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Safety in residential buildings: Evacuation from residential buildings without fire escape stairs

Пожарная безопасность жилых зданий - эвакуация из жилых зданий без пожарной лестницы

Безбедност у стамбеним зградама - евакуација стамбене зграде без пожарних степеница

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ABSTRACT:

Introduction/purpose: Safety in high residential buildings presents a very important and always actual task. In case of some unforeseen and dangerous occurrences, their residents must be evacuated. Fire, earthquakes, and terrorism are only some of such situations. The speed of evacuation from high residential buildings depends on many different factors. A particularly difficult and complex evacuation task concerns buildings without fire escape stairs.

Methods: The modeling method was used in this paper. Based on a real object – a residential building, an appropriate simulation model was realized in appropriate simulation software.

Results: The results of this paper have shown that, out of four scenarios, the fastest evacuation was for the evacuation speed of 1.75 m/s. The first two scenarios did not report any jams, unlike the third and fourth scenario; in the third scenario, the occupants' speeds were 0.75 m/s and 1.25 m/s while in the fourth scenario, the simulated occupants' speeds were from 0.75 m/s to 1.75 m/s.

Conclusion: The usage of appropriate simulation software enables fast, precise, safe and cheap calculation of evacuation times and it can significantly improve evacuation procedures and evacuation strategies.

KEYWORDS: evacuation, building, human, simulation.

Р е з ю м е :

Введение/цель: Безопасность в высотных жилых зданиях является очень важной и всегда актуальной задачей. В случае возникновения непредвиденных и опасных происшествий, жильцов необходимо эвакуировать. Пожары, землетрясения и терроризм – лишь некоторые из таких ситуаций. Скорость эвакуации из высотных жилых зданий зависит от множества различных факторов. Эвакуация во многом усложняется, если в зданиях нет пожарных лестниц.

Методы: В данной статье применялся метод моделирования. На основе реального объекта – жилого здания была создана соответствующая имитационная модель с помощью соответствующей имитационной программы.

Результаты: Результаты исследования показали, что из четырех сценариев наиболее быстрая эвакуация была при скорости жильцов 1,75 м / с. В первых двух сценариях не было выявлено ни одного затора, в отличие от третьего и четвертого сценариев; в третьем сценарии скорости жильцов составляли 0,75 м / с и 1,25 м / с, а в четвертом сценарии смоделированные скорости жильцов составляли от 0,75 м / с до 1,75 м / с.

Выводы: Применение соответствующего программного обеспечения для моделирования позволяет быстро, точно, безопасно и дешево рассчитать время эвакуации и может значительно улучшить процесс и стратегию эвакуации.

К л ю ч е в ы е с л о в а : эвакуация, здание, люди, моделирование.

ABSTRACT:

Увод/циљ: Безбедност у високим стамбеним зградама представља веома важан задатак. У случају неке непредвиђене и опасне појаве, станари тих зграда морају бити евакуисани. Пожар, земљотрес и терористичке акције само су неке од таквих ситуација. Брзина евакуације из високе стамбене зграде зависи од много различитих фактора. Задатак евакуације је посебно тежак и компликован уколико зграда нема пожарне степенице.

Методе: У овом раду коришћена је метода моделовања. На основу реалног објекта - стамбене зграде, реализован је одговарајући симулациони модел у одговарајућем симулационом софтверу.

Резултати: Резултати овог рада показали су да је најбржа евакуација остварена за сваки од четири сценарија при брзини станара од 1,75 m/s, с тим да за прва два сценарија нису забележени застоји, али су за трећи и четврти сценарио застоји уочени. Наиме, у трећем сценарију до застоја је дошло при брзини станара од 0,75 m/s и 1,25 m/s, а у четвртном сценарију за све симулиране брзине станара од 0,75 m/s до 1,75 m/s.

Закључак: Употреба одговарајућег симулационог софтвера омогућава брзо, прецизно, безбедно и јефтино израчунавање евакуационих времена и може знатно побољшати евакуационе процедуре и евакуациону стратегију.

KEYWORDS: евакуација, зграда, станари, симулација.

INTRODUCTION

An evacuation presents the most important measurement for population protection. This measurement generally comprises a planned and organized relocation of humans, animals, material properties, state authorities etc., from an endangered area to a safe area. Depending on a vulnerability degree and current damage, evacuation can be temporary or permanent. The reasons for evacuation can be different: fire, earthquake, floods, terrorism, nuclear disaster, tsunami, whirlwind, etc. Namely, it is important to note that there are differences between evacuation, displacement, and relocation of population.

Residential buildings present specific objects for evacuation, mostly because of a huge number of residents of different age. Besides this important factor, there are also other factors such as building construction and location, possibilities for fire fighters to approach the site, presence or absence of evacuation stairs, presence or absence of an escape rescue system, behavior of residents under stress, etc. For example, in the United States, in the period from 2007 to 2011, fire units had 15400 interventions because of fire in high buildings. These fires caused 46 victims, 530 civil injuries and more than 200 million dollars of damage, on the year level. It is interesting to note that 45 % of all fires were caused in apartments; 3 % of all fires were caused in hotels; 2 % of all fires were caused in offices, and 1 % of all fires was caused in elderly care objects (Mumović, 2019).

