SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2025
ORGANIZATION AND MANAGEMENT SERIES NO. 229

DETERMINATION OF EVACUATION TIMES OF EMPLOYEES FROM A PRODUCTION AND SERVICE BUILDING USING A COMPUTER APPLICATION

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Purpose: This paper presents the results of a computer simulation of the evacuation of employees from a manufacturing and service building. Pathfinder specialist software was used to carry out the simulation. As part of the research described in the article, a digital model of the analysed building was created, taking into account its architectural layout, the number and distribution of employees and the available evacuation routes. A number of simulations were carried out for different hazard scenarios and variants of space organisation and occupant behaviour. Based on the results, evacuation times were determined and possible bottlenecks and elements that need to be optimised in order to improve employee safety during emergencies were identified.
Design/methodology/approach: The main objective of the article was to examine the evacuation times of employees from the building. The article uses the results of computer simulations and trial evacuations of employees from the building.
Findings: The results obtained made it possible to check the time differences between the actual evacuation and the results of the computer simulation of the evacuation. In addition, the assumption of different scenarios in the computer simulation made it possible to determine the evacuation times when additional obstacles to its implementation occurred.
Practical implications: The results obtained made it possible to verify the effectiveness of evacuation for various emergency scenarios occurring in the analysed company.
Originality/value: The article is aimed at companies that, by using computer simulation for employee evacuation, can assume various evacuation scenarios and thus apply procedures to ensure the safety of employees in the event of an emergency.
Keywords: safety, evacuation, computer simulation, fire.
Category of the paper: research paper, case study.

1. Introduction

The primary duty of the employer is to ensure the safety of employees in the workplace. This obligation is fulfilled by means of the organizational measures taken and the technical means used, both in the area of occupational health and safety and the area related to the safety of the buildings and grounds on which employees work. In both of these spaces, the employer's actions result from the implementation of current regulations, which the employer's relevant departments monitor with regard to changes in new obligations and legal requirements. In accordance with the current provisions of the Decree of the Minister of Internal Affairs and Administration of June 7, 2010 on fire protection of buildings, other buildings and grounds (2023), more specifically - chapter 4, paragraph 17a, an obligation is imposed to conduct a trial evacuation in a building with more than 50 permanent occupants.

Checking the time to get all building occupants outside, if necessary, is a key element for life safety. In existing buildings, there is no problem with conducting a test evacuation in the organization, due to the participation of those responsible for health and safety at the enterprise and ensuring fire safety, as well as representatives of the State Fire Service. The situation may be different when constructing new buildings or carrying out construction work on the premises of existing buildings (reconstruction, expansion) if there are design or execution errors that require carrying out additional construction work or obtaining a variance in the scope of a particular provision, for example, when the building does not meet the maximum length of the evacuation access, an evacuation simulation is carried out, which reproduces the time of potential evacuation. This simulation is intended to show that despite the fact that all building requirements are not met, the safety of users will not be affected.

Using modern evacuation simulation software, it is possible to accurately plan the most effective evacuation routes and predict how people will move in emergency situations. The results obtained from the simulations are used by the employer to improve the safety of employees in emergency situations requiring evacuation, such as fire, chemical spills or terrorist threats. The primary purpose of conducting simulations is to identify potential hazards, traffic bottlenecks and evaluate the effectiveness of evacuation procedures. The models adopted in simulations allow a realistic representation of the behavior of people in the above-mentioned emergency situations, the literature distinguishes several main approaches to evacuation modeling: macroscopic models - e.g., flow-based models in which the crowd is treated as a liquid (Hughes, 2002), microscopic models - focus on the individual behavior of people, e.g., Agent-Based Modeling, where each worker is represented by an independent agent with specific characteristics and decisions (Pan et al., 2006), Cellular model - space is divided into a grid and simulated people move according to specific rules (Blue et al., 2001), Social Force Model - describes pedestrian behavior as a result of physical and psychological forces (Helbing et al., 2000).

Simulations are carried out using various programs and applications, e.g. Pathfinder - a tool based on the agent and force model, popular in building design, FDS+Evac - combines fire modeling (FDS) with human evacuation, AnyLogic - an agent modeling environment with extensive crowd simulation capabilities, A-evac (Aamks component) models human evacuation in a fire environment produced by a zonal fire model simulator.

