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SADRŽAJ - ***CONTENTS:***

Example of evacuation simulation from a high-rise residential building

Primjer simulacije evakuacije iz visoke stambene zgrade

dr. sc. Radoje Jevtić

SUMMARY

Modern high-rise residential buildings are facilities designed for the residence of a great number of people (men, women, kids, the disabled). With a great increase in the human population in cities, there is a lack of space which is the cause of ever-larger and taller buildings. This is especially characteristic of residential buildings. New technologies enable the construction of high-rise buildings with impressive architectural solutions and a very big number of tenants. However, the larger and the higher these facilities are, the more complicated they are to evacuate. Every residential building can be compromised by a variety of factors: fire, explosion, terrorism, earthquake, or else. Very often, partial or complete evacuation of tenants must be carried out. This paper was written to show the importance of analysing all possible factors and using all available resources to predict evacuation situations and protect human lives and material values as much as possible. The prediction of evacuation situations in this paper was realized by simulation.

Keywords: evacuation, building, humans, simulation.

Sažetak

Moderne visoke stambene zgrade predstavljaju objekte projektirane za stanovanje velikog broja ljudi (muškaraca, žena, djece, invalida). S velikim porastom ljudske populacije u gradovima, dolazi do nedostatka prostora što je uzrok sve većih i viših objekata. *Ovo je posebno karakteristično za stambene zgrade. Nove tehnologije omogućavaju konstrukciju visokih zgrada s impresivnim arhitektonskim rješenjima i velikim brojem stanara. Ali,* što *su ovi objekti veći i viši, to su kompliciraniji za evakuaciju.*

Svaka visoka zgrada može biti ugrožena različitim faktorima: vatra, eksplozija, terorizam, potres ili neki drugi faktor. Veoma često, *djelomična ili potpuna evakuacija stanara mora biti realizirana.*

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Ovaj rad je napisan sa ciljem da prikaže važnost analize svih mogućih faktora i korištenje svih raspoloživih resursa za predviđanje evakuacijskih situacija i zaštitu ljudskih života i materijalnih vrijednosti. Predviđanje evakuacijskih situacija u ovom radu realizirano je simulacijom.

Ključne reči: *evakaucija, zgrada, ljudi, simulacija*

INTRODUCTION

Uvod

The rapid growth of the human population all over the world implies the lack of space in cities and other settlements. One of the potential solutions for this problem is the construction of higher and higher residential buildings that can accept a lot of tenants. As an example, Khalifa Tower in Dubai can be noted with a height of 828 m, Shanghai Center Tower with a height of 632 m in China, Abraj Al Bait with a height of 601 m in Saudi Arabia, Shanghai World Financial Center with a height of 492 m and other. According to some resources, only in 2015, 106 high-rise buildings with a height of over 200 m were completed all over the world (http: //www.chinaasc. org/ news/zonghexiaoxi/20160313/112025.html, (accessed 11:02:00). The design and construction of one such building are always hard, complex, and open tasks. It is considered that New York has the highest standards and law regulations regarding high-rise buildings construction, and passive fire protection solved by the statute (http:// sindikatvatrogasaca.org.rs/1487-gasenje-visokih-objekata-i-evakuacija/). What is the definition of a high building? According to some resources, high buildings present multi-story structures where most tenants must use elevators (lifts) to reach their destinations. Those structures somewhere can be called "high-rise buildings", or, in some countries as "tower blocks" (Challinger 2008). According to other definition, a high building is any structure where the height has a great influence on the tenant`s evacuation. According to NFPA (National Fire Protection Institute), high buildings present structures higher than 75 feet (about 23 m), where the building height presents the measured value from the lowest level of fire department vehicle access up to the highest occupied floor (NFPA 2012).

However, the height and number of modern buildings keep increasing from year to year, but the evacuation methods and procedures are, in most cases, the same and unchanged. That implies that the largest number of high buildings use stairs, emergency stairs, evacuation elevators or some combination of all three noted possibilities.

a.

b.

