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Experimental and numerical evacuation study in tall office building

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ABSTRACT

The duration of the evacuation process in case of emergencies in tall buildings is a crucial issue. Various factors have significant impact on the evacuation time, e.g. stairwell geometry, speed, density, pre-evacuation delay, number of occupants and their familiarity with the building, behavior, age, gender, physical abilities, relationships between people, etc. Although there are many studies on the subject, research results from Bulgaria and comparison with those from other places in the world are not yet available. Also, studies performed by researchers who have professional operational firefighting experience are very limited. In this study, two evacuation experiments in a new 107 m tall office building in Bulgaria were designed under the supervision of professional firefighting personnel. The first experiment was conducted to estimate the free movement characteristics under "normal" conditions for determining the average duration of the evacuation and the range of the vertical speed. Thirteen participants were instructed to move down from 17F to outside the building, following their normal habits. Their evacuation times differed in the range from 192 s–328 s, while the vertical speed is highest at the upper floors 0.35 m/s and reduce to 0.20 m/s just before the exits. The second experiment was an evacuation drill of 177 people from the floors they work in the building. The evacuation duration of this experiment for all these people from the building was in the range of 2–6 min. The study is also enriched through Pathfinder software simulations for verification of the results, where a good match was observed (6:26 min total evacuation time). Another simulation at the maximum occupants' capacity of the building with 2195 people was also run (24:48 min for the total evacuation time). We believe that the benefits achieved on the differences in the real experimental data from different parts of the world can be valuable for validation of tall building evacuation models. In addition, the link between the evacuation drill findings and the professional firefighting considerations, problems and decision-making operations in case of fire is discussed.

1. Introduction

In recent decades, with increasing urbanization of the population, more and more people work and live in big cities. The tendency is to concentrate the economic development in cities where tall buildings are a pragmatic possibility to achieve this goal. With the emerging development of the economic indicators in recent years in Bulgaria as part of the European Union more and more tall

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buildings are needed and have been developed around the country [1]. The crucial importance of the knowledge about crowd dynamics acquired and applied by architects and building engineers in case of evacuation is usually in the realm of "normal" conditions. There is a big difference in movement characteristics and people's behavior [2–5] under the threat of danger like fire or other accidents. Although the best approach is to use data from real evacuations of tall buildings following real emergencies, this is not always possible. Moreover, from a firefighter's point of view, the evacuation strategy in tall buildings in case of real emergencies, fire for example, has a number of challenges with respect to firefighting equipment available that cannot be established or researched in advance. For example, the facts that the firefighter's access and equipment delivery to rescue people in need and fight the fire are through the same staircases of tall buildings where the evacuees coming down. These circumstances might severely affect the evacuation process and the firefighting schemes such as setting up fire hoses tactical configuration and rescue operations. The evacuation methods and strategies in tall buildings are critical for the occupants [6]. They mainly depend on different factors like the number of occupants, their gender, age, physical profile, behavior, initial position in the floor, the structural characteristics of the building. They also depend on some practical operational issues like water application and limitations of the firefighting equipment in handling heights in case of problems in the hose systems with lay-flat hose in the tall building itself. These include inadequate pump pressures from the fire engines, portable pumps in case of need, fire ventilation techniques, the pressurized staircases [7] and its effective performance in case of so many open doors, and fire hoses blocking the doors. The fire safety management schemes to avoid panic and mixing of firefighters going up and occupants doing down, i.e. use of means of access and means of escape is also a challenging factor. Based on the above, we will assume that fire drills can be used to roughly approximate the response and emergency behavior of individuals in real incidents.

The legal definitions of evacuation and place of safety can be found in ISO standard [8] where "evacuation" is defined as an orderly movement of persons to a place of safety (in case of fire or emergency). A place of safety is a place in which people are not in danger. This is an area that gives an adequate protection enclosure from other areas and from which there is alternative means of escape. According to these definitions, the evacuation ends when people reach a place of safety. When we are speaking about tall buildings, the most common rule for evacuation is not to standardize the evacuation time from the whole building because in the case of supertall buildings, it can last up to an hour, but the time to reach places of safety, which are pressurized fire resistant staircases [7] or refugee floors [9,10] for the case of fire.

The evacuation process in tall buildings due to fires and other emergencies is of paramount importance in buildings safety science, especially after 9/11 when this terrorist attack is considered a cornerstone in tall buildings safety development [11]. Based on the studies and the general principles, two main factors can be defined that are of decisive importance for the evacuation of tall buildings - flow capacity and human behavior [3,12]. The flow capacity depends on the structural components of the building itself, based on the relevant fire codes in the country in which the building is constructed, such as width of the doors, number of staircases and their width, etc. Human behavior is a parameter that is much more difficult to predict and analyze, since different people would react differently in speed, density, pre-evacuation time, etc. [13]. Pre-evacuation time is an extremely important factor which can be defined as the interval of time between the moment at which the fire alarm signal is given and the time at which evacuation starts [14–16]. Various values from the US have been reported from approximately 50 s found in three tall buildings [3], through 150 s in a real severe fire in a tall building [17] to 165 $\pm$ 71 s for office buildings [18]. In these case studies [19], 90–180 s is considered the average frame of the pre-evacuation time.

Tall building evacuation is currently an attractive topic to many researchers, and there are many scientific studies based on real experiments, fire drills, surveys, and software simulations. While some of the studies are focused on specific pedestrian characteristics like movement speeds [20], pre-evacuation time, merging behavior, crowd density [21,22], tendency of elevator usage [23,24], etc., others are formed as case studies in some of the most famous tall buildings in the world like Burj Khalifa [25], Shanghai Tower [26], Shanghai World Financial Center [27], Taipei 101 [28] as well as in different types of buildings like tall residential buildings [29–31] and university campus buildings [32–35]. In recent years more and more simulations with software products like Pathfinder [29,36], WayR [37], and EXODUS [38] were reported in a way to validate and better predict evacuation time and human behavior in case of emergency. In addition to this, the latest technologies like robots [39], Internet of Things [40] and innovative building information models [41] are researched for the purpose of more effective evacuation. However, there is still a need for further independent full-scale research on evacuation behavior from different places because people from different parts of the world tend to react differently in case of emergency evacuation based on their habits, customs and cultural competence [20].

As for the fire codes in various types of buildings, as a general rule, it can be assumed that evacuation during a fire or other emergency situation is carried out only through the stairs, and the elevators cannot be used (except the usage of fireman elevator used only by the firemen for rescue purposes) [42]. However the topic of evacuation of supertall buildings by means of fireproof elevators is discussed in scientific circles [43,44]. Since these buildings usually accommodate many people, the time to evacuate the entire building by stairs will be very long. For this reason, many architects, engineers and scientists are considering additional workable options to increase the safety of people in such buildings in case of emergency evacuation. Such options are the refugee floors, which are assumed to be places of safety from which evacuation could be carried out by fireproof elevators. Another option is to use sky-bridges to evacuate people from one tall building to another [45].

Also, different countries have different requirements for the time to leave the building in case of emergency. For example, in Bulgaria, only the time for which all the occupants of a given floor in a tall building will enter the staircase, which is considered a place of safety, is regulated. This time should not exceed 90 s, while the duration of the whole evacuation process of all occupants in the building, until they go outside, is not standardized [46]. The situation is identical in other countries. Table 1 shows a comparison with Hong Kong [47], the United Kingdom [48] and the United States of America [49] concerning the allowable evacuation times to a place of safety, the minimum number of evacuation exits and their widths.

Table 1
Information about the participants in the first experiment.