One very important event related to safety evacuation in high buildings was, unfortunately, the terrorist's attacks on the World Trade Centre in New York, on 11 September 2001. According to analyses, the evacuations of 87 % of all occupants were realized in less than two hours. However, evacuation times were pretty different and complex to explain. Because of that reason, many different experts agreed that safety in high buildings would be much improved with a better understanding and analysis of human behavior in panic and stress situations. In addition, several very important factors influenced occupant behavior in general. Taking into account demographic characteristics, it was noted that 58 % of all occupants were male with an average age of 44; 90 % of all occupants were well educated, 56 % of all occupants lived outside New York while 32 % of all occupants lived in the neighborhood. Health and injury status of occupants were also important - it was noted that 23 % of all occupants reported some medical problem. Familiarity with the building and installed fire safety measurements were very poor - it was confirmed that only 20 % of all occupants were introduced with proper actions after the alarm sounded (Gershon et al, 2011).

Regardless of building construction characteristics, evacuation from residential buildings can be realized in several ways: first, by stairs, and then by elevators or their combinations. Modern residential buildings built in recent times have several new and modern ways for evacuation, such as special security equipment, transport helicopters or some new construction solutions (connections between buildings or similar). In many cases, evacuation by stairs presents the only possible way for evacuation. Many high buildings have standard staircases and emergency stairs, many not. The realization of staircases demands detailed research about many factors, such as the position of the staircase, the material the stairs are made of, the staircase dimensions (width, riser and tread dimensions), stairs fire resistance, etc. (Pauls, 2005).

Although in the last twenty years fire protection systems and evacuation systems have significantly improved, accidents in high residential buildings have occurred. As an example, fires in residential buildings are presented in Figure 1 (a and b).



FIGURE 1

Huge fire in a residential building in Sao Paolo, Brazil, in 2018 (a) and a huge fire in the residential building Grenfell Tower in London, UK, in 2017 (b)

(a) (Fos Media, 2018); (b) (Hartley-Parkinson, 2019)

The usage of elevators for evacuation is questionable for many different reasons: the lack of power supply, collapse capabilities, the possibilities of dangerous gases penetration (especially carbon monoxide (CO)), the lack of space, etc. Because of the noted reasons, many different evacuation approaches do not recommend elevators usage for evacuation (Glavinić & Rasković, 2016).

The occupant behavior under stress and panic presents a very complex factor hard to define and predict. It is almost impossible to predict occupants' behavior in stress situations, no matter how educated or familiar with safety precautions they are. Occupants are, in normal conditions, aware and ready to find the best options, even in the cases when they should aid someone (help someone with disabilities, help children, etc.). However, are they able to do all this in the presence of smoke, flame, heat, crashes, explosions or other stress situations? A different age of occupants is also important and brings new moments of complexity and unpredictability (Ronchi & Nilsson, 2013), (Jevtić, 2016).

It is obvious that successful evacuation in an accident, especially from a complex object such as a residential building, must be realized in the early stage of the accident. Of course, it implies the timely detection of an accident or a disaster. Because of that, it is important to predict, as closely as possible, all potential evacuation scenarios and situations. One of the best ways to predict evacuation situations and calculate time needed for evacuation is the usage of simulation software. The usage of simulation software and the analysis of potential evacuation scenarios for different evacuation factors present a new, effective, safe, and "all in" approach in building architecture. Powerful computers enable detailed analyses of evacuation by simulation and prediction of almost all potential scenarios. The given facts show that this topic has a great importance, primarily in the protection of human lives. On the other hand, a timely and well-planned evacuation enables a fast evacuation of occupants and a fast approach of fire fighters, which can significantly decrease damage to material properties. This paper was written to show the prediction of evacuation scenarios and the calculation of evacuation times in the case of a building without emergency stairs, using adequate simulation software.

PATHFINDER SIMULATION SOFTWARE

A successful and safely realized evacuation as well as saving lives and material properties can be significantly improved by using simulation software. The reasons for simulation software usage lie in the fact that such usage is, above all, safe and economically cost-effective. In addition, it has potentials to predict many different evacuation scenarios and calculations of evacuation times. There is a number of simulation software for evacuation on the market. One of them is Pathfinder. This simulation software is based on human movement. Until today, several different versions of this program have been developed. This powerful simulator enables a graphical user interface for simulation design and execution. It is possible to simulate human movements through objects, in elevators, on stairs, etc. The Pathfinder environment presents a 3D triangulated mesh designed to match the real dimensions of a building model. This software can support two different simulation ways: the steering mode and the SFPE mode. In addition, this software has a very important ability to import files from different programs such as FDS, 3D Cad and PyroSim, what enables much faster drawing of a simulation model and the usage of the existent simulation models with minor remakes. The Pathfinder version used for this paper was 2020 version (Thunderhead, 2014).

SIMULATION MODEL

The object simulated in this paper was the building in the Bulevar Nemanjića Street, with numbers from 58 to 64. This object actually presents four buildings connected in one. The object has four exits/entrances without emergency stairs. The main advantage of such objects is in their great stability in case of earthquakes. Every building has the basement, the ground floor, ten floors and a roof terrace. The buildings are connected via terraces. The connected terraces serve for evacuation in case that residents cannot get out through the entrance/exit.