Figure 1. September 11, 2001-Was it possible to realize any kind of evacuation? (Figure a. source: https://www.google.rs/search?q=september+11+2001+disaster%2Bslike&tbm=isch&tbo=u&source=univ&sa=X&ved=2ahUKEwiMpvDhl7XdAhUMNOwKHXIaCyIQsAR6BAgGEAE&biw=1366&bih=631#imgrc=4a2TSDHd156VpM:, figure b. source: https://www.google.rs/search?q=september+11+2001+disaster%2Bslike&tbm=isch&tbo =u&source=univ&sa=X&ved=2ahUKEwiMpvDhl7XdAhUMNOwKHXIaCyIQsAR6BAgGEAE&biw=1366&bih=631#imgrc=qA3e_eewiFcYFM:)

Slika 1. 11. rujan – Da li je bilo moguće realizirati bilo kakvu evakuaciju (izvor slike pod a: https://www.google.rs/search?q=september+11+2001+disaster%2Bslike&tbm=isch&tbo=u&source=univ&sa=X&ved=2ahUKEwiMpvDhl7XdAhUMNOwKHXIaCyIQsAR6BAgGEAE&biw=1366&bih=631#imgrc=4a2TSDHd156VpM:, izvor slike pod b: https://www.google.rs/search?q=september+11+2001 +disaster%2Bslike&tbm=isch&tbo =u&source=univ&sa=X&ved=2ahUKEwiMpvDhl7XdAhUMNOwKHXIaCyIQsAR6BAgGEAE&biw=1366&bih =631#imgrc=qA3e_eewiFcYFM:)

The fast and safe evacuation from the high-rise building has become a very serious problem (multiple floors, the concentration of people, panic and stress effects) that demands a detailed and large research (Zhang 2017).

A tragic event on September 11, 2001, initiated hard and studious research about quick evacuation from high-rise buildings. This event showed that regardless of the excellent fire protection systems, sufficient number of elevators and emergency stairs, surprises are always possible and the number of human victims can be enormous. Many new strategies and many new approaches started to be considered and realised from the moment of this tragic event. So, the logical question follows - was it necessary for this event or similar ones to happen to start with the consideration, application and realisation of different new methods and strategies of evacuation? Some scenes of this event are presented in Figure 1, under a and b.

It can be said that the traditional evacuation method (sometimes the only one) is the evacuation by stairs. Stairs can be constructed in different ways, based on a different concept. The construction of stairs demands investigation and research of different parameters, such as the position of the stairs in a building, their number, width, slope, the dimensions of the riser and tread, the material the stairs are built from (at the first place its fire resistance), and similar (Pauls, 2005), (Ronchi et al 2013). It is often very difficult to find and choose the best evacuation route, so it is recommended to place the stairs near the elevator.

The use of elevators for evacuation has always presented an open problem and an important question. It can be found that the research about the evacuation by elevator started in the thirties in the last century (Bukowski 2009). The recommendation of many approaches implies that the elevators should not be used during evacuation (Glavinić & Rašković 2016). Many problems can occur in elevators during evacuation. The elevators have limited space and in the case of the evacuation, more tenants can enter inside the elevator than it is allowed, which implies that the elevator could be stuck or crash. In addition, especially in the case of fire, the elevator shafts present places where fire products, such as smoke, flame or heat can easily invade. One of the most dangerous things is the occurrence of carbon monoxide (CO) in elevators. This gas is easier than the air (28 gr/mol) so its position is always in the upper layers of some room or a facility. Also, this gas is an explosive-its band of explosion or explosive field is very wide (explosive lower limit amounts to 12.5 of volume percentages, while the explosive upper limit amounts to 74.2 of volume percentages (Group of authors 1987). Besides carbon monoxide, other dangerous gasses can also appear (carbon dioxide (CO_2), hydrogen sulphide (H_2S), phosphor derivatives, and other). The occurrence of the so-called piston effect is also possible - when the elevator moves, the smoke is sucked inside by negative pressure (Chien & Wen 2011).

However, this concept has been valid in the case of high-rise residential buildings, in order to provide fast evacuation, especially for people with disabilities and for people that need assistance. According to some calculations, in the case of buildings higher than 350 m, the evacuation time could be longer than several hours, and provided that the complete evacuation goes in perfect order, which is unlikely to happen. Also, one of the most important factors is the behaviour under pressure and stress – and although the assistance to the tenants with disabilities is humane and, in the end, necessary, it is very questionable would they be in a condition to think that way under the influence of flame, smoke, fire, heat, crush, screams, and many other factors that can significantly influence tenants behaviour (Nilsson & Jönsson 2011).