	Bulgaria [46]	Hong Kong [47]	United Kingdom [48]	United States of America [49]
Allowable evacuation time to a place of safety/s	90	150 (buildings without sprinklers) or 300 (buildings with sprinklers)	150	660 to outside the building
Min. Number of evacuation exits/num	up to 100 people – min. Two x 0.9 m each.; up to 200 people - three x 0.9 m each or two x 1.2 m each	up to 200 people – min. Two, total 1.75 m; up to 300 people - min. Two, a total of 2.5 m.	More than two for tall buildings	More than two for tall buildings
Width of evacuation exits			3.6mm/Person, min 0,8 m or 3.06mm/Person with fire alarm, min 0.8 m	min. 28 inches (≈0.7 m) each

In addition to all the above and the fact that there are not many studies on the subject with reference to real buildings under the supervision of professional firefighting personnel, and appropriate Bulgarian research, statistics and comparison with research findings from other places in the world are not yet available, in the current research real experimental drills and numerical simulations were conducted in a new tall office building in Bulgaria. Two experimental drills were designed - (1) free movement characteristics of 13 people under "normal" conditions for determining evacuation time and vertical speed and (2) evacuation of 177 people from the different floors of the building on the day of the fire drill. (3) The study is also enriched through Pathfinder software simulations [50] for verifying the results. As stated above there are so many factors in the evacuation process like the floors of the building, dimensions of the structural elements (staircase doors width, the stairs width, stairs tread, stair riser, etc.), as well as the number, gender, age, profile, behavior, initial position in the floor. The key parameter in our field test and simulations will be the number of evacuees per floor.

2. Materials and methods

2.1. Building characteristics

The evacuation experiments were conducted in a tall building, completed in 2021, located in Sofia, the capital of Bulgaria. It is a multi-purpose tall building with 21 floors above ground level with a total height of 107 m. 1F includes a central lobby with a reception desk, café, medical center and retail facilities. On 2F there are conference halls, fitness center, swimming pool, SPA center, beauty salon and massage studios. 3F includes a canteen and sports halls. The office part is located between 4F and 17F. 18F–21F are designed as residential premises. There are three underground levels with 268 parking spaces. The maximum total occupant capacity of the building is 2195 people. Images of the building are shown in Fig. 1.

There are 8 main elevators for the office part L1-L8, one of them a fireman elevator. In addition, two smaller elevators L9 and L10 are available for the residential part on the upper floors, not in operation from the office areas. During evacuation in case of emergency the evacuees can use two pressurized staircases S1 on the west part and S2 on the east part of the building as shown in Fig. 2.

According to the Bulgarian fire codes, direct access from the office areas to the staircases is not allowed. Two fire doors and a fire vestibule have to be passed before entering the pressurized staircase, which is considered a "safety place" in the codes. During an emergency, the elevators are stationed on the first floor by the building information management system and they are not used as an

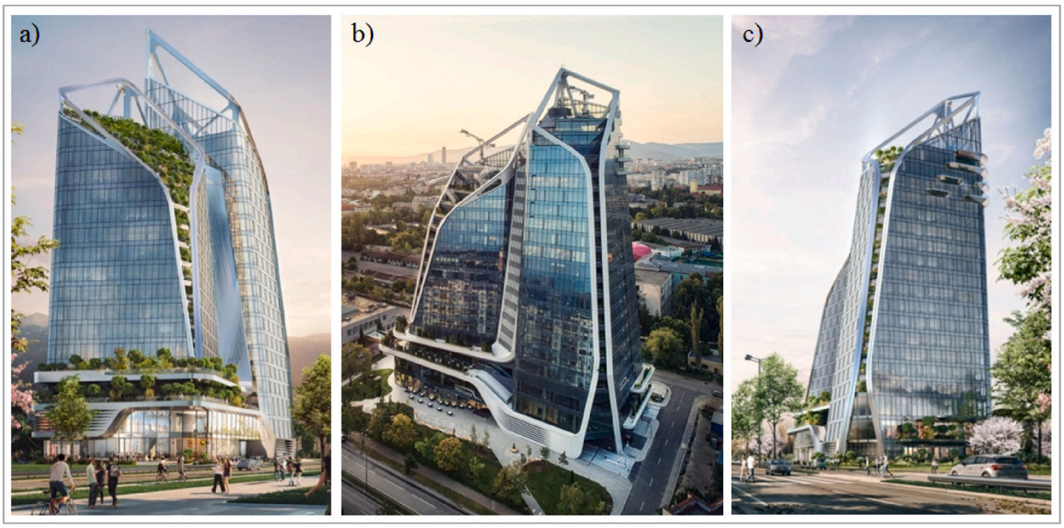


Fig. 1. Images of the building provided by the owner a) east side view, b) aerial view, c) west side view.

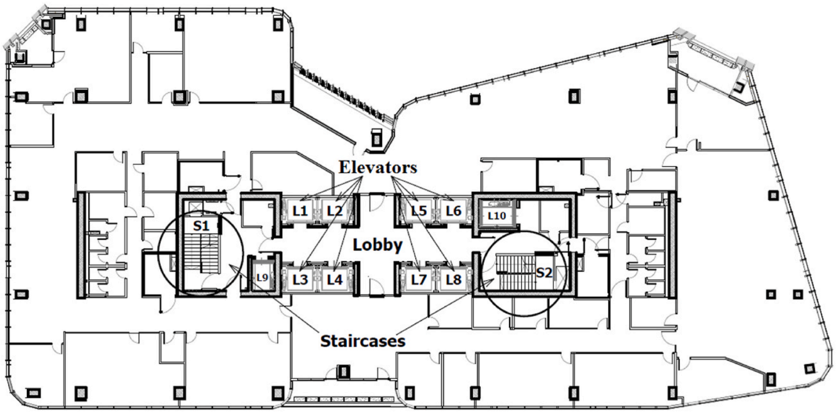


Fig. 2. Floor and evacuation staircases configuration provided by the owner.

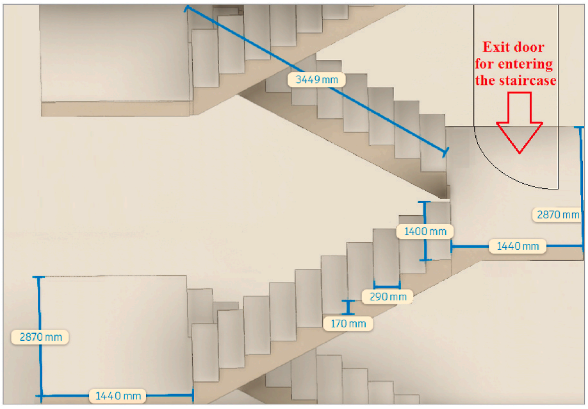


Fig. 3. Dimensions of the staircases.

evacuation option, except the fireman elevator operated by rescuers only for rescue purposes. The floor areas of the offices can be found in different interior configurations in the different floors. Generally, in case of fire alarm, the evacuees have to move a maximum distance of 37 m to the staircase. The staircase door width is 1.3 m, the stair width is 1.4 m. The stair tread is 0.29 m while the stair riser is 0.17 m. Dimensions of the staircases in the building are presented in Fig. 3.

2.2. *Experimental procedures*

All the participants in the two experiments work in the building therefore they are familiar with it. Mostly IT companies occupied the building, so there were no visitors in the office areas. All employees were informed two days in advance of the evacuation drill by the building management via emails. The experiments in the building were performed on July 15, 2022.

2.2.1. *Free movement characteristics*

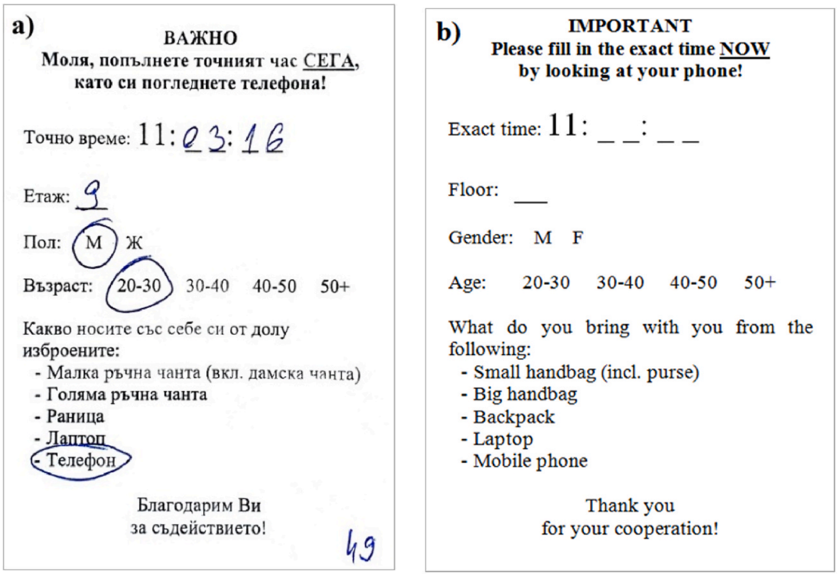
Thirteen randomly selected people from the building participated in the first experiment to estimate the free movement characteristics in "normal" conditions. In this experiment, the average duration of the evacuation and the range of the vertical speed were determined. The participants were instructed to move down from 17F to outside the building, following their normal habits without running down or jumping over the stairs. The participants started one after another at 60 s intervals. Another thirteen people accompanied the participants to monitor the movement and record the time on every floor with stopwatches. The age and gender of the participants are shown in Table 2.