Every building, taken separately, has two elevators, vault rooms, a loft and four flats on every floor started from the ground floor to the tenth floor. This means that every building, taken separately, has forty-four flats, i.e. there are one hundred and seventy six flats in total. There are two different flat types per floor, one with an approximate surface of 66 m^2 and one with an approximate surface of 50 m^2 . Every building separately has two different elevators: one with a total capacity of four persons and one with a total capacity of six persons. The elevators have different speeds. These speeds were measured, and, for a smaller elevator type, the speed was 1.1 m/s , while the speed of a bigger elevator was 0.92 m/s . The maximum distance between the floors is approximately 2.6 m , which means that the total height of the object is approximately $36\text{--}38 \text{ m}$ (measured from the ground to the elevator machine room on the top of the building). Related to this object, a proper simulation model with all its real dimensions was constructed in Pathfinder software.

The positions of the residents were per floors and in flats, based on the resident lists. Because of visibility, the HIDE function from Pathfinder was used. This means that only some elements were visible, such as stairs, doors, elevators, etc. The total number of residents was 699, which was confirmed from the resident lists for every of four buildings separately (179 residents in the entrance/exit with number 58, 168 residents in the entrance/exit with number 60, 169 residents in the entrance/exit with number 62, and 183 residents in the entrance/exit with number 64).

After the construction of the simulation model, it was decided to simulate four different scenarios. The first simulation scenario included all entrances/exits opened, with enabled and disabled elevators. The second simulation scenario included one entrance/exit blocked while other three entrances/exits were open (all potential 9 cases), with enabled and disabled elevators. The third simulation scenario included two entrances/exits blocked while other two entrances/exits were open (all potential 12 cases), with enabled and disabled elevators. The fourth simulation scenario was based on three entrances/exits blocked while one entrance/

exit was open (all potential 8 cases), with enabled and disabled elevators. Each of four scenarios was realized for different speeds of occupants: 0.75 m/s, 1 m/s, 1.25 m/s, and 1.5 m/s and 1.75 m/s (Jevtić, 2018), (Jevtić, 2019a).

The residential building in Bulevar Nemanjića Street, from 58 to 64, Niš, is presented in Figure 2 (a), while the appropriate Pathfinder simulation model of the residential building in Bulevar Nemanjića Street is presented in Figure 2 (b).

SIMULATION RESULTS

The complete simulation results are presented from Table 1 to Table 30. The simulation results for the first scenario are presented in Tables 1 and 2. The simulation results for the second scenario are presented in Tables from 3 to 10. The simulation results for the third scenario are presented in Tables from 11 to 22. The simulation results for the fourth scenario are presented in Tables from 23 to 30. All simulations of the evacuation were realized on a laptop Honor MagicBook 15 with AMD Ryzen 5 3500U processor at 3.7 GHz and 6 MB of CASH memory and 8 GB DDR4 2667 MHz. It is desirable to possess a strong hardware configuration for any kind of computer simulation.

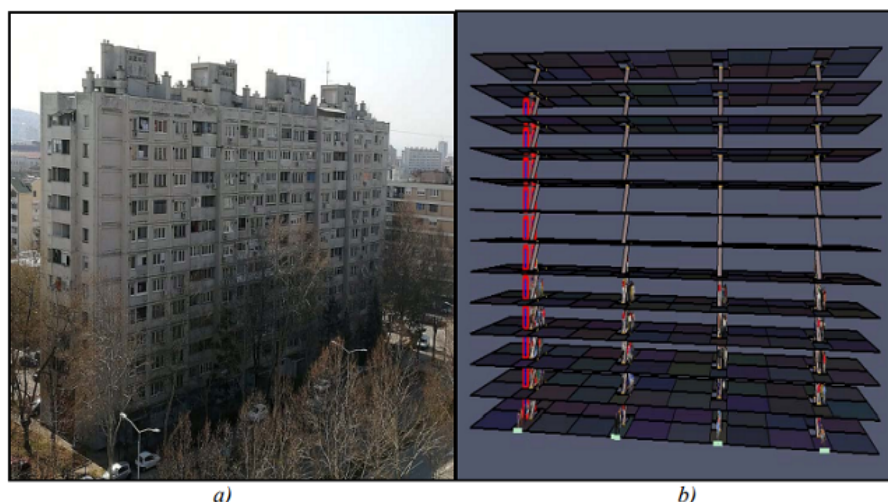


FIGURE 2

Building in Bulevar Nemanjića Street, from 58 to 64 (a) and the Pathfinder simulation model of the residential building in Bulevar Nemanjića Street (b)

TABLE 1

Simulation results in seconds for the first scenario, with elevators enabled and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	133	183	230	286	332	365
Time for speed of occupants 1 m/s	0	105.7	141.6	183.4	221	256	293
Time for speed of occupants 1.25 m/s	0	84	127	159	197	234	256
Time for speed of occupants 1.5 m/s	0	72.2	105.8	148	176	209	236
Time for speed of occupants 1.75 m/s	0	50	79	123	140	180	209

TABLE 2

Simulation results in seconds for the first scenario, with elevators disabled and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	145	203	255	313	351	442
Time for speed of occupants 1 m/s	0	123	177.6	219.4	257	292	334
Time for speed of occupants 1.25 m/s	0	113	156	188	226	263	288
Time for speed of occupants 1.5 m/s	0	95.2	128.8	171	199	232	267.6
Time for speed of occupants 1.75 m/s	0	74	88.7	133	150	187	232

TABLE 3

Simulation results in seconds for the second scenario, with elevators enabled and the first entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	190	225	291	398	562	796
Time for speed of occupants 1 m/s	0	160	195	254	342	501	627
Time for speed of occupants 1.25 m/s	0	134	165	231	311	472	554
Time for speed of occupants 1.5 m/s	0	118	136	201	284	420	499
Time for speed of occupants 1.75 m/s	0	100	120	172	235	367	434