One of the possible evacuations from high-rise buildings is the usage of sky bridges. This is not a new concept-it was noted that one of the first sky bridges was realized in Venice in the 17th century (Wood et al 2005). Sky bridges are used to link buildings at the level upper than ground level. One of the greatest benefits of this way of evacuation is the significant reduction of the vertical evacuation travel distance. Of course, there are several problems related to this way of evacuation- planning, realisation, costs, efficiency, and other (Ronchi. & Nilsson 2013).

According to the noted facts, it is obvious that is very hard to design, predict, realize, and test maximal secure and safe evacuation. So, it is very important to somehow predict the maximal number of potential evacuation options that should occur. This must be done in a maximal accurate, safe, and financially economic way. The simulation software presents an excellent tool for noted tasks.

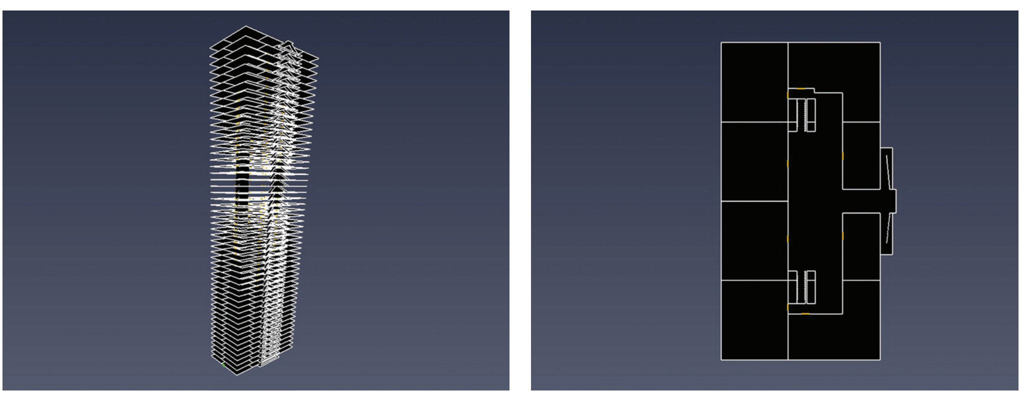
The use of computer technologies and computer software can have a great role in evacuation. Computer technologies are of great significance regarding the dynamics of information during the evacuation, of critical routes, and potential jam points. Computer modelling and simulations are very important for the creation of virtual scenarios and predictions. Using simulation, the crowd behaviour can be analysed and the potential danger points in the facility can be determined: the older tenants move more slowly, while the younger and children move faster; the tenants would commonly stuck together in case they are member of the same family, while in other cases they usually keep distance from anyone unknown. Also, they can have an important role in the evaluation and estimation of standards and technical regulations. Many simulation software can be successfully used for noted tasks, such as Pathfinder, PyroSim, Exodus, Evac tunnel, and others. Of course, the experimental check is always recommended when it is possible (Laban et al 2015; Jevtić & Blagojević 2013; Jevtić 2014; Yunchun 2014).

This paper was written to show potential evacuation scenarios and calculate the potential evacuation times in evacuation of the high-rise residential buildings realized by simulation software.

SIMULATION MODEL-*Simulacijski model*

The simulation model for this paper was simulated in Pathfinder software, version 2018. This software was specially designed as a graphical user interface for simulation design and execution. The software enables two-movement simulation models: steering and SFPE. The software also enables us to import files designed in other software such as PyroSim, FDS, 3D Cad, or else which significantly reduces the time and improves the visual presentation of the project (Thunderhead 2018; Jevtić 2016; Jevtić 2015).

The simulated object presents a high-rise residential building constructed as two connected buildings. Each building has a basement and 50 floors. The height between floors is 2.6 m. The maximum height of each building is 132.6 m. The maximal base surface of each building is 400 m^2. Every floor in both buildings, except the basement, consists of four flats, four elevators, ordinary stairs and an exit to the emergency stairs. The surfaces of flats are 84 m^2, 84 m^2, 87 m^2 and 47 m^2. Each flat has ordinary rooms (bedrooms, sitting rooms, kitchen, bathroom, anterooms, and



a. b.

Figure 2. Pathfinder building simulation model, view of the whole building (a) and top view (b)

Slika 2. Simulacijski model zgrade u Pathfinder-u, prikaz cijele zgrade (a) i prikaz odozgo (b) hallways) with ordinary furniture (beds, desks, dressers, and similar). The width of every flat`s door is 90 cm. The width of the outer building doors is 200 cm. The width of ordinary stairs is 105 cm while the width of the emergency stairs is 120 cm. Both buildings are connected to the emergency stairs by the hallway of a 3 m width. The surfaces of the two smaller elevators are 1.32 m^2 (1.2 m x 1.1 m) and of the two bigger elevators are 3.19 m^2 (3 m x 1.06 m). The Pathfinder presentations of the simulation object, the whole building from the side, and top view of the whole building are presented in Figure 2, under a and b.

