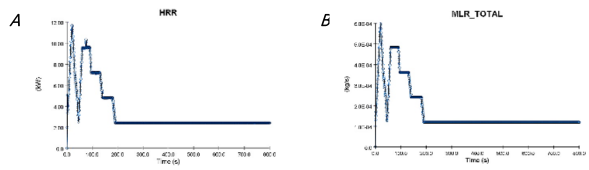
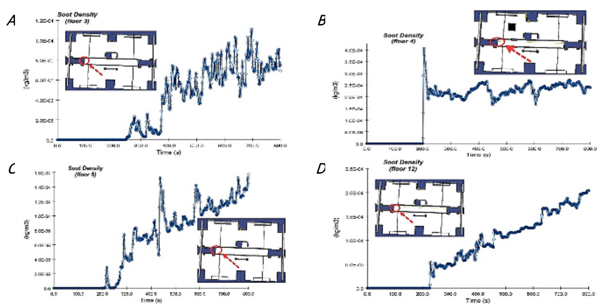



**Figure 9.** (A) the max HRR=11.9 kW and (B) the max rate of volumetric release of total fuel per unit time = 0.0006 kg⁄s at 20s.




https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-139-2022  

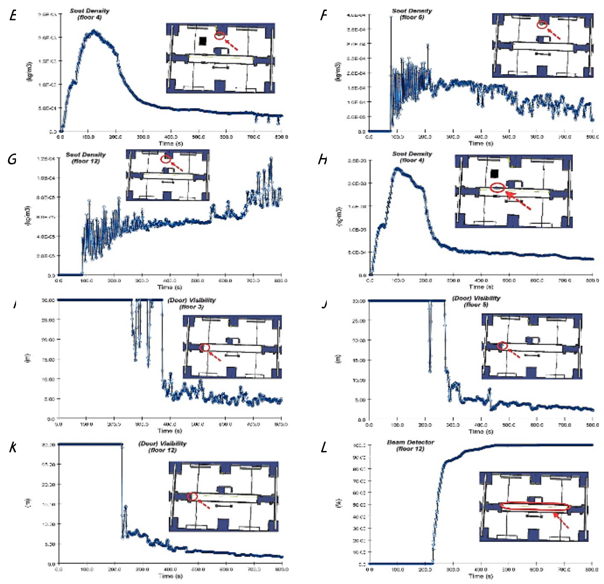


**Figure 10.** Diagrams of measured smoke by the sensors

## 6. STEP 3:EMERGENCY EVACUATION OF PEOPLE

In this step, appropriate strategies for emergency evacuation of occupants with different profiles in terms of age, gender, and physical abilities are presented and evaluated. Specifically, the effect of using of elevators to evacuate people with disabilities, besides of using of stairs, was examined. Figure 11 demonstrates the position of elevators and stairs in the building.

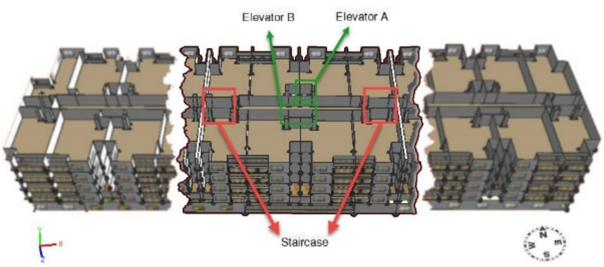



**Figure 11.** The location of elevators and stairs in the case study

The emergency evacuation strategies were evaluated using Pathfinder software and the results considered the impact of heat on the body, decreased vision, and the impact of toxic gases on lungs.

### 6.1 Data required for emergency evacuation

The 3D building model (Section 4) created by the CityEngine software, is utilized as the geometric data model of the building in this step (Figures 4-6).

As explained above, the fire has been occurred in unit B2 on the 4$^{th}$ floor of the middle tower. Dimensions of the cross-section of the combustible body are equal to 2.4 × 3.2 square meters, and the amount of heat released from this surface is similar to the amount of 2000 kW per square meters.

### 6.2 Evacuation strategies

People with physical and motion disabilities, such as the elderly, sick and disabled, commonly affect the flow rate and increase the evacuation time due to their low speed (or inability to move) and the additional space they may need. Therefore, it is assumed that it is possible to transport disabled and older people via the elevator (according to the existing conditions and to confirm the safe use of elevators by evacuation officers (Klote et al., 1997; Xiong et al., 2005) and healthy people through the stairs. In this study, arriving at the ground floor of the building was considered as arriving to the safe area.