Table 2
Information about the participants in the first experiment.

	Part. 1	Part. 2	Part. 3	Part. 4	Part. 5	Part. 6	Part. 7	Part. 8	Part. 9	Part. 10	Part. 11	Part. 12	Part. 13
Age	54	56	37	50	43	51	24	35	45	39	51	36	34
Gender	F	M	F	M	M	M	F	M	M	M	M	M	M

2.2.2. Mass evacuation

All occupants in the building on the day of the evacuation drill took part in the second experiment. They were all announced about the date of the fire drill (but not for the hour) and instructed simply to leave the building. No specific routes were suggested to them in advance, only to move as fast as they could but kept themselves safe. An hour before the lunch break, at 11 p.m. sharp a hand fire alarm button was activated on the sixth floor and the evacuation process started. At every final exit point, all evacuees were asked to fill out a short survey form by themselves, which included information about the exact time they passed through the final exit, floor, gender, age, and additional question if they carry something with them (small handbag, big handbag, backpack, laptop, or mobile phone). The survey form itself is shown in Fig. 4 in a) the original form in Bulgarian language and b) in English translation for the purpose of this research.


a)
ВАЖНО
Моля, попълнете точният час СЕГА, като си погледнете телефона!

Точно време: 11:03:16

Етаж: 9

Пол: М Ж

Възраст: 20-30 30-40 40-50 50+

Какво носите със себе си от долу изброените:
- Малка ръчна чанта (вкл. дамска чанта)
- Голяма ръчна чанта
- Раница
- ~~Лаптоп~~
- Телефон

Благодарим Ви за съдействието!

49

b)
IMPORTANT
Please fill in the exact time NOW by looking at your phone!

Exact time: 11: _ _: _ _

Floor: ___

Gender: M F

Age: 20-30 30-40 40-50 50+

What do you bring with you from the following:
- Small handbag (incl. purse)
- Big handbag
- Backpack
- Laptop
- Mobile phone

Thank you for your cooperation!

Fig. 4. The survey form which every evacuee received and filled out by themselves on the final exits a) original survey form in Bulgarian, filled by a random evacuee, b) translation into English for the purpose of the research development.

Table 3
Information about the participants in the second experiment.

Floor	Total evacuees per floor	Gender	Total evacuees by gender	Age range of the participants			
				20–29	30–39	40–49	50+
4F	33	M	24	19	4	–	1
		F	9	5	1	3	–
5F	10	M	8	6	2	–	–
		F	2	0	2	–	–
6F	31	M	21	10	10	1	–
		F	10	2	6	–	2
7F	Empty floor						
8F	1	M	1	1	–	–	–
		F	–	–	–	–	–
9F	10	M	10	3	6	1	–
		F	–	–	–	–	–
10F	11	M	5	3	2	–	–
		F	6	1	5	–	–
11F	9	M	4	1	2	–	1
		F	5	1	3	1	–
12F	14	M	10	3	5	2	–
		F	4	1	2	1	–
13F	22	M	13	7	5	1	–
		F	9	5	3	1	–
14F	16	M	12	5	5	2	–
		F	4	1	1	1	1
15F	8	M	6	1	4	1	–
		F	2	1	1	–	–
16F	Empty floor						
17F	12	M	5	3	2	–	–
		F	7	3	3	1	–
Total	**177 evacuees**	**119 male/58 female (or 67,2% male/32,8 female)**		**82 (or 46,3%)**	**74 (or 41,8%)**	**16 (or 9.0%)**	**5 (or 2,8%)**

Table 4
Number of evacuees per floor (layer) in the Pathfinder simulation models.

Floor	1F	2F	3F	4F	5F	6F	7F	8F	9F	11F	11F	12F	13F	14F	15F	16F	17F	Total
Pathfinder simulation in the building with 177 occupants [a]																		
Ppl/floor	–	–	–	33	10	31	–	1	10	11	9	14	22	16	8	–	12	**177**
Pathfinder simulation in the building with 2195 occupants[b]																		
Ppl/floor	10	20	166	226	212	225	–	178	171	167	122	174	114	178	102	48	82	**2195**

[a] - 177 people, exactly as many people as in the real experiment.
[b] - 2195 people, the maximum capacity of the building according to the investment project provided by the owner.

Detailed cross-tabulation information about the participants in the second experiment is extracted from the survey forms and presented in Table 3.

Also, the whole process of the mass evacuation was captured on the cameras in every floor lobby, the staircases and the building exterior in GF. All measured times from the cameras were synchronized and the data for the participants were manually extracted and verified from the video recordings.

2.3. Software simulations

The software simulations were performed via Pathfinder with the aim of verifying the results of the real experiment and predicting the evacuation time at full capacity. Two types of simulations were performed with the assumption that the most important parameter is the number of evacuees per floor. The first one is with 177 people, exactly as many people as in the real experiment from Section “2.2.2 Mass evacuation” distributed by floors as it was in reality during the experiment with the information extracted from the survey forms. The second experiment was generated with 2195 people, which is the maximum capacity of the building distributed per floor according to the investment project provided by the owner. The numbers of evacuees per floor (layer) in the Pathfinder simulation models are shown in Table 4. Both types of experiments were generated with “Office” evacuees’ profile with a uniform speed distribution of 1.19 ± 0.25 m/s (SFPE speed-density relationship) and “Goto Any Exit” behavior. The current locations of the evacuees on the different floors before the start of the simulations were randomly placed and there are no people with special needs and assistance.

Geometry visualizations of the Pathfinder model of the building are shown in Fig. 5.

Here it must be noted again that following the fire codes in Bulgaria, in the event of a fire or an emergency, the elevators cannot be used for evacuation by the occupants. However, only for the purposes of the current research and using the capacities of the software product, we ran two simulations of each experiment, respectively without (all eight elevators L1-L8 from Fig. 2 were disabled) and with (all ten elevators were enabled) the use of elevators, to investigate and compare the difference in evacuation time.

3. Results and discussion

3.1. Free movement characteristics

In this first experiment, free movement evacuation duration under “normal” conditions was investigated by determining each participant’s time and vertical speed. The time for the participants to go down the stairs from the 17th floor to the outside of the building varies in the range of 3–5 min. Detailed readings of the times of the evacuating people are shown in Table 5.

There are large differences in the evacuation times. This can be explained by the difference in age and gender of the participants.

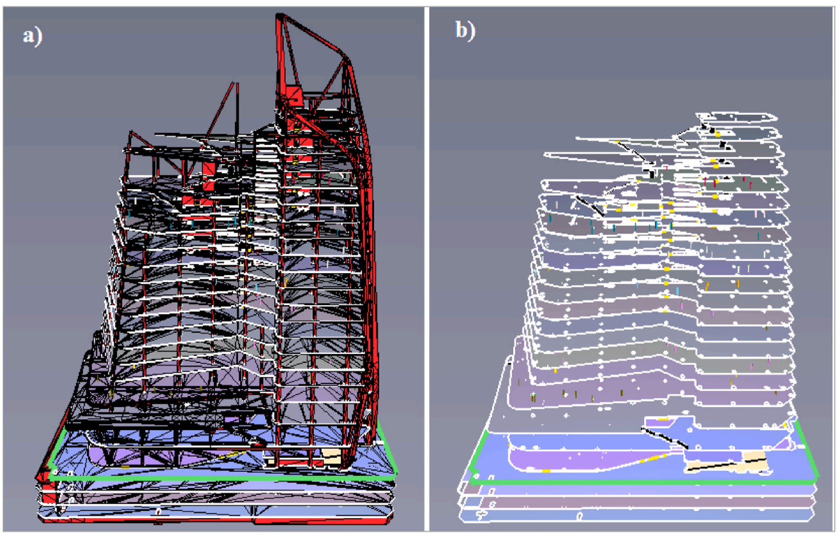


Fig. 5. Visualization of the Pathfinder simulation [50] a) imported geometry, b) navigation geometry.