According to the presumption that each flat has four tenants (two over 30 years of age and two under 30), it was set that the total number of tenants was 1632 (4 by flat, 32 by floor counting in both buildings) at 51 floors. The tenants were in their flats at the moment the simulations started. There were four potential scenarios analysed.

The first scenario implied evacuation from the building using the ordinary stairs only. The second scenario implied evacuation from the building using the emergency stairs only. The third scenario implied evacuation from the building both using the ordinary stairs and the emergency stairs. The fourth scenario implied evacuation from the building using the ordinary stairs and the elevator. Each one of the four scenarios was realized for different speeds of tenants: 0.8 m/s, 1 m/s, 1.2 m/s, and 1.4 m/s, while the elevators speeds were 1.7 m/s (smaller elevators) and 1,1 m/s (bigger elevators) for each scenario.

SIMULATION RESULTS- *Simulacijski rezultati*

All simulations for the purposes of this paper were realized on laptop HP 15-bs018nm - 2GS52EA, with the processor model Intel® Celeron® N3060 at 2.48GHz, 500GB HDD, and 4GB of RAM. Some of the simulation moments from different scenarios are presented in figures from 3 to 5, while the complete simulation results for all four scenarios are presented in figures from 6 to 9.

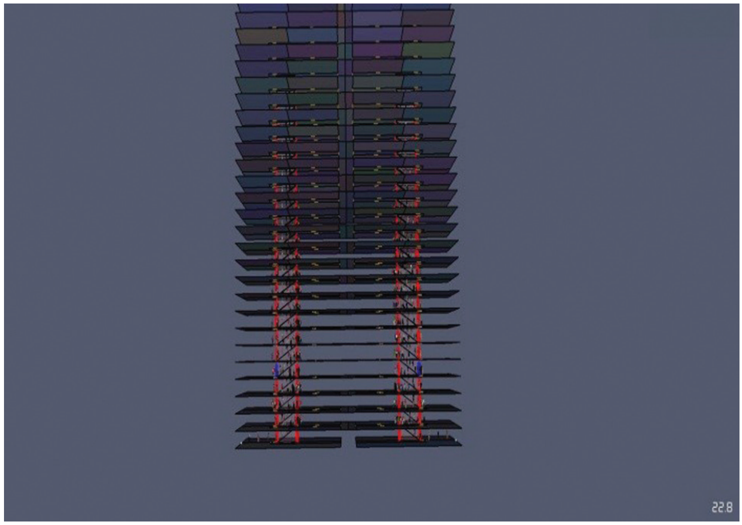


Figure 3. Simulation moments from the third scenario after 22.8 seconds after the simulation started for the tenant`s speed of 1 m/s.

Slika 3. Simulacijski momenti iz trećeg scenarija poslije 22.8 sekundi od početka simulacije za brzinu stanara od 1 m/s.

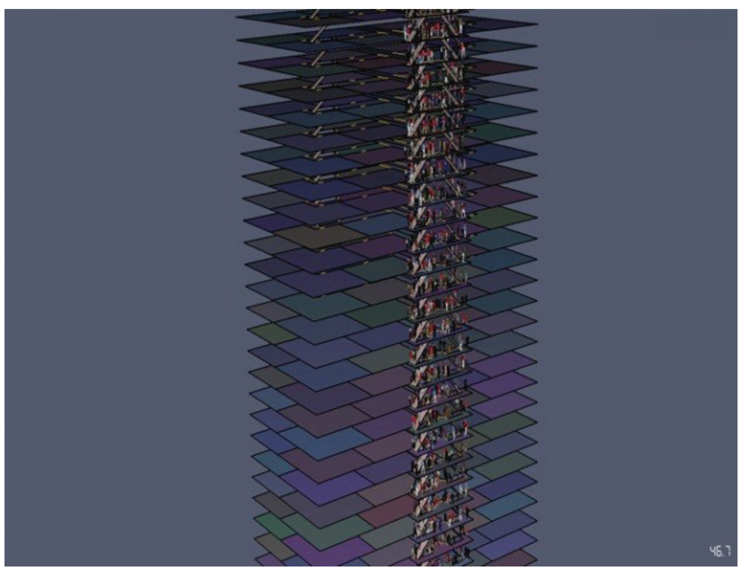


Figure 4. Simulation moments from the second scenario after 46.7 seconds after the simulation started for the tenant`s speed of 1 m/s.