TABLE 4

Simulation results in seconds for the second scenario, with elevators enabled and the second entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	184	213	275	380	546	772
Time for speed of occupants 1 m/s	0	155	184	239	320	487	600
Time for speed of occupants 1.25 m/s	0	128	155	218	295	455	530
Time for speed of occupants 1.5 m/s	0	113	126	190	266	406	468
Time for speed of occupants 1.75 m/s	0	95	110	166.4	221	351	422

TABLE 5

Table 5 – Simulation results in seconds for the second scenario, with elevators enabled and the third entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	199	225	290	397	566	789
Time for speed of occupants 1 m/s	0	167	199	253	336	506	615
Time for speed of occupants 1.25 m/s	0	136	174	234	311	475	543
Time for speed of occupants 1.5 m/s	0	122	150	202	280	422	480
Time for speed of occupants 1.75m/s	0	104	132	180	235	369	432

TABLE 6

Simulation results in seconds for the second scenario, with elevators enabled and the fourth entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	210	239	306	415	588	811
Time for speed of occupants 1 m/s	0	178	213	269	354	526	639
Time for speed of occupants 1.25 m/s	0	147	185	250	330	496	566
Time for speed of occupants 1.5 m/s	0	135	164	217	297	444	503
Time for speed of occupants 1.75 m/s	0	116	144	194	253	390	457

TABLE 7

Table 7 – Simulation results in seconds for the second scenario, with elevators disabled and the first entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	270	306	372	480	642	873
Time for speed of occupants 1 m/s	0	240	278	337	420	582	700
Time for speed of occupants 1.25 m/s	0	215	248	315	390	553	634.9
Time for speed of occupants 1.5 m/s	0	199	217	281.3	363	499	579.5
Time for speed of occupants 1.75 m/s	0	181	200	250	313	447	515

TABLE 8

Simulation results in seconds for the second scenario, with elevators disabled and the second entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	220	250	313.6	418.4	580	812
Time for speed of occupants 1 m/s	0	193.4	223	280.9	361.6	528.2	642
Time for speed of occupants 1.25 m/s	0	162	192	260	330	493	569
Time for speed of occupants 1.5 m/s	0	152	168	229.5	302	443	525
Time for speed of occupants 1.75 m/s	0	133.7	149	205.3	260	390.4	460

TABLE 9

Simulation results in seconds for the second scenario, with elevators disabled and the third entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	264.4	295	357.4	462	620	856
Time for speed of occupants 1 m/s	0	237.6	267.6	324.4	402	567	684
Time for speed of occupants 1.25 m/s	0	206.6	237.6	303	370.4	537	613
Time for speed of occupants 1.5 m/s	0	197.4	224.6	276.4	345	481	569
Time for speed of occupants 1.75 m/s	0	149	198.5	248.6	305	434	503.5

TABLE 10

Simulation results in seconds for the second scenario, with elevators disabled and the fourth entrance/exit blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	292	330	393	494	657	893
Time for speed of occupants 1 m/s	0	274	304	361	439	603	720.2
Time for speed of occupants 1.25 m/s	0	243	273	340	405.3	573.5	649
Time for speed of occupants 1.5 m/s	0	214	258	314.4	382	525.6	606
Time for speed of occupants 1.75 m/s	0	195	234	284.4	341	471.5	541.5

TABLE 11

Simulation results in seconds for the third scenario, with elevators enabled and the first and the second entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	314	357	416	517	679	915
Time for speed of occupants 1 m/s	0	296	325	384	460	624	742
Time for speed of occupants 1.25 m/s	0	264	294.6	360.9	426.7	595.2	671
Time for speed of occupants 1.5 m/s	0	235.2	278.7	336	402	547.7	627
Time for speed of occupants 1.75 m/s	0	216	254	304	361	494	565

TABLE 12

Simulation results in seconds for the third scenario, with elevators enabled and the first and the third entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	326	369	428	529	691	927
Time for speed of occupants 1 m/s	0	308	337	396	472	636	754
Time for speed of occupants 1.25 m/s	0	276	306.6	373.4	439	607.2	683
Time for speed of occupants 1.5 m/s	0	248	290.7	348	414	560.2	639
Time for speed of occupants 1.75 m/s	0	228	266	316	373	506	577

TABLE 13

Simulation results in seconds for the third scenario, with elevators enabled and the first and the fourth entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	353	397	453	558.4	718.3	952.9
Time for speed of occupants 1 m/s	0	334.4	364	423	500	661.6	782.1
Time for speed of occupants 1.25 m/s	0	304	331	401.8	465	635.6	709
Time for speed of occupants 1.5 m/s	0	274	318.3	374	440	591	665
Time for speed of occupants 1.75 m/s	0	254.7	292	342	400.5	532	605

TABLE 14

Simulation results in seconds for the third scenario, with elevators enabled and the second and the third entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	298	340	400	500	663	899
Time for speed of occupants 1 m/s	0	281	310	369	445	609	727
Time for speed of occupants 1.25 m/s	0	249	279.6	345.9	411.7	579.8	656
Time for speed of occupants 1.5 m/s	0	220.2	263.7	320.5	387	531.2	612
Time for speed of occupants 1.75 m/s	0	201	240.4	290.2	345.5	479	550