The above-mentioned simulation models and software provide a very wide range of possibilities for application in industry. Boonmee et al., (2021) presented an integrated evacuation model for an industrial plant, combining multi-criteria decision analysis (MCDA) techniques with fire and evacuation simulation. The study used also Fire Dynamics Simulation to model fire development and Pathfinder to simulate agent evacuation. Various scenarios were analyzed, taking into account factors such as the location of the fire, the number of people and the presence of people with disabilities. Lu T et al. (2015) studied the influence of behavioral factors in evacuation, where an agent-based approach was used with varying levels of employee knowledge of exit placement and knowledge of procedures. Scenarios with low knowledge of procedures led to bottlenecks and chaotic crowd movement. In office buildings and skyscrapers, Ronchi et al. (2013) analyzed the effectiveness of evacuation using passenger lifts. In traditional systems, elevators are automatically deactivated during a fire.

However, simulations with Pathfinder and an additional queuing algorithm have shown that the use of elevators according to specific strictures (NFPA 101 standard) can significantly reduce evacuation times, especially for people with limited mobility. In a study by Alazbah et al. (2023), artificial intelligence (AI) techniques, particularly multi-agent systems (MAS), were used to build a simulation model of evacuation from hazardous locations. NetLogo was used as a simulation tool to comprehensively understand human behavior in hazardous environments, using AI and MAS, a simulation model was created to capture the complex dynamics of evacuation scenarios. Lovreglio et al. (2016) studied the behavior of office workers, analyzing the impact of stress levels and familiarity with the building on decision-making during an evacuation. The study used a virtual reality (VR) environment. Kuligowski et al. (2010, 2013) included empirical data from evacuees after the 9/11 attack in their analysis of the World Trade Center evacuation, the study found that lack of information and ambiguous messages were significant factors in delaying evacuation. Computer simulations confirmed that fast, unambiguous communication could reduce evacuation times by up to 25%.

Evacuation from a shopping center was analyzed by Cao et al. (2018), and the work included experiments and simulation modeling at different levels of visibility, analyzing the evacuation behavior of evacuees under conditions of good and limited visibility, focusing on the choice of emergency exits and evacuation time. The results showed that limited visibility significantly affects evacuation decisions and can lead to delays in exiting a building. Niu et al. (2023) presented a study that used an improved version of the YOLOv5s model in conjunction with AnyLogic to simulate emergency evacuation. The study focused on analyzing crowd behavior under conditions of reduced visibility due to smoke and optimizing evacuation strategies based on video detection data. The results showed that integrating video detection data with agent-based simulations can significantly improve the effectiveness of emergency evacuation.

This paper presents results from a simulation of employee evacuation from a service and production building using Pathfinder software. The research presented in the article and its results are original findings of work carried out by a researcher and a student who is a member of a research club, and are being published for the first time.

2. Methods and results

During the research work described in this article, two research methods were used: the experimental method, involving a physical evacuation from a building, and the computer simulation method, using the commercially available Pathfinder software. This choice was dictated by the nature of the article and the authors' access to a specific computer application.

In order to be able to evaluate the evacuation time of all people from the building, it is necessary to carry out a trial evacuation, this is usually done on the basis of an evacuation scenario, prepared by health and safety services. On the other hand, new possibilities are provided by a program used to simulate evacuation. The result of the evacuation time obtained as a result of the simulation is an information or warning for the employer about the possibility of problems during the evacuation of employees. Before the actual evacuation as well as carrying out its computer simulation, technical data must be established, such:

- fire resistance class,
- fire load density,
- human hazard category,
- number and area of fire zones,
- the height category of the building and the use of the zones.

Having established the above-mentioned parameters in the enterprise, compliance with the regulations on escape routes, the width and number of emergency exits, signage, water supply for external firefighting, the number and filling of fire extinguishers, the efficiency of fire extinguishing systems, the layout of the fire route, the timing of inspections of equipment, the list of people familiarized with the fire safety manual in the production and warehouse building with office and social facilities was checked.

The longest passage in the hall is 115 m (allowed due to the height of the hall >5 m, which gives the possibility of extending the evacuation passage by 25%), in the gatehouse building 5 m and in the administration building 28 m, and in each case the passage does not exceed 3 rooms and has an appropriate width.