Slika 4. Simulacijski momenti iz drugog scenarija poslije 46.7 sekundi od početka simulacije za brzinu stanara od 1 m/s.

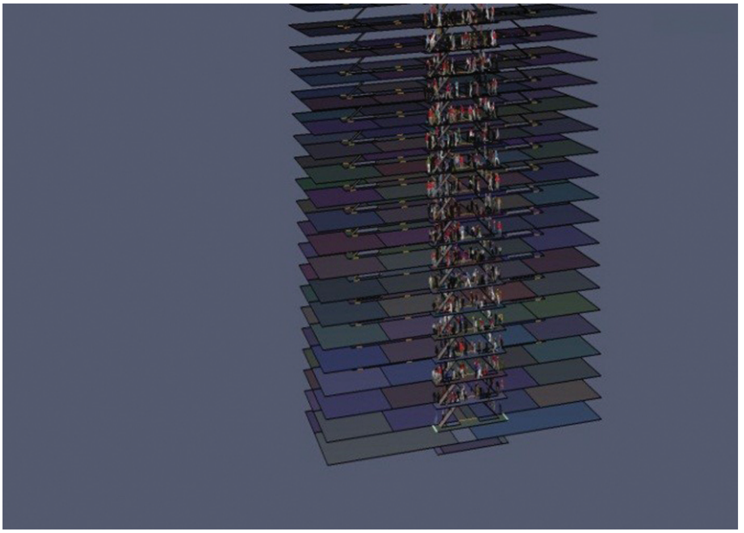


Figure 5. Simulation moments from the second scenario after 321.0 seconds after the simulation started, for the tenant`s speed of 1 m/s.

Slika 5. Simulacijski momenti iz drugog scenarija poslije 321.0 sekunde od početka simulacije za brzinu stanara od 1 m/s.