TABLE 15

Simulation results in seconds for the third scenario, with elevators enabled and the second and the fourth entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	337	380	439	541.5	702	938
Time for speed of occupants 1 m/s	0	319	348	407	483	647	765
Time for speed of occupants 1.25 m/s	0	287	317.6	385.7	450	618.2	694
Time for speed of occupants 1.5 m/s	0	259	302	359	426.2	574	650
Time for speed of occupants 1.75 m/s	0	239	278.3	327	384	517	588

TABLE 16

Simulation results in seconds for the third scenario, with elevators enabled and the third and the fourth entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	346	390.5	448	551	711	947
Time for speed of occupants 1 m/s	0	328	358.4	416	493	656	775.3
Time for speed of occupants 1.25 m/s	0	297.4	325	394	459	628	703
Time for speed of occupants 1.5 m/s	0	268	311	368	434	584.3	659
Time for speed of occupants 1.75 m/s	0	248	286	335.8	393	526	598.3

TABLE 17

Simulation results in seconds for the third scenario, with elevators disabled and the first and the second entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	366	410.4	570	569	731	966
Time for speed of occupants 1 m/s	0	348	377.5	436	511.9	676	794
Time for speed of occupants 1.25 m/s	0	316	346.6	413.34	479	648	723
Time for speed of occupants 1.5 m/s	0	288	331.6	388	454	600	679
Time for speed of occupants 1.75 m/s	0	268	306	356.11	413	546	617

TABLE 18

Simulation results in seconds for the third scenario, with elevators disabled and the first and the third entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	377.45	420	479	580	742	977
Time for speed of occupants 1 m/s	0	359	388	447	523	687.4	805
Time for speed of occupants 1.25 m/s	0	327	358	424.4	425	659	734.7
Time for speed of occupants 1.5 m/s	0	299.11	341.7	399	465	611.2	691.3
Time for speed of occupants 1.75 m/s	0	279	316.7	367	424	557	628

TABLE 19

Simulation results in seconds for the third scenario, with elevators disabled and the first and the fourth entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	403.4	447	503	608.4	768.3	1003
Time for speed of occupants 1 m/s	0	384.4	414.56	473	550	711.6	832.1
Time for speed of occupants 1.25 m/s	0	354	383.1	451.8	516.67	685.6	759
Time for speed of occupants 1.5 m/s	0	325	368.3	424	491.34	641	715
Time for speed of occupants 1.75 m/s	0	304.7	342	392.5	450.5	582	655.33

TABLE 20

Simulation results in seconds for the third scenario, with elevators disabled and the second and the third entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	347	390.66	449	549	711.71	948.2
Time for speed of occupants 1 m/s	0	330.34	359.67	418	493.98	658	777
Time for speed of occupants 1.25 m/s	0	298	328.6	394.9	461.5	628.8	705.29
Time for speed of occupants 1.5 m/s	0	269.2	312.7	369.5	436	580.2	661
Time for speed of occupants 1.75 m/s	0	251.12	289.4	339.2	394.5	529.45	599

TABLE 21

Simulation results in seconds for the third scenario, with elevators disabled and the second and the fourth entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	383	428	487	590	750	989
Time for speed of occupants 1 m/s	0	368	396	455	531	695	813
Time for speed of occupants 1.25 m/s	0	335.7	364	434.29	498	667	742
Time for speed of occupants 1.5 m/s	0	307.56	350	407	474.2	622	698
Time for speed of occupants 1.75 m/s	0	287.2	326.3	376.06	432.22	566.45	636

TABLE 22

Simulation results in seconds for the third scenario, with elevators disabled and the third and the fourth entrances/exits blocked and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	393.23	438	496.6	599.3	758	995.27
Time for speed of occupants 1 m/s	0	374.9	405.37	463.78	541.12	703	822.3
Time for speed of occupants 1.25 m/s	0	344.4	372.3	441	506	674.88	750.31
Time for speed of occupants 1.5 m/s	0	317	358	415	481	631.3	707.3
Time for speed of occupants 1.75 m/s	0	296.6	335	382.8	440	573	645.3

TABLE 23

Simulation results in seconds for the fourth scenario, with elevators enabled and the first entrance/exit opened, while the second, the third and the fourth entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	443.6	678.3	915.9	1150.7	1388.3	1623
Time for speed of occupants 1 m/s	0	322	496.5	672	846.3	1021.8	1198.3
Time for speed of occupants 1.25 m/s	0	310	470	620	780	834	992
Time for speed of occupants 1.5 m/s	0	304	432.6	594	700	800	900
Time for speed of occupants 1.75 m/s	0	274	373.4	474.9	585.5	689	794

TABLE 24

Simulation results in seconds for the fourth scenario, with elevators enabled and the second entrance/exit opened, while the first, the third and the fourth entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	483.2	718.8	949.6	1183	1414.3	1646.5
Time for speed of occupants 1 m/s	0	335	515	694	869	1044.6	1220.3
Time for speed of occupants 1.25 m/s	0	286	426.4	566.8	707.8	849.1	988.6
Time for speed of occupants 1.5 m/s	0	263	404.5	531.6	651.7	772.6	890.3
Time for speed of occupants 1.75 m/s	0	242.3	355.2	463.2	569.8	675.7	780.2