Emergency exits (Figure 1) located in the production and storage hall must open to the outside (condition fulfilled) due to the possibility of more than 50 people at once. Due to the insufficient anticipated number of people, the provision does not apply to the administrative part as well as the gatehouse building.

Figure 1. Emergency exit.

Source: Own elaboration.

Doors used to evacuate people from the hall and from the office building met the minimum width of min.1.2 m and 0.9 m respectively.

The length of the evacuation access is measured along the axis of the evacuation route, according to the wording of Article 256 of the Ordinance of the Minister of Infrastructure of April 12, 2002 on the technical conditions to be met by buildings and their location (2022), the length of the evacuation route from the exit of a room on this route to the exit to another fire zone or outside the building, hereinafter referred to as "evacuation access". If the evacuation access is terminated by a fire vestibule, this length is measured to the first door of this vestibule, the permissible lengths of evacuation accesses in different types of fire zones for production and storage (PM)/hazardous people (ZL) buildings are shown in Table 1.

Table 1.
Length of emergency accesses

Number	Type of fire zone	Length of access (m)	
		with one access	with at least 2 accesses
1	With explosive room	10	40
2	PM with fire load density Q > 500 MJ/m^2 without explosive room	30	60
3	PM with fire load density Q < 500 MJ/m^{2}without explosive room	60	100
4	ZL I, II i V	10	40
5	ZL III	30	60
6	ZL IV	60	100

Source: Own elaboration based on: Regulation of the Minister of Infrastructure of April 12, 2002 on technical conditions to be met by buildings and their location.

In the hall area, the length of the access does not exceed 70 m (allowed 100 m due to the presence of more than one access in the zone), while in the office building, which also has more than one evacuation access, the length does not exceed 30 m.

An additional factor that contributes to a more efficient exit from any place in the hall or social and office building are visible signs (at least one), so that you know which way to go to get to the nearest emergency exit (Figure 2).

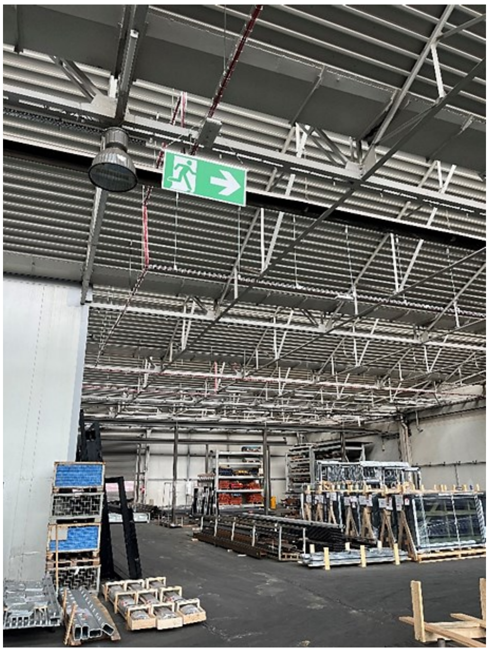

Figure 2. Evacuation sings.

Source: Own elaboration.

After analyzing the regulations on the efficiency of movement along evacuation routes to the outside or to an adjacent fire zone, it was concluded that technical conditions should not negatively affect evacuation times. In addition, the distribution of fire extinguishing agents in key locations and evacuation routes was also checked. It was found that they were selected in accordance with the regulations, i.e. for each 100 m^2 of the zone classified as a human hazard, min. 2 kg of extinguishing agent and, in the case of a zone classified as production and storage, for every 300 m^2 also min. 2 kg of extinguishing agent. In the fire zone classified as PM, internal hydrants have been placed to provide water coverage over the entire area of the hall. According to the provisions of §6(3) of the Regulation of the Minister of Internal Affairs and Administration of July 24, 2009 on fire water supply and fire roads (2009), the basis for adopting the calculation of the amount of water needed for the entire plant is the fire zone requiring the largest amount of water, i.e. 30 l/s. Using the same provision, a compliant fire road was brought to the plant. Due to the volume exceeding 1000 m^3, a fire safety instruction was developed, regularly updated every two years, and the facility was secured with a fire circuit breaker, which cuts off the flow of electricity to all circuits excluding those needed during a fire.