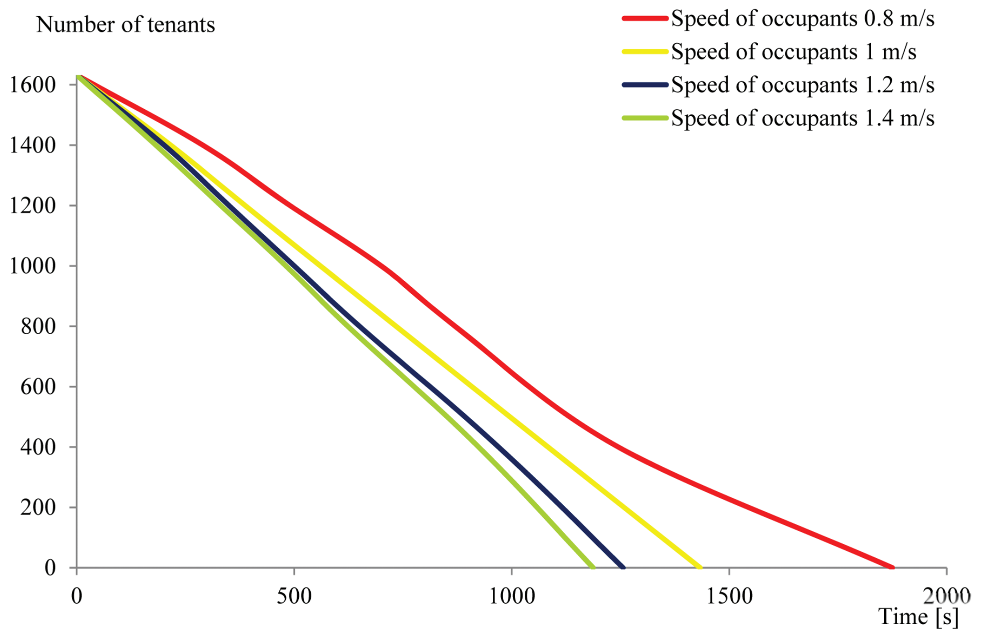


Figure 6. The complete simulation results for the first scenario

Slika 6. Kompletni simulacijski rezultati za prvi scenarij

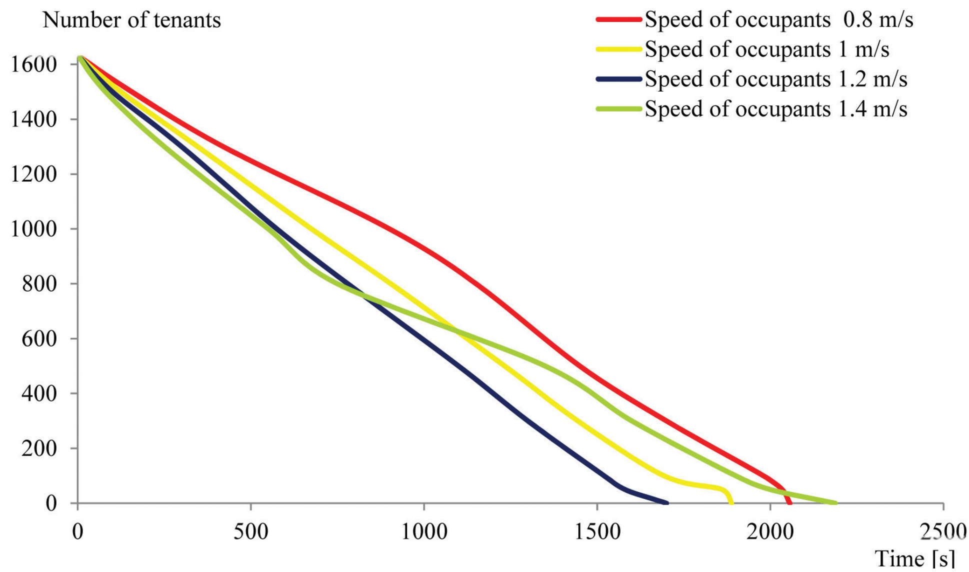


Figure 7. The complete simulation results for the second scenario

Slika 7. Kompletni simulacijski rezultati za drugi scenarij

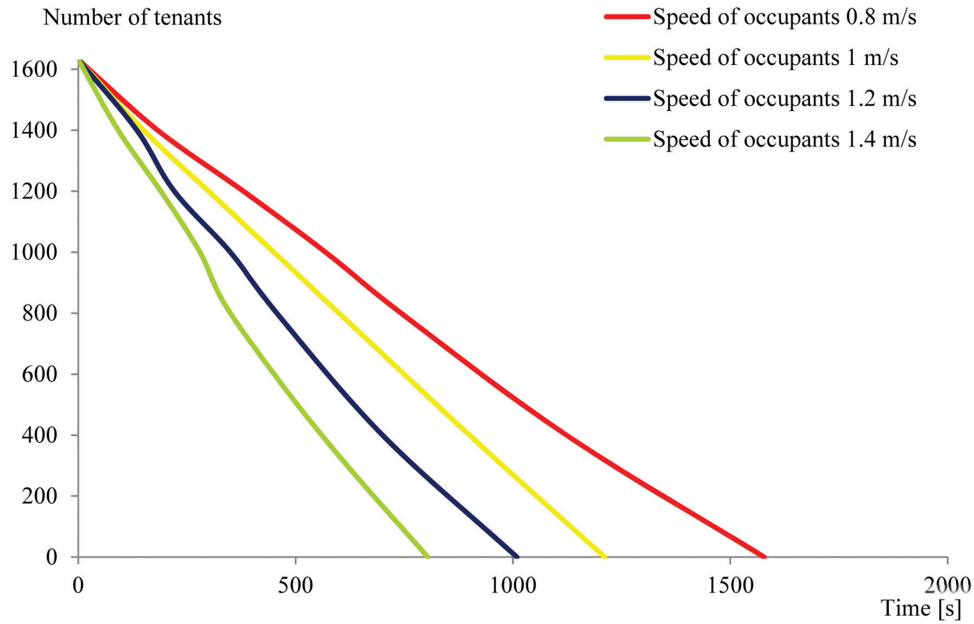


Figure 8. The complete simulation results for the third scenario

Slika 8. Kompletni simulacijski rezultati za prvi scenarij

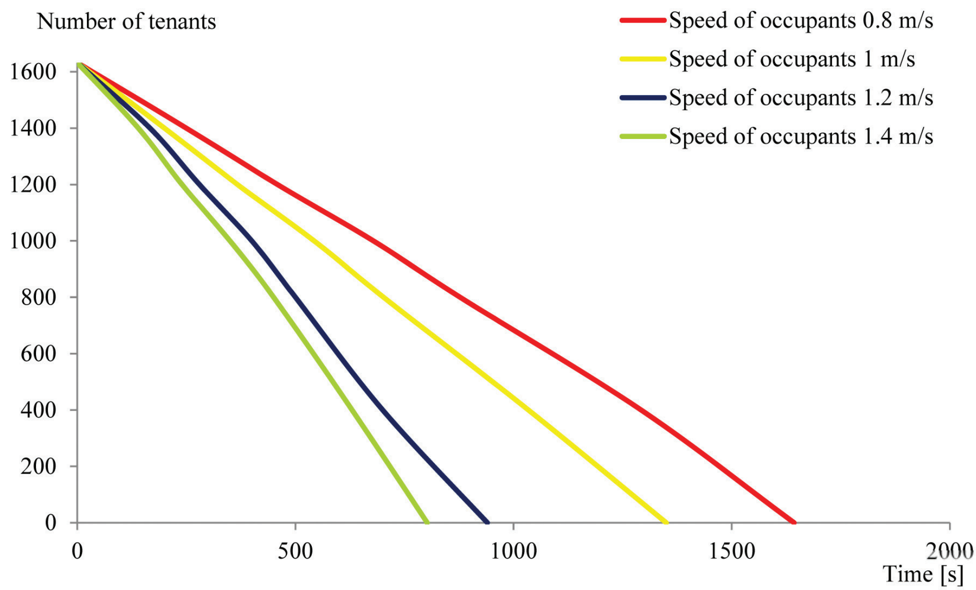


Figure 9. The complete simulation results for the fourth scenario

Slika 9. Kompletni simulacijski rezultati za četvrti scenarij

RESULTS ANALYSIS-*Analiza rezultata*

The results for the first scenario showed that all of the tenants succeeded to evacuate from the building. The longest evacuation time was for the tenants with the tenant's speed of 0.8 m/s (1875.12 seconds), while the shortest time was for the tenants with the tenant's speed of 1.4 m/s (1187.34 seconds). The potentials for jams were appearing at the tenant's speed greater than 1.61 m/s.

The results for the second scenario also showed that all of the tenants succeeded to evacuate from the building. The longest evacuation time was for the tenants with the tenant's speed of 1.4 m/s (2456.79 seconds), while the shortest time was for the tenants with the tenant's speed of 1.2 m/s (1700.53 seconds). The potentials for jams were appearing at the tenant's speed greater than 1.54 m/s.

The results for the third scenario also showed that all of the tenants succeeded to evacuate from the building. The longest evacuation time was for the tenants with the tenant's speed of 0.8 m/s (1578.04 seconds), while the shortest time was for the tenants with the tenant's speed of 1.4 m/s (804.93 seconds). The potentials for jams were appearing at the tenant's speed greater than 1.55 m/s. The tenants in this scenario were divided into the tenants that used ordinary stairs and the tenants that used emergency stairs. More tenants used the ordinary stairs.

The results for the fourth scenario also showed that all of the tenants succeeded to evacuate from the building. The longest evacuation time was for the tenants with the tenant's speed of 0.8 m/s (1643.56 seconds), while the shortest time was for the tenants with the tenant's speed of 1.4 m/s (802.12 seconds). The potentials for jams were appearing at tenant's speed greater than 1.67 m/s. This scenario was particularly interesting. The realised results were related to the tenants' behaviour to use the nearest way to the exit and to wait for the appropriate elevator for no more than 30 seconds. But, for the other forms of behaviour (for example, that the tenants from the upper third or half of the building used the elevator while the rest used the stairs) results could have been different in terms of the evacuation time decreasing or (if more than three-quarters of the tenants waited for the elevators no more than 30 seconds, for example) in terms of increasing the evacuation time. In addition, it is very important to note that these speeds were not chosen randomly; according to some statistics and experimental results and measuring, the speeds greater than 1.5 m/s to 1.65 m/s for the tenants moving downstairs is hardly achievable, particularly with the bigger density of tenants related to the surface. However, there are a lot of possibilities that can be set and calculated and, according to that results, it can be decided which evacuation strategy to apply (Ma et al 2012; Alesandrov et al 2015; Proulx 2001).