Table 5
Information about the participants in the second experiment.

	Part. 1	Part. 2	Part. 3	Part. 4	Part. 5	Part. 6	Part. 7	Part. 8	Part. 9	Part. 10	Part. 11	Part. 12	Part. 13
Free movement evacuating time between landings, s													
Lobby 17 F - Staircase 17F	13.12	06.00	06.00	11.24	08.87	09.09	03.81	04.94	06.54	06.25	08.36	12.67	09.10
17F - 16F	09.31	09.73	09.73	10.44	13.50	17.46	10.19	12.68	11.21	08.81	13.05	09.98	15.26
16F - 15F	09.31	09.73	09.73	10.44	13.50	17.46	10.19	12.68	11.21	08.81	13.05	09.98	15.26
15F - 14F	12.11	08.96	08.96	13.24	13.58	17.27	10.06	13.19	10.93	09.51	12.20	09.78	13.84
14F - 13F	11.11	09.28	09.28	15.21	15.13	16.53	11.17	13.50	12.18	10.17	11.75	09.89	12.91
13F - 12F	12.35	09.38	09.38	15.70	16.03	18.56	10.47	13.36	11.10	11.97	11.87	09.55	13.69
12F - 11F	10.30	09.48	09.48	16.29	14.50	18.65	11.13	14.23	11.68	10.00	11.63	10.53	13.78
11F - 10F	12.43	10.23	10.23	16.57	13.90	18.47	11.43	13.79	11.23	10.45	11.78	11.58	14.70
10F - 9F	10.33	10.60	10.60	14.90	14.98	16.80	11.55	14.26	11.40	10.96	12.41	11.29	15.07
9F - 8F	13.13	10.46	10.46	17.12	15.64	18.06	12.40	14.12	11.86	10.00	12.12	09.93	14.33
8F - 7F	11.41	10.41	10.41	17.41	13.77	17.83	12.61	13.87	11.33	11.16	12.15	10.26	14.51
7F - 6F	16.70	11.38	11.38	16.89	13.13	16.25	13.15	14.03	11.75	11.60	12.03	10.71	14.61
6F - 5F	11.18	10.65	10.65	14.90	14.43	17.28	13.68	12.29	11.47	10.86	11.38	10.94	13.68
5F - 4F	11.06	10.80	10.80	13.56	16.08	18.46	14.29	13.41	11.78	11.49	12.06	11.53	13.08
4F - 3F	10.28	10.53	10.53	21.28	24.36	25.63	16.48	12.05	16.86	10.00	18.15	09.90	20.06
3F - 1,5F	10.80	20.96	20.96	20.89	23.60	24.66	19.07	25.24	16.87	21.26	18.02	11.03	20.38
1,5F - OUT	29.36	23.36	23.36	33.15	36.08	39.25	25.29	31.10	29.38	24.65	31.45	36.41	27.41
Total time	**225 s — 03:45 min**	**192 s — 03:12 min**	**192 s — 03:12 min**	**280 s — 04:40 min**	**281 s — 04:41 min**	**328 s — 05:28 min**	**217 s — 03:37 min**	**249 s — 04:09 min**	**219 s — 03:39 min**	**198 s — 03:18 min**	**234 s — 03:54 min**	**206 s — 03:26 min**	**262 s — 04:22 min**

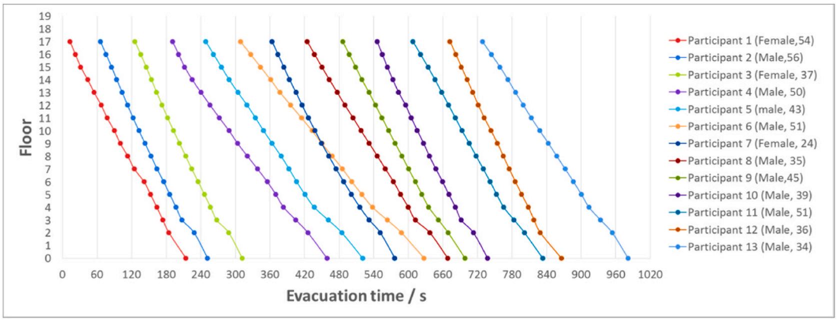


Fig. 6. Evacuation times of the participants in the first experiment.

For example, if we compare the time of Participant 6 (51-year-old man), who showed the longest time, and Participant 7 (24-year-old woman), who was one of the fastest, it is clear that despite the 60-s interval during which the participants started, on 9F Participant 7 passed Participant 6, as this was checked and reported by the participants after the experiment. A graph of participants' evacuation times is presented in Fig. 6.

As for the vertical speed, an interesting trend can be observed. After the start of the experiment, the participants begin to evacuate at a high speed for the first few floors (around 0.35 m/s), after which the speed drops slightly, remaining at approximately constant values in the middle range of the building (around 0.3 m/s), after which there is a sharp drop from the fifth floor down, the speed decreasing to approximately half of the initial speed. Our data differ substantially from the values 0.7–0.8 m/s reported by Pauls [51] and are approximately the same as a more recent experiment by Ma et al. with 0.33–0.38 m/s [27]. The vertical velocity of all participants and the mean velocity are shown in Fig. 7.

Several interesting observations can be made.

- At the beginning of the evacuation, the mean speed is the highest, which is completely understandable, considering that people are presumably trying to act quickly;
- The lower they go, the mean speed drops. This can be explained by two main factors, the fatigue of the evacuees and the understanding that they are getting closer to the final exit.

3.2. Mass evacuation

In the second experiment all occupants in the building at that time were evacuated. The survey was significant for the current research because this was the way to understand the exact number of people occupying the floors at the moment of the evacuation drill. This information is very important for the development of the paper with the Pathfinder simulations. Statistical analysis software

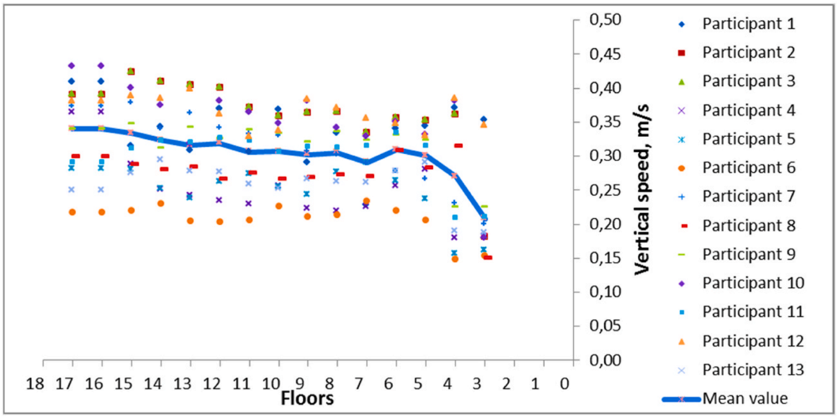


Fig. 7. Vertical speed in the participants in the first experiment.

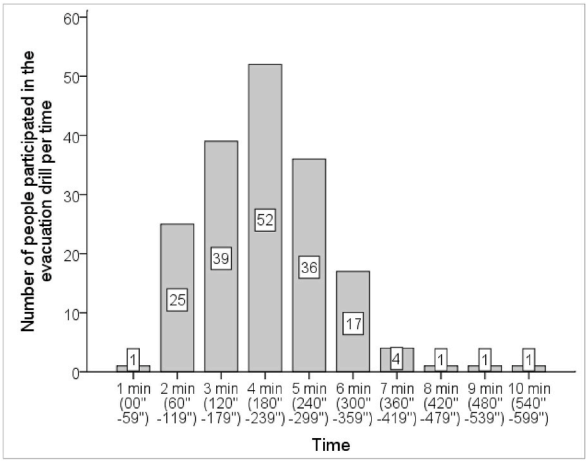


Fig. 8. Number of participants by evacuation time in the mass evacuation drill (generated via SPSS Statistics [52]).

product IBM SPSS Statistics [52] was used to process the survey results [53].