TABLE 25

Simulation results in seconds for the fourth scenario, with elevators enabled and the third entrance/exit opened, while the first, the second and the fourth entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	443.7	680	917.6	1152.5	1390.2	1623.6
Time for speed of occupants 1 m/s	0	336.6	510	686	861.6	1036.5	1204.7
Time for speed of occupants 1.25 m/s	0	264.8	400	540.8	681.4	823.4	962.8
Time for speed of occupants 1.5 m/s	0	247.4	387.5	519.6	641.4	763.7	884.5
Time for speed of occupants 1.75 m/s	0	241.3	351.7	460	565.3	669.6	800

TABLE 26

Simulation results in seconds for the fourth scenario, with elevators enabled and the fourth entrance/exit opened, while the first, the second and the third entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	446	677	910	1145	1376.9	1603.6
Time for speed of occupants 1 m/s	0	332	509.6	709	857.6	1032.1	1206
Time for speed of occupants 1.25 m/s	0	320	487	683	832	992	1132
Time for speed of occupants 1.5 m/s	0	302	457	588.4	714.5	836.6	953.7
Time for speed of occupants 1.75 m/s	0	295.4	406.7	539.5	648.6	754.7	860

TABLE 27

Simulation results in seconds for the fourth scenario, with elevators disabled and the first entrance/exit opened, while the second, the third and the fourth entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	550.3	787	1021.9	1257.4	1493.5	1729.3
Time for speed of occupants 1 m/s	0	428	602	778.5	953	1126.9	1302
Time for speed of occupants 1.25 m/s	0	416.1	576	726.54	885.3	940	1099.3
Time for speed of occupants 1.5 m/s	0	410.32	538	701.5	806.4	906.2	1006
Time for speed of occupants 1.75 m/s	0	380.5	480	580.9	693.4	795	900.02

TABLE 28

Simulation results in seconds for the fourth scenario, with elevators disabled and the second entrance/exit opened, while the first, the third and the fourth entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	547	781	1019.9	1255	1493	1727
Time for speed of occupants 1 m/s	0	426.2	600	776	951	1126	1303.5
Time for speed of occupants 1.25 m/s	0	413.34	574.7	723.4	882.4	938.4	1096.71
Time for speed of occupants 1.5 m/s	0	408	539.17	699.8	804	904	1003.4
Time for speed of occupants 1.75 m/s	0	378	476.6	579	890	793	898

TABLE 29

Simulation results in seconds for the fourth scenario, with elevators disabled and the third entrance/exit opened, while the first, the second and the fourth entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	545.02	781.4	1018.6	1254	1492	1725
Time for speed of occupants 1 m/s	0	438	612.11	787	963.9	1137	1305
Time for speed of occupants 1.25 m/s	0	365.16	500.31	643.2	787	925	1064.8
Time for speed of occupants 1.5 m/s	0	349	489	621.7	743	867.5	986
Time for speed of occupants 1.75 m/s	0	343.6	453	561	667.8	771	902.3

TABLE 30

Simulation results in seconds for the fourth scenario, with elevators disabled and the fourth entrance/exit opened, while the first, the second and the third entrances/exits are blocked, and for the occupants' speeds from 0.75 m/s, 1 m/s, 1.25 m/s, 1.5 m/s, and 1.75 m/s

Number of occupants	669	500	400	300	200	100	0
Time for speed of occupants 0.75 m/s	0	543.6	776.7	1009	1243	1476	1702
Time for speed of occupants 1 m/s	0	431.31	608.29	808.3	955	1130	1306.8
Time for speed of occupants 1.25 m/s	0	417.23	587.6	782	931	1091	1231.4
Time for speed of occupants 1.5 m/s	0	401.5	556.9	688	811.3	936.24	1053
Time for speed of occupants 1.75 m/s	0	394	504.75	636.18	746	850.53	959

RESULTS ANALYSIS

The realized simulation results for the first scenario (Tables 1 and 2) have shown that the elevators usage increases the evacuation of the complete object. The fastest evacuation time was for the occupants' speed of 1.75 m/s and the elevators enabled (209 seconds, in Table 1), while the slowest evacuation time was for the occupants' speed of 0.75 m/s and the elevators disabled (442 seconds, in Table 2). In this scenario, the occupants left the building via their own entrance/exit. There were no jams for simulated occupants' speeds.

The realized simulation results for the second scenario (Tables from 3 to 10) have shown that the fastest evacuation time was realized when the occupants' speed was 1.75 m/s, the second entrance/exit blocked and the elevators enabled (422 seconds, in Table 4). The slowest evacuation time was realized when the occupants' speed was 0.75 m/s, the fourth entrance/exit blocked and the elevators disabled (893 seconds, in Table 10). In this scenario, the occupants from the building with the blocked entrance/exit had to use the building roof terraces to reach the nearest stairs that lead to the open entrance/exit. There were no jams for the simulated occupants' speeds. Some simulation scenes from the second scenario are presented in Figure 3 (a and b).