SAFETY ASPECTS OF USING SIMULATIONS FOR OCCUPANTS- *Sigurnosni aspekti upotrebe simulacija za stanare*

It is very important to note that all of the tenants had the same speed and that every installation used for all four scenarios was correct (stairs, elevators, doors), which is unlikely in reality. In the state of panic and fear, tenants can hardly control themselves, and, what is probably the most important, they can hardly calm down as much as possible and think clearly. All of that leads to the fact that the tenants move at higher speeds, where the possibilities for faltering and falling are significantly higher which, with the presence of the flame, smoke, fire, or other factors can cause situations that can be very hard to realize in the used software or experimentally. The statistics showed that humane aspects of tenants in noted situations declined significantly – it is hard to expect that someone who is under stress, fear, in a hurry and who was not properly educated to have regard for other persons. The tenants were introduced to the basic procedures and rules in the case of fire and evacuation. Also, the presence of other often present psychological factors such as stress, fear, some of the tenant`s death, wound, blood, panic, or similar lead to hardly predictable situations with, in most cases, tragic epilogue.

The simulation presentations of such situations are of great significance in the education of the tenants that reside in high-rise buildings. The tenants were introduced to the basic procedures and rules in the case of fire and evacuation. Also, they were introduced to the basic psychological technics that could help them calm themselves, in the first place, and influence other tenants to calm themselves as well, which leads to calm behaviour that significantly increases chances for fast, safe, and effective evacuation. Only properly educated tenants can give themselves and others, and of course, the fire-fighters the maximum assistance in evacuation. (Vorst 2010; Luh 2012; Živaljević & Jugović 2014; Gaćinović 2012; Nair 2016; Suvek at al 2018).

The presence of tenants with disabilities is a very important factor for evacuation. It is likely that tenants with disabilities live in high residential buildings. These tenants can be in a wheelchair, medical bad or they can use other kinds of apparatus for their movement and functioning. This automatically implies that they need help and assistance from other persons; otherwise, they can hardly or no way evacuate themselves or can cause jams and other problematic situations.

The tenants in a medical bed ordinarily have other apparatus installed with them (ECG, infusion pack, lung device, or similar), which significantly complicates the evacuation and makes it harder. Using simulation for those cases significantly improves the insight into the potential situations so as into the choice for the best evacuation solution in terms of the tenants' safety. In this case specifically, the presence of the tenants with disabilities or the tenants who have difficulty moving, doesn't affect the total evacuation times because their number was not big. But, in other cases, their influence can be significant, even fatal (Wilson 2015; Department for Health, Social, Services and Public Safety 2011; Jevtić 2018; Jevtić 2019).

CONCLUSION AND FUTURE RESEARCH-*Zaključak i buduća istraživanja*

The results of the realised simulation showed that, according to the dimensions of the building and elevators' capacity and speed, the fastest evacuation would be in the case of the third scenario, when the tenants were divided into the groups that used ordinary stairs and the emergency stairs. For greater elevators' speeds and for shorter elevator waiting time, the fastest evacuation would be definitely by using the elevators. The results also showed the evacuation situations that could take place under the influence of some factors such as fire, earthquake, terrorism, or else. It is not always possible to use every predicted evacuation route and resources; very often it is necessary to change the evacuation direction, route, or even a rule, and all of that under stress, panic, fear, and with the presence of a threat. So, it is always an open question what is the best thing that could be done in a particular situation? Which is the way to realise the fastest evacuation, with none or minimal human victims?

Obviously, the use of simulation software can certainly solve a great part of these problems. Using the computer simulation software, it is possible to design a great number of potential evacuation scenarios and analyse them without any danger. Many of them cannot be experimentally confirmed, so it is very important to have a good and wide knowledge and experience to, as much as possible, design real evacuation situations. The analyses of a large number of evacuation situations under the influence of different factors (tenants' speed, elevators' speed, elevator waiting time, position and dimensions of the emergency stairs, and many others) can significantly improve the efficiency, safety, and speed of evacuation, especially for firefighters (Li et al 2014; Cocking and others 2012; Gerges 2017).

This and similar papers present a very good base for future investigation in terms of reducing the evacuation time and increasing the safety of tenants and the total number of the saved tenants. Of course, their permanent perfection is important in order to reach higher accuracy. In relation to that, the use of less typical modern evacuation procedures and ways and their implementation in proper computer software is particularly interesting. For example, a very interesting way of tenants' evacuation from a high-rise residential building is by using the spiral stairs, fire evacuation chutes, special spirals, so-called SOS parachutes (can open at 100 feet) or the so-called "dragons" - made of canvas on the aluminum crossed poles.

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