The number of people present in the building (per floor, room, and hallway), the diversity of people in terms of age, gender, and physical ability will affect performance and evacuation time. Evacuees were classified into five types: children, women, men, elderly, and disable/wheelchairs persons.

| *Characteristics* / *Profiles* | *Dimensions (cm)* | *Speed (m/s)* | *Height (cm)* |
|---|---|---|---|
| *Child* | 22 – 28 | 8/0 – 2/1 | 140 – 130 |
| *Man* | 40 – 45 | 15/1 – 27/1 | 180 – 155 |
| *Woman* | 45 – 54 | 25/1 – 35/1 | 165 – 190 |
| *Elderly* | 42 – 50 | 8/0 – 1/1 | 175 – 150 |
| *Disabled (wheelchair)* | 72×115 | 68/0 – 8/0 | 100 |

**Table 2.** A sample of the residents at the case study, in NFPA and SFPE evacuation simulation.

Eventually, in order to figure out the health of individuals during their evacuation time, the effect of toxic gases on respiration and vision of a number of people were evaluated by considering the performance of the main combustion effects: heat, smoke and toxic gases.

### 6.3 Result of Implementation of evacuation strategy

Pathfinder software uses two modes: Steering and SFPE (Thunderhead, 2014). In Steering mode, Pathfinder uses a combination of steering mechanisms and collision handling to control how the occupant follows their seek curve. These mechanisms allow the occupant to deviate from the path while still heading in the correct direction toward their goal. SFPE mode implements the flow-based modeling techniques presented in the SFPE Handbook of Fire Protection Engineering and the SFPE Engineering Guide: Human Behavior in Fire. The SFPE calculation as described in the handbook is a flow model, where walking speeds and flow rates through doors and corridors are defined.

The evacuation process was simulated in both modes of Steering and SFPE and a grid consisting of 5327 triangles was used in Pathfinder to perform the process of evacuation and routing individuals as shown in Figure 12.

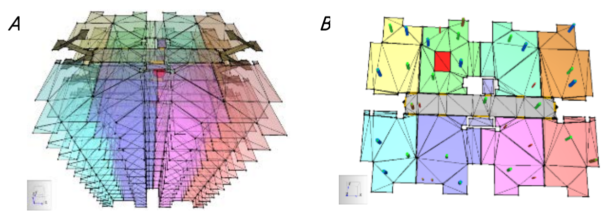


**Figure 5.** Triangulation network in Pathfinder software to route individuals from (a) top-facing views of all classes without agents and (b) top the 4$^{th}$ floor with agents.

The total evacuation time and the effect of toxic gases from smoke emission on 45 identified individuals were investigated (Table 3).

- **Steering mode**

The evacuation time, in this case, was 72.2 seconds, and all people reached the safe area in 460 seconds. The highest density was reported at second of 3 at the 3$^{rd}$ floor hallway, all of which reached the ground floor within 373 seconds of evacuation (Figure 13).

| *Floor* | *Child* | *Woman* | *Man* | *Elderly* | *Disabled* | *Total* |
|---|---|---|---|---|---|---|
| *1th* | - | 1 | 2 | - | 1 | 4 |
| *2th* | - | - | 1 | 1 | 1 | 3 |
| *3th* | 1 | 1 | - | 1 | - | 3 |
| *4th* | 1 | 2 | 2 | 2 | - | 7 |
| *5th* | 1 | 1 | 1 | - | - | 3 |
| *6th* | - | 2 | 1 | 1 | 1 | 5 |
| *7th* | - | - | 1 | 1 | 1 | 3 |
| *8th* | 1 | - | 1 | 1 | - | 3 |
| *9th* | 1 | - | 1 | 1 | - | 3 |
| *10th* | 1 | - | 1 | 1 | - | 3 |
| *11th* | 1 | 1 | 1 | - | 1 | 4 |
| *12th* | 1 | 1 | 1 | 1 | - | 4 |
| *Total* | 8 | 9 | 13 | 10 | 5 | 45 |

**Table 3.** A sample of selected individuals to investigate the effect of combustion effects on their health.

Figure 13 represents the results in charts as follows: (A) is the number of people evacuated (purple line) and remained (green line) at different simulation times; (B) is the maximum density of people in the corridor of the 3rd (purple line), 12th and 2nd floors; (C) The number of people moving through two elevators A (blue line) and B (brown line) with 8 and 9 movements (number of peaks) between the ground floor and other floors, respectively; (D) Presents a diagram of the movement of a large number of people through two steps, left (blue dot) and right (red dot).