The total number of participants by evacuation time is presented in Fig. 8.

Fig. 9 shows the participants' evacuation time depending on the floor from which they are evacuating.

Formation of crowds of people in the staircases was not observed for the participating 177 people in the experiment. The moments with the most densely populated staircases are shown in Fig. 10 by snapshots from the S1 and S2 cameras in the building, respectively 15 and 12 people in an equal area of two stairwells and two landings.

We observe that most evacuees did not carry additional or bulky items, and they mainly take only their mobile phones, which is considered a good point for faster evacuation. The results about additional items carried by the participants during evacuation were extracted from the survey forms and are presented in Table 6.

The following conclusions can be drawn from the results obtained.

- Contrary to expectations that the lowest floors will be evacuated the fastest, the residents of 4F were continuously evacuated from the second to the fifth minute. For example, the people of 6F were evacuated in the range of 2–3 min. The behavior of 4F people can be explained by their attitude that they are closest to the exits, which gives them an apparent calmness and can cause a significant delay;
- Contrary to the above case, the people from the highest floor 17F evacuated very fast, which is clearly shown by the cameras and during the subsequent interviewing of the participants. Since they were in the worst place possible with the longest time in a forced evacuation, they were in a hurry to pour out.

3.3. Software simulations

3.3.1. Pathfinder simulations with 177 occupants

By comparing the real experiment with the Pathfinder simulation, we can conclude that there is a high similarity in the results, with the evacuation time during the real experiment being about 6 min, while in the simulation all occupants are evacuated in 386 s, both without using elevators. Summary details about this simulation are presented in Table 7 and snapshots in Fig. 11 respectively.

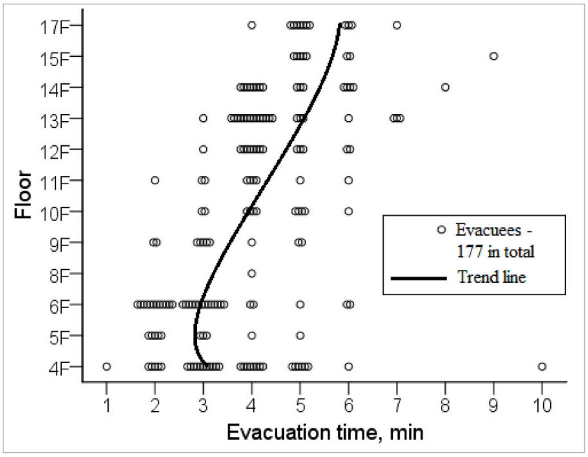


Fig. 9. General data for the evacuees in the mass evacuation drill by time and floors (generated via SPSS Statistics [52]).

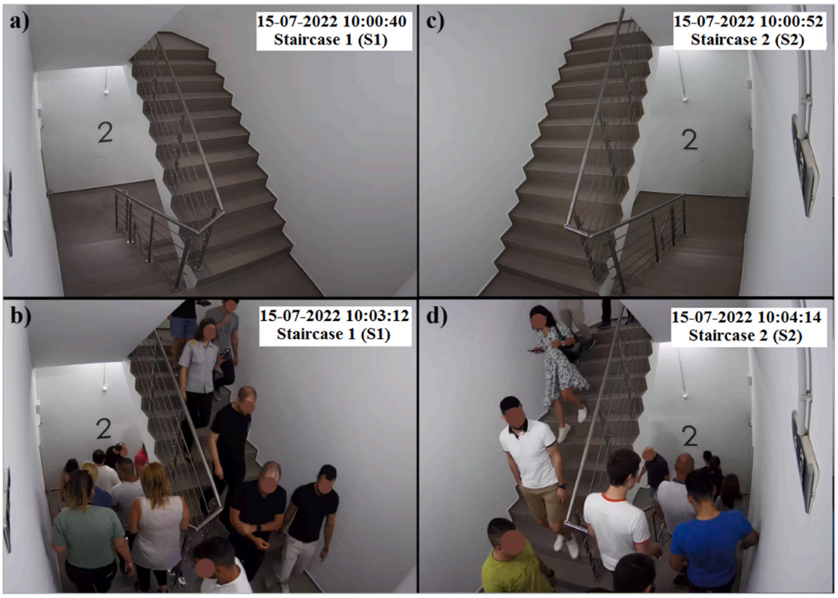


Fig. 10. Staircases details snapshots a) empty S1 in 2F, b) S1 with the max occupants load in the experiment - 15 people for two landings and two arms, c) empty S2 in 2F, d) S2 with the max occupants load in the experiment - 12 people for two landings and two arms.

Table 6
Survey results about additional items carried by the participants during the evacuation experiment.

What do you bring with you during the evacuation drill?									
Small handbag (incl. purse)		Big handbag		Backpack		Laptop		Mobile phone	
Yes	No	**Yes**	No	**Yes**	No	**Yes**	No	**Yes**	No
25	152	**4**	173	**18**	159	**6**	171	**133**	44
14,1 %	85,9 %	**2,3 %**	97,7 %	**10,2 %**	89,8 %	**3,4 %**	96,6 %	**75,1 %**	24,9 %

Fig. 12 shows the simulation data with 177 occupants regarding the number of occupants using the two main exits EXIT 2 and EXIT 2 from S1 and S2 and the two exits' flow rate. The simulation shows that EXIT 1 (people alighting from S1) was used by 118 people, while EXIT 2 (people alighting from S2) was used by 60 people. After manually counting the people using the corresponding exits in the real experiment, a very good match was observed, with the people using EXIT 1 counted by the cameras in the building being 72, and the people using EXIT 2 being 105. Furthermore, the maximum flow rate for EXIT 1 in the simulation was observed at 123 s with 0.9 people per second and the maximum flow rate for EXIT 2 in the simulation is observed at 203 s with 1 person per second.

Table 7
Summary details about Pathfinder simulation with 177 occupants (without elevators) [50].

Simulation: 177 without elevators			[Components] All: 829		
Version: 2019.3.1217			[Components] Doors: 481		
Total Occupants: 177			Triangles: 16,594		
Mode: Steering			Startup Time: 2.3s; CPU Time: 105.7s		
Completion Times for All Occupants (s):		Completion Times by Behavior (s):		Completion Times by Profile (s):	
		Behavior:	Goto Any Exit	Profile:	Office
		Count:	177	Count:	177
Min:	**100.9**	Min:	100.9	Min:	100.9
Max:	**386.2**	Max:	386.2	Max:	386.2
Average:	**228.1**	Average:	228.1	Average:	228.1
StdDev:	**85.7**	StdDev:	85.7	StdDev:	85.7
Travel Distances for All Occupants (m):		Movement Distance by Behavior (m):		Movement Distance by Profile (m):	
		Behavior:	Goto Any Exit	Profile:	Office
		Count:	177	Count:	177
Min:	**63.8**	Min:	63.8	Min:	63.8
Max:	**275.8**	Max:	275.8	Max:	275.8
Average:	**154.7**	Average:	154.7	Average:	154.7
StdDev:	**51.5**	StdDev:	51.5	StdDev:	51.5

Just for the purposes of this study with the assumption that this is not allowed by the Bulgarian fire codes, we ran the same Pathfinder simulation with the enabled option to use the elevators. The duration of the evacuation, in this case, was observed as 595 s, which is almost twice as long as without the use of elevators. This shows that the use of elevators significantly increases the evacuation time for our case study building. It should be clarified here that we are evaluating a building with a height of 107 m, and these conclusions may not be valid for supertall buildings.

The Pathfinder simulation results with 177 occupants are presented in Fig. 13.

3.3.2. Pathfinder simulations with 2195 occupants

Based on the reliability of the results of the previous experiment with 177 people, we performed a Pathfinder simulation with the full capacity of the occupants in the building - 2195 occupants. The results show that the duration of the evacuation of the entire building without using elevators is 1488 s. Summary details about this simulation are presented in Table 8 and snapshots in Fig. 14 respectively.