2.1. Running simulations using Pathfinder software

The first stage of the work was to model the geometry of the object. To do this, a CAD file in a suitable format (e.g., DWG or IFC) was imported, and if necessary - missing elements were completed or drawn directly in the Pathfinder editor (Figure 3). Care was taken to ensure that all relevant building components, such as walls, doors, staircases, elevator shafts and emergency exits, were correctly mapped. The floors were then defined - each level was assigned a height and its connections to other levels were defined, creating logical connections (stairs, ramps, vertical passages).

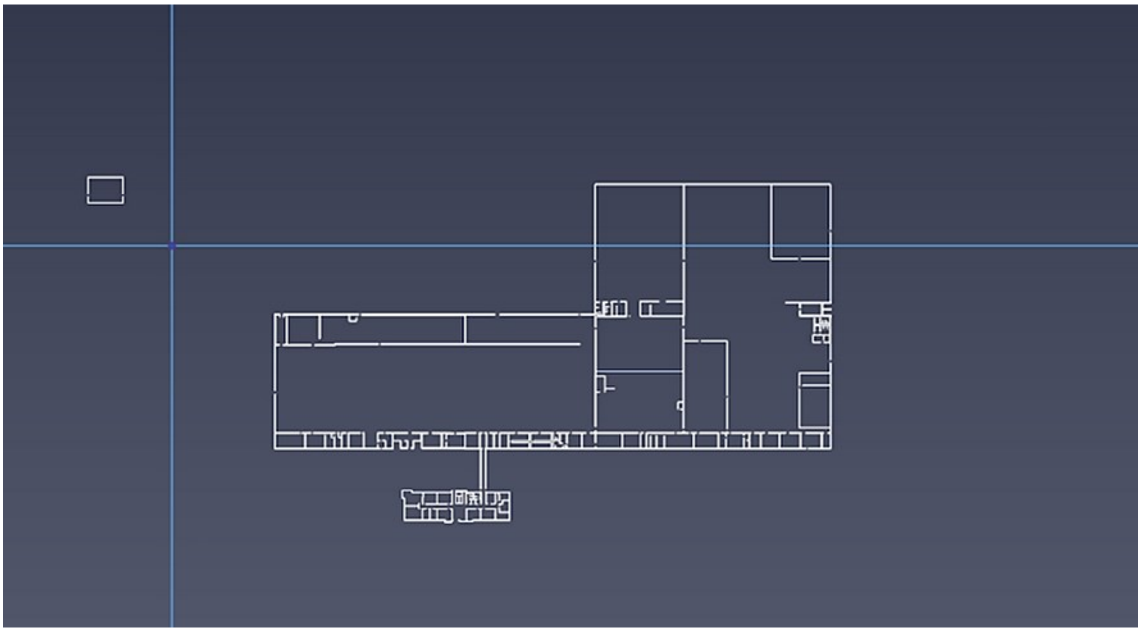

Figure 3. Imported projections to Pathfinder.

Source: Own elaboration.

In the following part, the usable area of the building (Figure 4) and the space surrounding the plant were determined, which made it possible to simulate the removal of people to the assembly areas, as shown later in the article in Figure 7. In the later stage of the work, on mapping the space of the building, more than 100 m^2 of free space was removed due to the locations of industrial machinery or racks, so that this space was not included in the simulation performed by the computer application. The program requires the user to map the area in such a way as to ensure the free movement of workers and other people scheduled for evacuation. Subsequently, doorways with a minimum width of 0.9 m were plotted according to the actual situation based on the floor plan, and a staircase with a mezzanine floor was added (Figure 5), which makes it possible to simulate the evacuation of people on the upper floor. Traffic on the staircase was adopted in accordance with the standards-right-hand traffic.