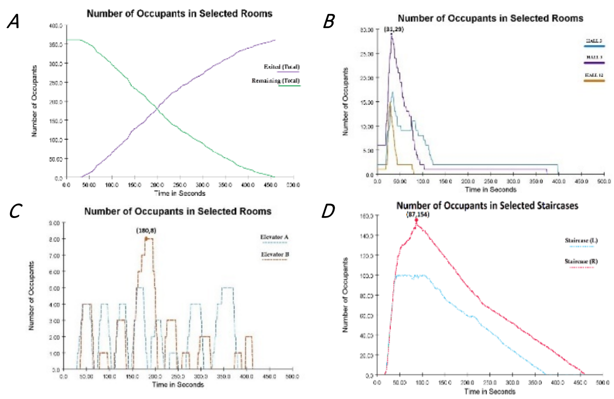



**Figure 6.** Evacuation results in Stereen mode

All elderly and disabled people in wheelchairs reached the safe area in 413 seconds. Table 4 shows the results and statistics data of the Steering mode.

| *Statistics* / *Profiles* | *Min-Max evac time (s)* | *Min-Max distance (m)* |
|---|---|---|
| *Child* | 34.3 – 460 | 13.6 – 147.6 |
| *Man* | 41.6 – 451.5 | 19.6 – 198.8 |
| *Woman* | 30.4 – 453.6 | 14.8 – 199.6 |
| *Elderly* | 58.5 – 412.9 | 6.4 – 116.8 |
| *wheelchair* | 65.1 – 380.2 | 17.6 – 31.2 |
| *Average* | 212.4 | 79.6 |

**Table 4.** Results of Steering mode.

- **SFPE mode**

It took 387 seconds to complete the evacuation process, which the render time was 40 seconds. In the seconds of 29 and 32, the maximum number of 30 people was presented at the 3rd floor corridor that they reached the safe zone after 346s (Table 5 and Figure 14).

The charts in Figure 14 show the results in SFPE mode as follows: (A) is the number of people evacuated (purple line) and remaining (green line) at different simulation times; (B) shows a diagram of the maximum density of people in the hallway of the third floor (purple line), the twelfth and second floors, respectively, the first (orange line) and the last (blue line) floors that were vacated; (C) is the number of people moving through two elevators A (blue line) and B (brown line) with 8 and 9 movements (number of peaks) between the ground floor and other floors, respectively; (D) is the diagram of the movement of a large number of people through two steps, left (blue dot) and right (red dot).

| *Statistics* / *Profiles* | *Min-Max evac time (s)* | *Min-Max distance (m)* |
|---|---|---|
| *Child* | 42.1 – 380.6 | 12.4 – 123.2 |
| *Man* | 52.4 – 371 | 18.8 – 134.4 |
| *Woman* | 35.7 – 359.9 | 13.6 – 138.8 |
| *Elderly* | 67.5 – 387.3 | 5.6 – 41.6 |
| *wheelchair* | 71.4 – 33–.7 | 15.2 - 24 |
| *Average* | 206.2 | 63.6 |

**Table 5.** Results of SFPE mode

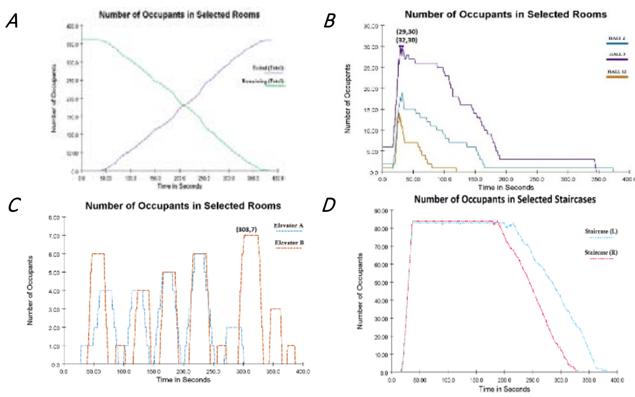



**Figure14.** Evacuation results in SFPE mode

## 7. DISCUSSION AND CONCLUSION

In this paper we presented a workflow for fire and evacuation simulations that uses 3D detailed models of high-rise buildings. We have shown that the lack of the 3D models of buildings can be compensated by using detailed cadastral 2D apartments plans. Such maps still cannot provide information about the used materials in various parts of the buildings and the exact location of the doors and windows, which are critical for modeling the movement of smoke in a building. Other parameters such as friction and existing objects such as furniture, could further improve the result of simulation.