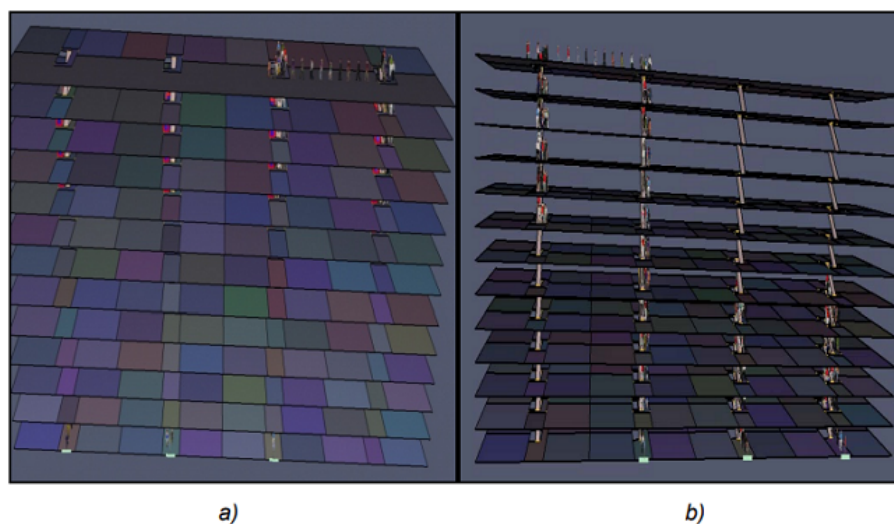


FIGURE 3

Simulation scene for the second scenario where the first entrance/exit was blocked and the elevators were enabled and for the occupants' speeds of 1 m/s (a) and the simulation scene for the second scenario where the fourth entrance/exit was blocked and the elevators were disabled and for the occupants' speeds of 0.75 m/s (b)

The realized simulation results for the third scenario (Tables from 11 to 22) have shown that the fastest evacuation time was realized when the occupants' speed was 1.75 m/s, the second and the third entrances/exits blocked and the elevators enabled (550 seconds, in Table 14). The slowest evacuation time was realized when the occupants' speed was 0.75 m/s, with the first and the fourth entrances/exits blocked and the elevators disabled (1003 seconds, in Table 19). In this scenario, the occupants from the buildings with the blocked entrances/exits had to use the building roof terraces to reach the nearest stairs that lead to the open entrance/exit. The simulations showed that jams can occur, mostly for the occupants' speed of 0.75 m/s and 1.25 m/s. Some simulation scenes from the third scenario are presented in Figure 4 (a and b).

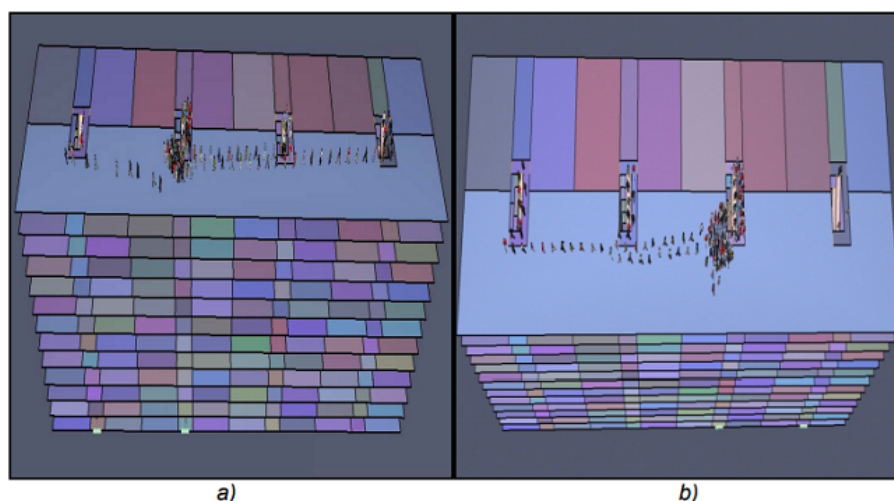


FIGURE 4

Simulation scene for the third scenario where the first and the second entrances/exits were blocked and the elevators were enabled and for the occupants' speeds of 1.25 m/s (a) and a simulation scene for the third scenario where the third and the fourth entrances/exits were blocked and the elevators were disabled and for the occupants' speeds of 1.5 m/s (b)

The realized simulation results for the fourth scenario (Tables from 23 to 30) have shown that the fastest evacuation time was realized when the occupants' speed was 1.75 m/s, the first entrance/exit opened and the second, the third and the fourth entrances/exits blocked and the elevators enabled (794 seconds, in Table 23). The slowest evacuation time was realized when the occupants' speed was 0.75 m/s; with the first entrance/exit opened, and with the second, the third and the fourth entrances/exits blocked and the elevators disabled (1729.3 seconds, in Table 27). In this scenario, the occupants with the blocked entrances/exits had to use the building roof terraces to reach the nearest stairs that lead to the single open entrance/exit. The simulations showed that jams can occur, mostly for the occupants' speed of 0.75 m/s. The simulations showed that jams in this scenario can occur and that these jams can be significant, for every occupants' speed from 0.75 m/s to 1.75 m/s. Some simulation scenes from the fourth scenario are presented in Figure 5 (a and b).