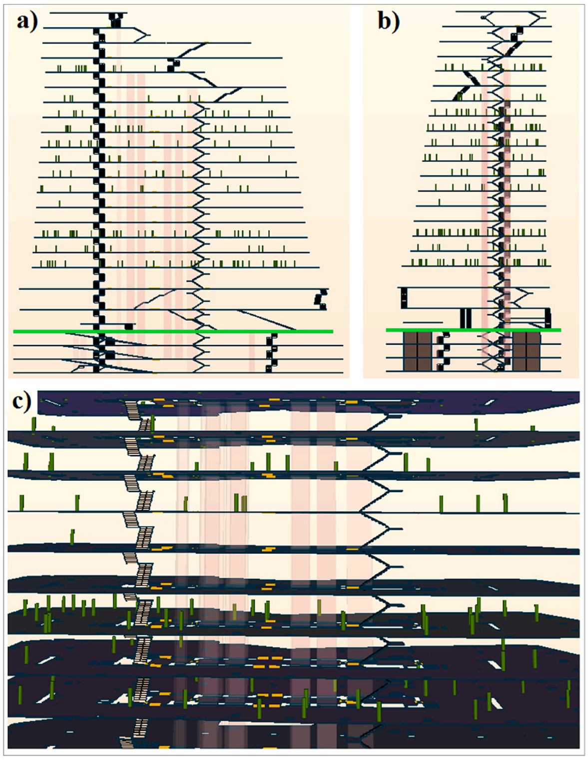


Fig. 11. Snapshots from the simulation with 177 occupants [50] a) front view, b) left view, c) perspective view.

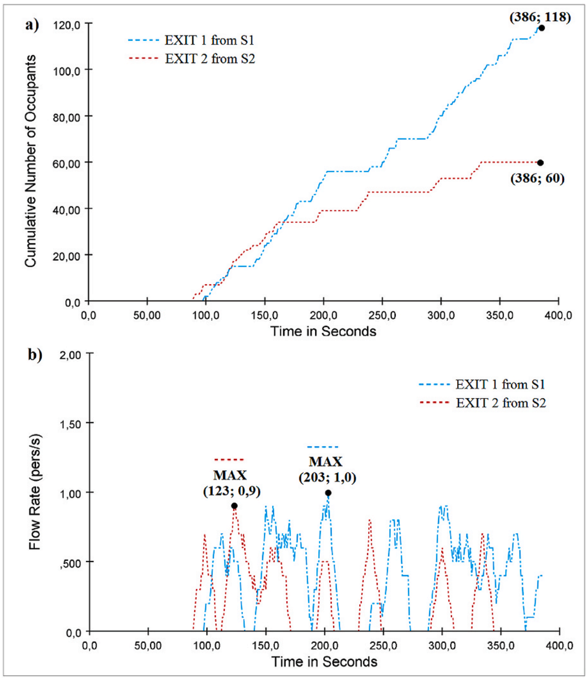


Fig. 12. Simulation data for 177 occupants [50] a) the total number of occupants used both main exits EXIT 2 and EXIT 2 from S1 and S2, b) flow rate for EXIT 2 and EXIT 2 from S1 and S2.

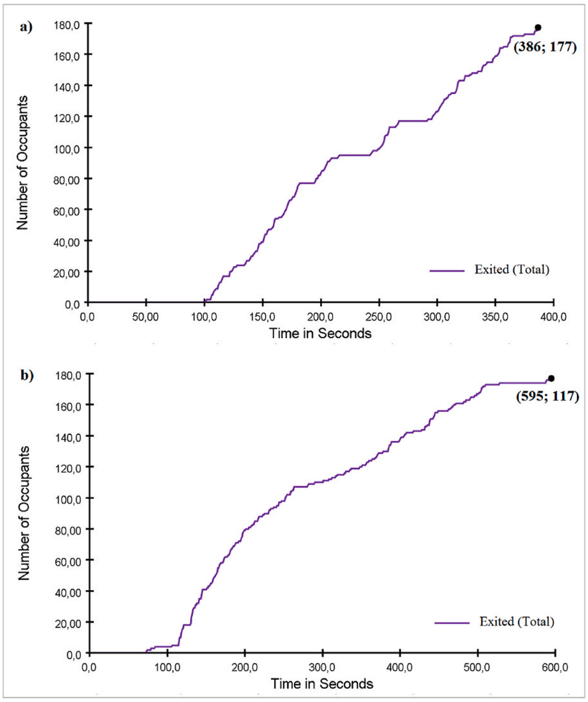


Fig. 13. Pathfinder simulation results with 177 occupants [50] a) evacuation simulation without elevators (386 s), b) evacuation simulation with elevators (595 s).

Fig. 15 shows the simulation data with 2195 occupants regarding the number of occupants using the two main exits EXIT 2 and EXIT 2 from S1 and S2 and the two exits' flow rate. The simulation shows that EXIT 1 was used by 1132 people, while EXIT 2 was used by 1038 people. After the good coincidence of the results of the real experiment and the simulation with 177 people, here we can assume that there will probably be a similarity in the result as well. Here the maximum flow rate for EXIT 1 in the simulation was

Table 8
Summary details about Pathfinder simulation with 2195 occupants (without elevators) [50].

Simulation: 2195 without elevators			[Components] All: 829		
Version: 2019.3.1217			[Components] Doors: 481		
Total Occupants: 2195			Triangles: 16,594		
Mode: Steering			Startup Time: 0.8s; CPU Time: 2606.7s		
Completion Times for All Occupants (s):		Completion Times by Behavior (s):		Completion Times by Profile (s):	
		Behavior:	Goto Any Exit	Profile:	Office
		Count:	2195	Count:	2195
Min:	**10.9**	Min:	10.9	Min:	10.9
Max:	**1488.7**	Max:	1488.7	Max:	1488.7
Average:	**747.7**	Average:	747.7	Average:	747.7
StdDev:	**388.4**	StdDev:	388.4	StdDev:	388.4
Travel Distances for All Occupants (m):		Movement Distance by Behavior (m):		Movement Distance by Profile (m):	
		Behavior:	Goto Any Exit	Profile:	Office
		Count:	177	Count:	177
Min:	**10.0**	Min:	10.0	Min:	10.0
Max:	**414.9**	Max:	414.9	Max:	414.9
Average:	**192.9**	Average:	192.9	Average:	192.9
StdDev:	**81.5**	StdDev:	81.5	StdDev:	81.5

observed at 305 s with 1,3 people per second and the maximum flow rate for EXIT 2 in the simulation is observed at 784 s with 1,2 person per second.

Again, just for the current study purposes, we repeated the simulation with the possibility of elevators being used, which shows twice longer evacuation time - 2850 s. The results with 2195 occupants are presented in Fig. 16.

Here the question arises, according to the fire codes in Bulgaria, whether in 90 s all 2195 occupants (full capacity) will be in a place of safety, i.e. in the pressurized staircases with the necessary degree of fire resistance. In Fig. 17, screenshots from the Pathfinder simulation (without elevators) are presented with the current position of the occupants at the ninetieth second.

The number of people is manually counted, and the information is presented in Table 9. The results showed that at the ninetieth second, 1374 people or 62.6% of all the building's occupants would already be in the staircases. Also at the same time, the simulation shows that there will be 71 people, which is 3.2% of all 2195 occupants, who will still be in the danger zone, i.e. in the office areas, where the danger (fire) will hypothetically be. Another 750 people will be located in the floors lobbies, which, although separated from

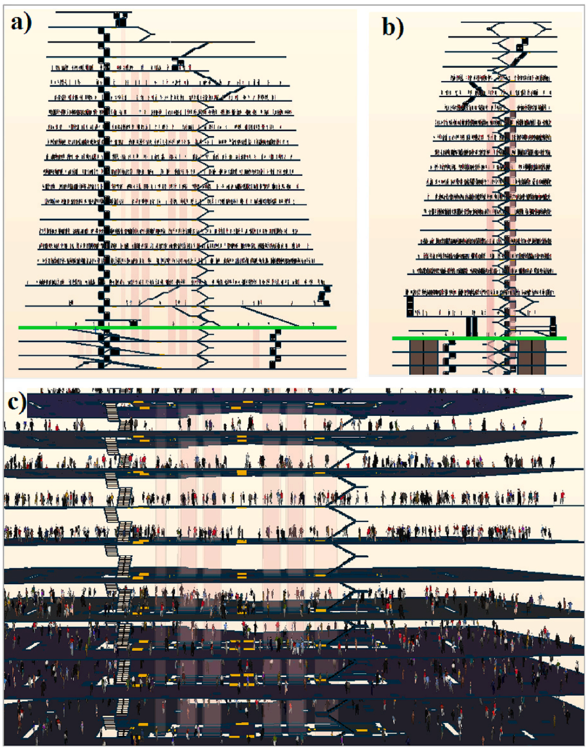


Fig. 14. Snapshots from the simulation with 2195 occupants [50] a) front view, b) left view, c) perspective view.