The results indicate that the 3D model based on utilizing 2D cadastral data and the corresponding modeling of the movement and emission of smoke from the fire under different scenarios still provide acceptable results and have the potential to examine and evaluate different evacuation strategies in the emergency evacuation of residents.

The results obtained from the simulation of smoke emission in the created model indicate that ensuring the closure of ducts will be one of the factors controlling the emission of smoke to other floors. Smoke barriers play an important role as a dam to spread smoke at the floor level, especially after the backdraft phenomenon. On the other hand, windows at the shared areas have a significant effect on the transfer and release of toxic gases to the upper floors. Overall, windows to the shared areas, smoke barriers, and ducts are among the most critical vents and paths prone to smoke in high-rise buildings; the role of the first two is more reported than the others.

As expected, the results of the resident evacuation simulation show that the total evacuation time in SFPE mode is shorter than in Steering mode. Temperature and duration of time when a person is exposed to heat are considered as effective parameters. In both modes of evacuation, 1⁄12 of the identified individuals was exposed to temperatures above 49°C, which could increase heart rate, dehydration, fatigue, burning, and even blockage of the upper respiratory tract.

In addition to the toxicity of smoke, it is vital to consider smoke effect on vision. 1⁄3 of the specified persons were evacuated while their field of vision was restricted by smoke; In this case, it will be difficult for people to be recognized and to identify obstacles and ways out.

The effect of toxic gases from combustion or FED did not approach the critical state for any of the individuals (FED = 0.0455 (Thunderhead 2019), but the duration of exposure to these toxic gases was more than one minute, and in some cases up to five minutes. This result confirms that in addition to the concentration of toxic gases, the duration of exposure to these gases is significant, and the health of persons is significant in these results.

Having information about the usage of building units can help planners and decision-makers before, during, and after a fire occurrence. Therefore, for data enrichment and detailed display of the building as a 3D model, it is suggested to use the IFC file related to the building.

Concluding, this research has demonstrated that:

- 2D cadastral data of apartments have sufficient details information and can be employed to create realistic 3D models of buildings.
- High-rise 3D building models allow to examine more accurately the emergency evacuation of residents by including the smoke simulation spread in the building.

## 8. REFERENCES

Aguiar, F.H.M., 2010. Crowd simulation applied to emergency and evacuation situations. Thesis submitted to master in Informatics and Computing Engineering, FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO.

Aleksandrov, M. Rajabifard, A. Kalantari, M. Lovreglio, R. González, V.A., 2018. People Choice Modeling for Evacuation of Tall Buildings. *Fire Technol*, 2018(54), 1171–1193.

Alexandrov, M., Zlatanova, S., and Heslop, D.J., 2021a, Voxelisation Algorithms and Data Structures: *A Review*, *Sensors*, 21(24), 8241

Alexandrov, M., Heslop, D.J. and Zlatanova, S,. 2021b, 3D Indoor Environment Abstraction for Crowd Simulations in Complex Buildings, *Buildings*, 11(10), 445

Almeida, J.E., Rosseti, R.J. & Coelho, A.L. 2013. Crowd simulation modeling applied to emergency and evacuation simulations using multi-agent systems. *arXiv,*1303.4692.

Barki, H., Fadli, F., Shaat, A., Boguslawski, P. & Mahdjoubi, L., 2015. BIM models generation from 2D CAD drawings and 3D scans: an analysis of challenges and opportunities for AEC practitioners. Building Information Modelling (BIM) in Design, *Construction and Operations*, 149, 369-380.

Black, W., 2009a. Pressurization of Floors to Improve Life Safety During a High-Rise Fire. *ASHRAE Transactions*, 115.

Black, W., 2009b. Smoke movement in elevator shafts during a high-rise structural fire. *Fire Safety Journal*, 44, 168-182.

Black, W., 2010. COSMO—Software for designing smoke control systems in high-rise buildings. *Fire Safety Journal*, 45, 337-348.

Bozorgzad, B., 2013. Major causes of deaths in the fire [Online]. IMNA: IMNA News Agency. Available: www.imna.ir/news/116420/ [Accessed].

Chen, T. B. Y., Yuen, A. C. Y., Yeoh, G. H., Timchenko, V., Cheung, S. C., Chan, Q. N., ... & Lu, H. (2018). Numerical study of fire spread using the level-set method with large eddy simulation incorporating detailed chemical kinetics gas-phase combustion model. *Journal of computational science*, 24, 8-23.