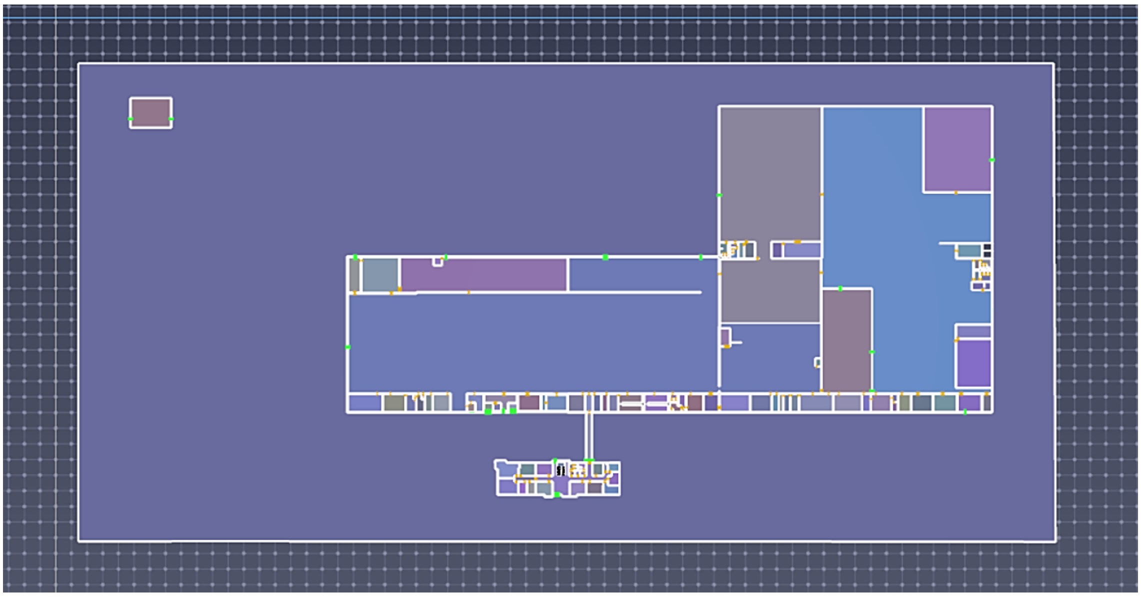

Figure 4. Mapping surfaces and exits.

Source: Own elaboration.

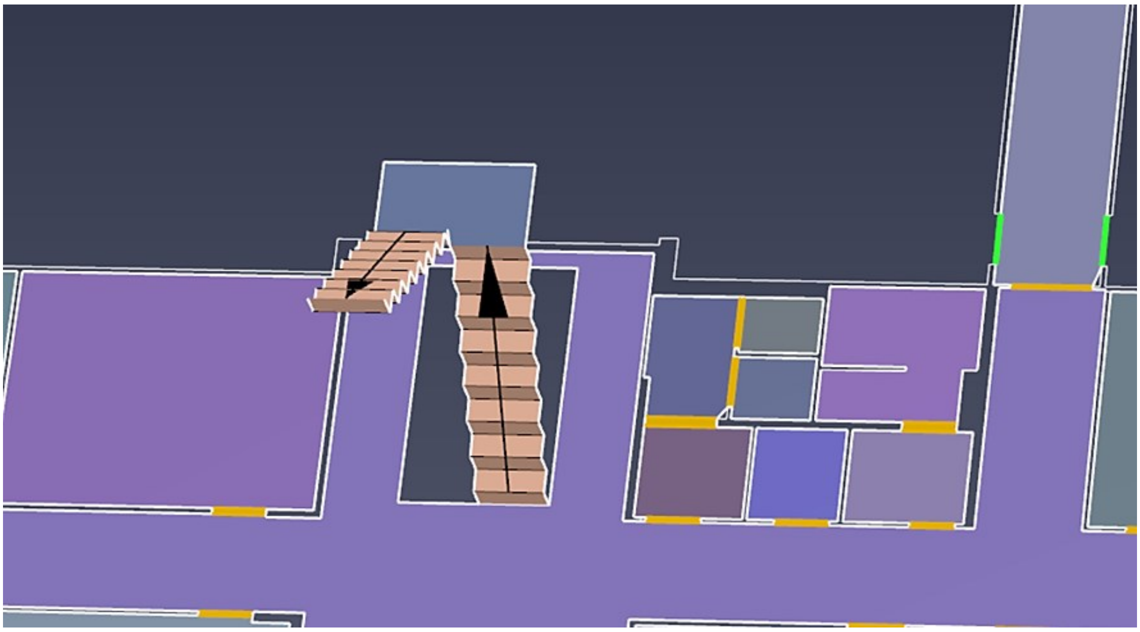

Figure 5. Staircase.