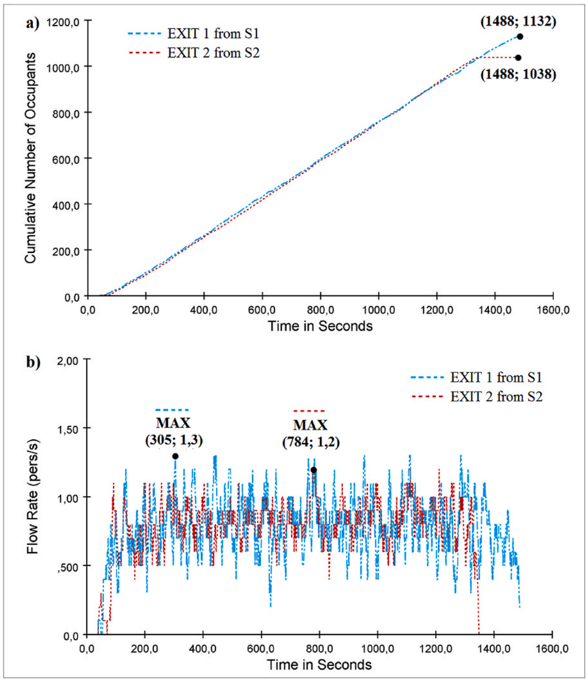


Fig. 15. Simulation data for 2195 occupants [50]a) the total number of occupants used both main exits EXIT 2 and EXIT 2 from S1 and S2,b) flow rate for EXIT 2 and EXIT 2 from S1 and S2.

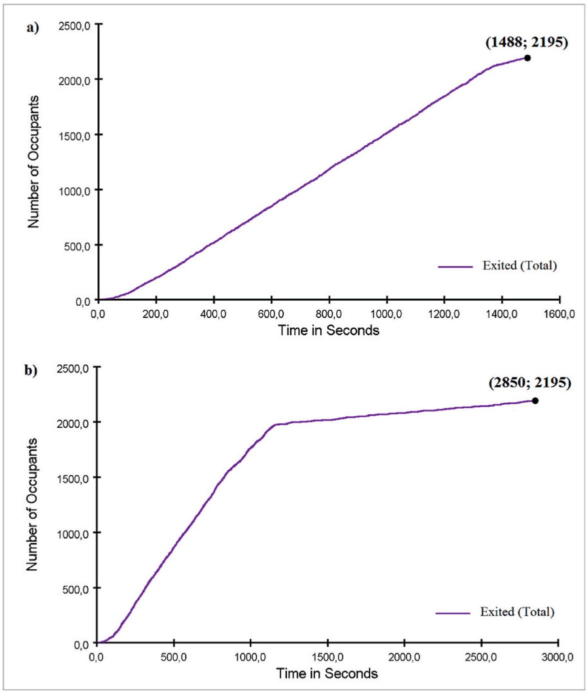


Fig. 16. Pathfinder simulation results with 2195 occupants [50] a) evacuation simulation without elevators (1488 s), b) evacuation simulation with elevators (2850 s).

the office areas with EI90 fire doors, are not considered as places of safety. At this very moment, all the people who are not in the staircases will most probably try to reach it as quickly as possible in the emotion of panic, ignoring polite manners and norms. This phenomenon has also been studied by other authors, as the people who are already in the stairs at high density hardly allow the doors to be opened from the floors and, accordingly, more people to enter the staircases [54].

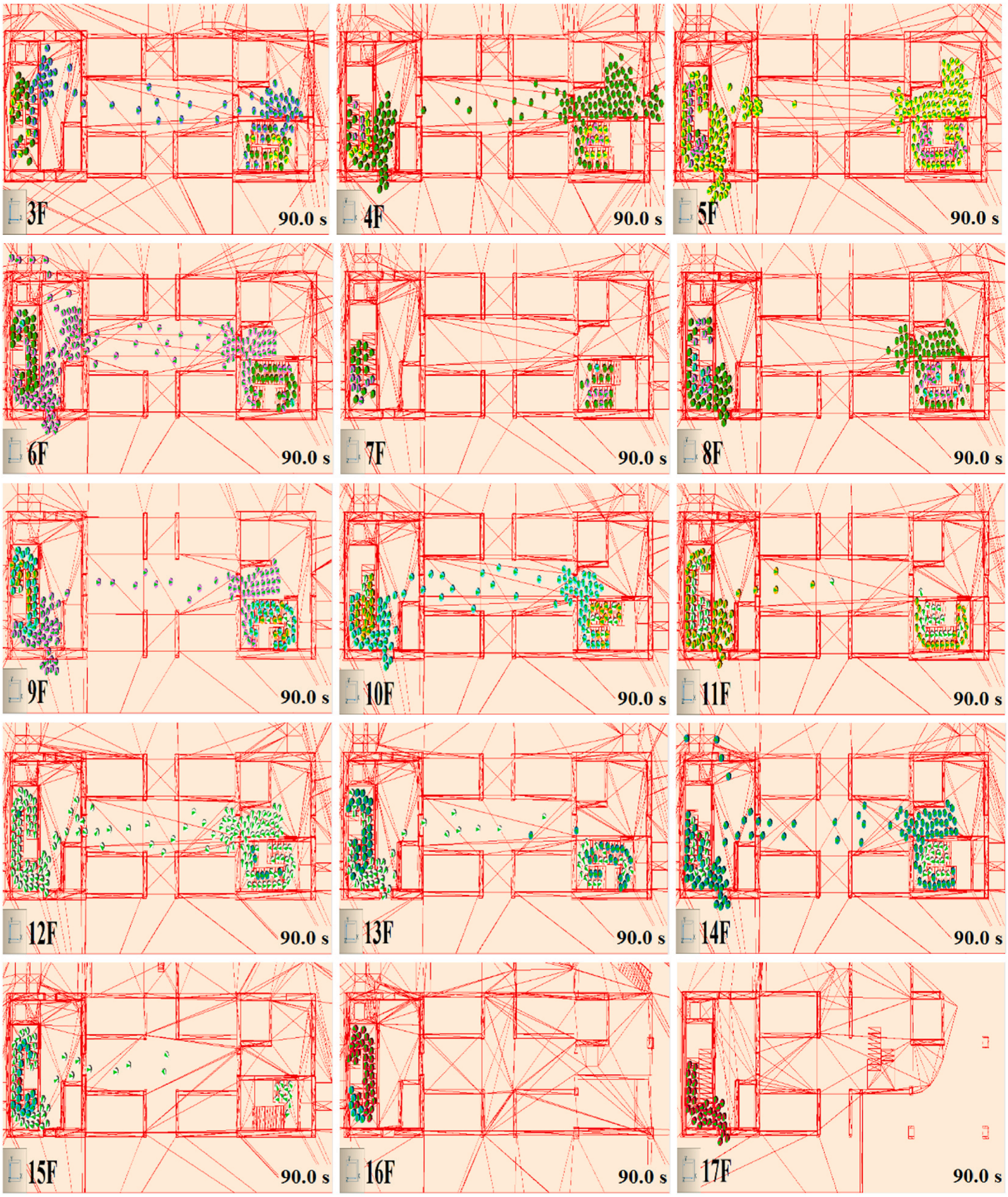


Fig. 17. Evacuees' position at the regulated ninetieth second [50].

Table 9
Position of all evacuees at 90 s at maximum capacity following the requirement in the Bulgarian fire codes.