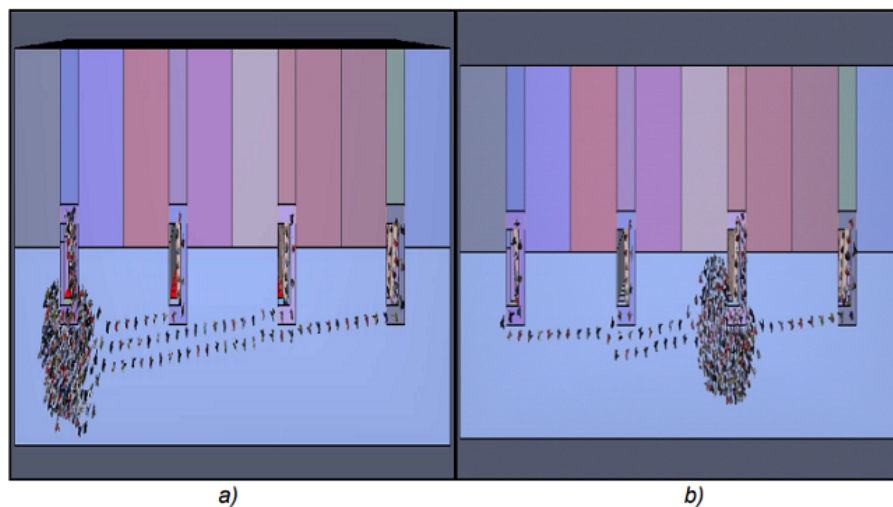


FIGURE 5

Simulation scene for the fourth scenario where the fourth entrance/exit was opened while other entrances/exits were blocked, the elevators enabled and for the occupants' speeds of 0.75 m/s (a) and a simulation scene for the fourth scenario where the second entrance/exit was opened while other entrances/exits were blocked, the elevators disabled and for the occupants' speeds of 1.75 m/s (b)

The realized simulations have shown that times needed for an evacuation increased depending on the number of blocked entrances/exits and on whether the elevators were used or not. In reality, many of potential evacuation situations imply that elevators are not used and that was the main reason why every of four scenarios was analysed with enabled and disabled elevators. The factors that are important for elevators usage are, most frequently, the floor level where occupants are located and the acceptable waiting time. Experience and research have shown that higher locations in residential buildings are more likely to imply elevator usage than usage of ordinary or emergency stairs. It is also important to note that the acceptable waiting time increases according to the height of the floor level (Kinatader et al, 2014).

One very important factor that has a great influence on the evacuation time is panic. Panic causes fearful and chaotic behaviour which is, most frequently, demonstrated with an increase of speed of occupants. This speed increment results in crowds and jams that can be very unpredictable and very hard to solve. It means that the evacuation time can be significantly extended, which the simulation results proved.

It is also important to note that, in reality, every occupant has his/her own speed, while in the simulation all occupants had the same speed. Also, in reality, occupants' personal characteristics are very different and can affect the overall evacuation time and cause problems in the crowd (Kady & Davis, 2009), (Jevtić, 2019b).

DISCUSSION

The usage of simulation software for simulating the evacuation in high-rise buildings is becoming more frequent and more extensive. The main reasons for that are: increase of safety in order to protect as many human lives as possible; increasingly frequent construction of high-rise buildings with a huge number of occupants; prediction and determination of optimal evacuation routes; prediction of potential occupants' behaviors, etc.

There are many residential buildings with and without emergency stairs. Very often, emergency stairs in residential buildings can be useless because of many reasons (fire, earthquake, smoke, jams, etc.) so that the only way to the exit is via ordinary stairs and elevators. As it has been noted before, the usage of elevators in many crises that need evacuation, such as fires or earthquakes, is not recommended. It does not mean that

elevators should not be used at all but that there is a significant risk if they are used. This is a very important reason why evacuation simulations should be considered for cases with and without elevators usage. In some situations that can occur in high residential buildings or other objects with a significant presence of immobile persons, it is almost impossible to realize evacuation without elevators usage. The obtained results confirmed that the evacuation times were shorter in the cases where the elevators were enabled.

One very important factor in every evacuation is a so-called „human factor”. This factor presents a very complex factor in sense of prediction and calculation. For example, people will not behave in the same way individually and in a group. During evacuation, parents will always tend to run towards their children which can significantly complicate the evacuation. Frequently, occupants in high residential buildings in disaster cases show apathetic behavior and non-acceptance of obvious facts. Taking into account many important factors related to occupants in simulations (occupants physical dimensions, occupants' reduction factor, occupant comfort distance, occupants slow factor, speed, and many others) presents a very important task that demands knowledge from different sciences and disciplines.

The obtained simulation results were in the range of the obtained simulation results in similar cases. It is a very good and accurate way to compare the obtained simulation results with calculated results and experimental results, since it is not always possible to carry out such experiments in reality (Ding et al, 2017), (Poon, 1994), (Kasereka et al, 2018), (Rozo et al, 2019), (Xing & Tang, 2012).

CONCLUSION

The results obtained in this paper have shown the maximum evacuation times in a building without emergency stairs with and without elevators usage. In reality, it is unlikely that, for example, all three entrances/exits are blocked, maybe only in case of a huge fire or a huge earthquake. However, it is very important to predict as many evacuation scenarios as possible and calculate adequate evacuation times.

Calculation of evacuation time and prediction of the best evacuation route presents a very complex and responsible task. Very often, it is almost impossible to predict every potential situation than can occur during evacuation. Because of that reason, usage of simulation software presents a very good, effective, cheap, and safe way for predicting potential evacuation situations in many different objects, which gives this topic great importance and motivation in order to save human lives and material properties. The main contributions of this paper are in its potential to determine optimal evacuation routes and calculate evacuation times in high buildings with or without emergency stairs, taking into consideration the influence of many different mentioned factors that can affect the evacuation progress and complete the evacuation epilogue.

Future investigations will relate to a simulation of evacuation with the presence of immobile persons of varying degrees of immobility, a simulation of evacuation via spiral staircases, a simulation of evacuation under different conditions, etc.

The usage of simulation software for the prediction and calculation of optimal evacuation routes can significantly improve the procedures and strategies of evacuation from some specific objects such as residential buildings.

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