Dinenno, P. J. 2008. SFPE handbook of fire protection engineering, SFPE.

Ding, Y., Jiang, N., Yu, Z., Ma, B., Shi, G. & Wu, C., 2017. Extrusion Approach Based on Non-Overlapping Footprints (EABNOF) for the construction of geometric models and topologies in 3D cadasters. *ISPRS International Journal* of *Geo-Information*, 6, 232.

Emamgholian, S., Taleai, M., & Shojaei, D., 2021. Exploring the applications of 3D proximity analysis in a 3D digital cadastre, *Geo-spatial Information Science*, 24(2), 201-214.

Emamgholian, S., Taleai, M., & Shojaei, D., 2018. A Novel Approach for 3D Modeling and Geovisualization of Easement Rights in Apartments. *Jgit*, 6 (3) :163-175.

Emamgholian, S., Taleai, M., & Shojaei, D. 2017. A novel approach for 3D neighbourhood analysis. Karimipour, F (Ed.) Samadzadegan, F (Ed.) *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, XLII-4/W4, 42, (4W4), 361-365.

Ewer, J., Galea, E.R., Patel, M., Jia, F., Grandison, A., & Wang, Z., 2010. SMARTFIRE-the fire field modelling environment. In The Fifth European Conference on Computational, Fluid Dynamics, ECCOMAS CFD 2010. Lisbon, Portugal.

Fichtner, F.W., Diakité, A.A., Zlatanova, S., and Voûte, R., 2018. Semantic enrichment of octree structured point clouds for multi-story 3D pathfinding, *Transactions in GIS*, 22(1), pp. 233-248.

Gawad, A.A., & Ghulman, H.A., 2015. Prediction of smoke propagation in a big multi-story building using fire dynamics simulator (fds). *American Journal of Energy Engineering*, 3(4-1), 23-41.

He, Q., Ezekoye, O.A., Tubbs, B. & Baldassarra, C., 2015. CFD simulation of smoke spread through elevator shafts during fires in high rise buildings. ASME 2015 international mechanical engineering congress and exposition, 2015. American Society of Mechanical Engineers Digital Collection.

Hietaniemi, J. & Mikkola, E., 2010. Design fires for fire safety engineering. Technical Research Centre, Helsinki, Finland.

Hosseini, H. & Taleai, M., 2021. A Review of Recent Researches on Integration of Building Information Modeling (BIM) and GIS. *Iranian Remote Sensing & GIS* 13(3): 33-58.

Kinateder, M., Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P. & Mühlberger, A., 2014. Virtual reality for fire evacuation research. 2014 Federated Conference on Computer Science and Information Systems, 2014. IEEE, 313-321.

Klote, J.H., Levin, B.M. & Groner, N.E., 1997. Emergency elevator evacuation systems. American Society of Mechanical Engineers (ASME) 2nd Symposium on Elevators. *Fire and Accessibility Baltimore*. ASME.

LI, X., Sun, X.-Q., Wong, C.-F. & Hadjisophocleous, G., 2016. Effects of Fire Barriers on Building Fire Risk-A Case Study Using CUrisk. *Procedia Engineering*, 135, 445-454.

Liu, L.B., Zlatanova, S., van Oosterom, P., 2021. Indoor navigation supported by the Industry Foundation Classes (IFC): A survey, *Automation in Construction*, 121(January 2021), 10436

Lo, S., Yuen, K., Lu, W. & Chen, D., 2002. A CFD study of buoyancy effects on smoke spread in a refuge floor of a high-rise building. *Journal of Fire Sciences*, 20, 439-463.

Mcgrattan, K. B., Baum, H. R., Rehm, R. G., Hamins, A. P. & Forney, G.P., 2000. Fire Dynamics Simulator: Technical Reference Guide (NISTIR 6467).

Mcgrattan, K., Hostikka, S., Mcdermott, R., Floyd, J., Weinschenk, C. & Overholt, K., 2013. Fire dynamics simulator technical reference guide, volume 1: mathematical model. NIST special publication.

Mokhtari M. & Taleai M., 2020. Simulation of Smoke Emission from Fires in High-Rise Buildings Using the 3D Model Generated from 2-Dimensional Cadastral Data. *JGST* 9 (4) :19-37. URL: http://jgst.issge.ir/article-1-875-en.html

Mutthulakshmi, K., Wee, M. R. E., Wong, Y. C. K., Lai, J. W., Koh, J. M., Acharya, U. R., & Cheong, K. H. (2020). Simulating forest fire spread and fire-fighting using cellular automata. *Chinese Journal of Physics*, 65, 642-650.