Source: Own elaboration.

The next stage of the work within the created simulation was the construction of profiles of the plant's occupants during the evacuation, consisting of office, production, and security personnel (Figure 6). The aforementioned people were given their physical appearance using available 3D models. They were tasked with a speed corresponding to standard moving conditions, i.e. 1.2 m/s. Each person occupied an area with a diameter of 45 cm around their own axis.

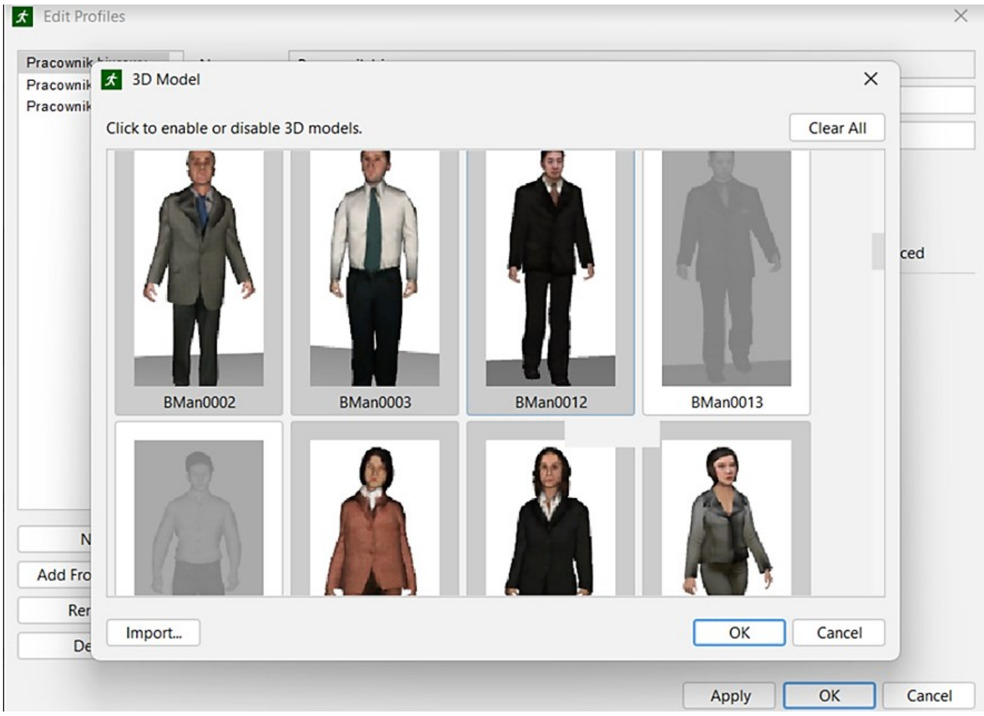

Figure 6. Attribution of characteristics to employees.

Source: Own elaboration.

Next, evacuation paths were defined for each group, which meant that production workers, together with a security officer, were directed to an assembly point located at the gatehouse, and office workers to an assembly point in front of the office part of the building (Figure 7). The team of blue-collar workers had 9 opportunities to get out of the zone, while the rest had a well-defined track marked in green in Figure 8. To make this possible, behaviors of going to designated places were created and assigned to people located in accordance with the place corresponding to the type of work performed.