Floor	Total people per floor (max capacity)	Place of the evacuees at 90 s at max capacity					
		In the office areas (danger zone)		In the floor lobby		In the staircases (place of safety)	
		Number of people		Number of people		Number of people	
1F	10	***0***	***0 %***	0	0 %	10	100 %
2F	20	***0***	***0 %***	0	0 %	20	100 %
3F	166	***0***	***0 %***	56	33,7 %	110	66,3 %
4F	226	***15***	***6,6 %***	101	44,7 %	110	48,7 %
5F	212	***10***	***4,7 %***	104	49,1 %	98	46,2 %
6F	225	***13***	***5,8 %***	98	43,6 %	114	50,7 %
8F	178	***4***	***2,2 %***	48	27 %	126	70,8 %
9F	171	***8***	***4,7 %***	72	42,1 %	91	53,2 %
10F	167	***4***	***2,4 %***	59	35,3 %	104	62,3 %
11F	122	***2***	***1,6 %***	27	22,1 %	93	76,2 %
12F	174	***1***	***0,6 %***	76	43,7 %	97	55,7 %
13F	114	***3***	***2,6 %***	19	16,7 %	92	80,7 %
14F	178	***8***	***4,5 %***	64	36 %	106	59,6 %
15F	102	***0***	***0 %***	17	16,7 %	85	83,3 %
16F	48	***0***	***0 %***	0	0 %	48	100 %
17F	82	***3***	***3,7 %***	9	11 %	70	85,4 %
Total	2195	***71***	***3,2 %***	750	34,2 %	1374	62,6 %

*7F is a technical floor (not occupied).

3.4. Firefighting support considerations

The link between the evacuation drill findings with the professional firefighting considerations, problems and decision-making operations in case of fire is an important point to be discussed. As already reported above, there are not so many tall buildings evacuation studies in the literature performed by researchers who at the same time have professional operational firefighting experience.

In general, in case of a fire in a tall building, it is expected that the passive and active fire protection systems shall localize and extinguish the fire. The fire detection system is expected to detect the fire and alarm the management staff and occupants timely, the sprinkler system shall not allow the fire to expand and should extinguish it accordingly and the hose systems with lay-flat hose on the floors will be used by the occupants themselves before they start to evacuate or by the firefighters using the fireman lift to go up for further response. Usually, the key problem in the case of tall building fires remains in the smoke impact and the effective and timely evacuation process of the occupants. The occupants should enter the staircases, considered as places of safety, as soon as possible (not later than 90 s according to the Bulgarian fire codes) and evacuate themselves based on the building's fire safety management procedures.

However, if the worst-case scenario happened and there are faults in the fire protection systems for any reason (e.g. technical malfunctions, explosions, terrorist attacks, etc.) the firefighting operational activities need to be performed by the firefighters through the staircases using hose lines from the fire truck. The main concern here is that the evacuation process will be ongoing at the same time (for the examined building it will approximately last for 24 min according to the Pathfinder simulation, presented in Table 8) and at the same place (the staircases where the evacuees going down) where the firefighting operations shall be performed upstairs. This might cause difficulty in the movement of the evacuees.

It is almost impossible to keep the evacuees in an "urgent" state in a fire drill. As required by the fire codes, tall buildings have specific characteristics and requirements in comparison with the other types of buildings. In this respect, the staircases and the refuge floors (if any) are places of safety where danger for the people already there shall not exist. Our field observations also prove that in case of real emergency in a tall building it will be most probably that people out of the danger area (the floor with a fire) will not even understand what the emergency is until they evacuate themselves outside of the building following clear procedures from the fire safety management (fire alarm, voice instructions, evacuation trough the stairs, meeting at the assembly point). Based on the above the main consideration of the professional firefighting personnel is to prepare the building occupants for an emergency evacuation with regular fire drills. These drills shall be announced in advance for safety reasons, but the main aim is to run the evacuation process in the buildings in "normal" environment. We hope that the fire safety culture of the evacuees will be enhanced and in case of real evacuation, they will act as "normal" in efficient and effective way. When they go out and see the fire trucks, they will realize the emergency (fire, accident, whatever) but they will be already out of danger. This is the idealistic approach but the panic will probably put the process from the "normal" to the "urgent" state, which is very difficult to predict in advance.

Serious problems which can occur during the firefighting operations include the following.

- In case of hose lines from the fire trucks need to be used for firefighting, this will affect the evacuation process in relation to the means of escape and means of access. As seen in Fig. 2, two staircases are available which is clearly shown by the full-scale fire drill and the Pathfinder simulations that they are approximately equally loaded by the evacuees. At the same time, the evacuation process will last about 24 min which is a considerably long time in case of a big fire.

- If a fire breaks out on the upper floors, the firefighting equipment limitations become the prime factor. These can be inadequate pressure from the fire trucks, or the use of specialized fire equipment e.g. portable water pumps, tanks, etc.
- It will be extremely hard for the firefighters to put a hose line upstairs in the loaded staircase during evacuation.
- Once and if the hose lines are placed in the staircases accordingly, they will act as unexpected obstacles for people evacuating, which will affect the safety and the whole evacuation process.
- In the case of hose lines from the fire trucks used for firefighting, the fire doors of the staircase on the ground floor and the floor with the fire cannot be completely closed because of the hose lines, which can affect the effectiveness of the pressurized staircase system.

Key considerations and problems that can occur during the evacuation process

- In case of the maximum capacity of the building occupants, not all the people will be in the staircases in the regulated time of 90 s as seen by the Pathfinders simulation results presented in Fig. 17 and Table 9.
- In the same scenario of the full capacity of the building occupants, problems can occur when the people from the floors try to open the fire door and enter the staircase because the evacuees already there will not allow the door to be opened because the evacuation process in the staircase will be blocked (the door opens in the direction of evacuation as shown in Fig. 3, i.e. in the direction from the floor to the staircase). It is expected the people who are already in the staircases and those who are trying to enter the staircase to be in the emotion of panic, ignoring polite manners and norms.
- However, if the door is opened somehow, it will be hard to be closed and it will stay fully open based on the same reason as in the previous point until all the occupants from this current floor enter the staircase. This will affect the effectiveness of the pressurized staircase system.
- During the first minutes while all the fire doors from the floors to the staircases are fully or partly opened, the pressurized staircase system will not be effective and it is possible for smoke to enter the staircase.

The crucial point that can greatly affect the process is the effective fire safety management procedures undertaken by the building management, e.g. regular fire evacuation drills for the occupants, promoting fire safety culture and awareness by the building management, strict control and regular inspections of the fire protection systems, sectored evacuation strategies and regular firefighting exercises, both theoretical and full-scale.

4. Conclusion

In the current research experimental and numerical evacuation studies were performed in a new 107 m tall office building in Bulgaria under the supervision of professional firefighting personnel. As there are so many factors affecting the evacuation time, in the study the key parameter in the field tests and Pathfinder simulations is chosen to be the total number of evacuees per floor. In the first field experiment in the building, thirteen randomly selected occupants estimated the free movement characteristics in "normal" conditions. Results indicated that the evacuation time was between 192 s and 328 s, while the vertical speed is between 0.35 m/s and 0.20 m/s. The mean speed is the highest on the top floors. The lower the people go, the mean speed drops because of the fatigue of the evacuees and the understanding that they are getting closer to the final exit. The second experiment was an evacuation drill with 177 people. The evacuation duration of this experiment for all people in the building at that moment was in the range of 2–6 min. Formations of crowds of people in the staircases were not observed. The Pathfinder simulation result with the same number of 177 evacuees with a 6:26 min total evacuation time show that there is a good match with the field experiment. Another Pathfinder simulation at the maximum occupants' capacity of the building with 2195 people was also run, showing a 24:48 min total evacuation time. The Pathfinder simulation results also showed that the evacuation times with elevators are around twice as long compared with the case of not using elevators. Based on the link between the evacuation drill findings and the professional firefighting considerations, problems, and decision-making operations, the effectiveness of the fire safety management procedures is considered a crucial point.

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Author statement

Martin Lyubomirov Ivanov:Conceptualization; Methodology; Formal analysis; Investigation; Software; Resources; Data curation; Validation; Visualization; Writing - original draft; Writing - review & editing. Wan-Ki Chow:Conceptualization; Methodology; Validation; Writing - review & editing; Supervision; Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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