Nikoohemat, S., A. A. Diakité, S. Zlatanova and G. Vosselman, 2020 Indoor 3D reconstruction from point clouds for optimal routing in complex buildings to support disaster management, *Automation in Construction*, Volume 113, May 2020, 103109

Peacock, R. D., Jones, W, Reneke, p. & Forney, G. 2005. CFAST–Consolidated Model of Fire Growth and Smoke Transport (Version 6) User's Guide. NIST Special Publication, 1041.

Peacock, R. D., McGrattan, K. B., Forney, G. P., & Reneke, P. A. (2015). CFAST–Consolidated fire and smoke transport (version 7) volume 1: Technical reference guide. Technical Note, National Institute of Standards and Technology, Gaithersburg, Maryland, 1, 69-71.

Peterson, I. & Jonsson, E. 2018. Simulation and evaluation of strategies for emergency evacuation of high-density crowds.

Pope, S. B. 2001. Turbulent flows. *IOP Publishing*.

Ren, A., Chen, C. & Luo, Y. 2008. Simulation of emergency evacuation in virtual reality. *Tsinghua Science and Technology*, 13, 674-680.

Ren, A., Chen, C., Shi, J. & Zou, L. Application Of Virtual Reality Technology To Evacuation Simulation In Fire Disaster. CGVR, 2006. *Citeseer*, 15-21.

Rezazadegan, M., 2018. What we need to know about fire. Pars Fire. Available: https://parsfire.com/what-we-should-know-about-fire.

Ronchi, E. and D. Nilsson, 2013, Fire evacuation in high-rise buildings: A review of human behaviour and modeling research. *Fire Sci*. *Rev*. 2013, 2, 1–21.

Sagun, A. Anumba, C.J. Bouchlaghem, D. 2013, Designing buildings to cope with emergencies: Findings from case studies on exit preferences. *Buildings* 2013, 3, 442–461.

Thunderhead 2014. Pathfinder Technical Reference. www.thunderheadeng.com/wp-content/uploads/downloads/2014/10, Thunderhead Engineering.

Thunderhead 2019. Pathfinder Verification and Validation Manual. www.thunderheadeng.com/downloads/14293/, Thunderhead Engineering.

Wahlqvist, J. & Van Hees, P. 2013. Validation of FDS for large-scale well-confined mechanically ventilated fire scenarios with emphasis on predicting ventilation system behavior. *Fire Safety Journal*, 62, 102-114.

Walton, G. & Dols, W. 2008. CONTAMW 2.4 user manual. Gaithersburg, MD, USA, National Institute of Standards and Technology, 286.

Wang, Y., Hadjisophocleous, G. & Zalok, E. 2013b. Smoke movement in multi-storey buildings using CUsmoke. *Safety science*, 52, 13-27.

Wu, G.-Y. & Huang, H.C., 2015. Modeling the emergency evacuation of the high rise building based on the control volume model. *Safety science*, 73, 62-72.

Wu, Y., Shang, J., Chen, P., Zlatanova, S., Hu, X., and Zhou, Z., 2020, Indoor mapping and modeling by parsing floor plan images, *International Journal of Geographical Information Science*, 20(3), pp. 257-279.

Black P., 2011. Computer modeling of stairwell pressurization to control smoke movement during a high-rise fire. *ASHRAE Transactions*, 117, 786.

Xing, Z. & Tang, Y., 2012. Simulation of fire and evacuation in high-rise building. *Procedia Engineering*, 45, 705-709.

Xiong, B., Luh, P.B. & Chang, S.C., 2005. Group elevator scheduling with advanced traffic information for normal operations and coordinated emergency evacuation. Proceedings of the 2005 IEEE international conference on robotics and automation, IEEE, 1419-1424.

Yang, P., Li, C. & Chen, D., 2013. Fire emergency evacuation simulation based on integrated fire–evacuation model with discrete design method. *Advances in engineering software*, 65, 101-111.

Yin, R. & Chow, W., 2002. Building fire simulation with a field model based on large eddy simulation. *Architectural Science Review*, 45, 145-153.

Yin, X., Wonka, P. & Razdan, A., 2008. Generating 3d building models from architectural drawings: A survey. *IEEE computer graphics and applications*, 29, 20-30.

Zheng, Y., Jia, B., Li, X.G. & Jiang, R., 2017. Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading. *Safety science*, 92, 180-189.