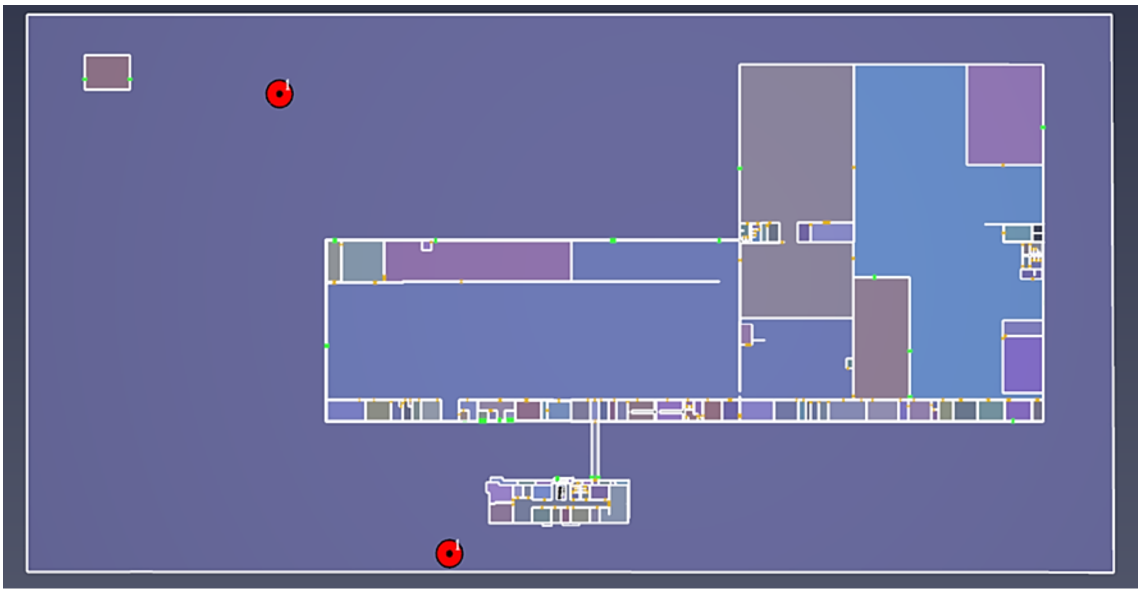

Figure 7. Designated assembly points for evacuation.

Source: Own elaboration.

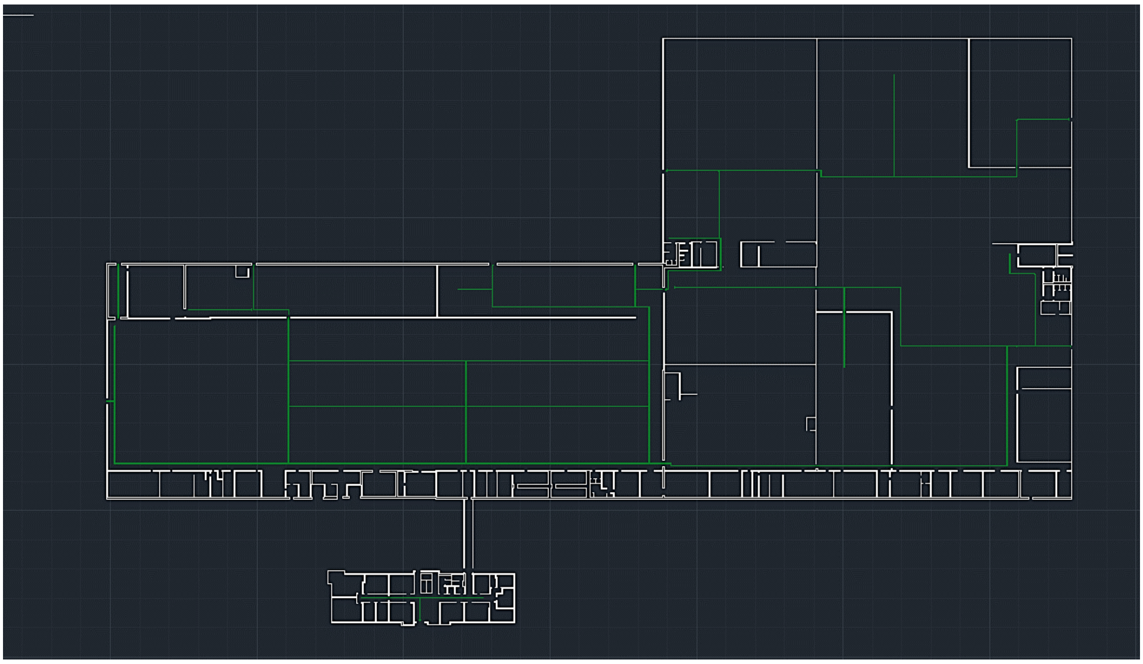

Figure 8. Evacuation routes (ground floor).

Source: Own elaboration.

The trial evacuation scenario is designed not only to test the effectiveness of procedures, but also to increase the sense of security among employees and prepare them for an actual emergency.

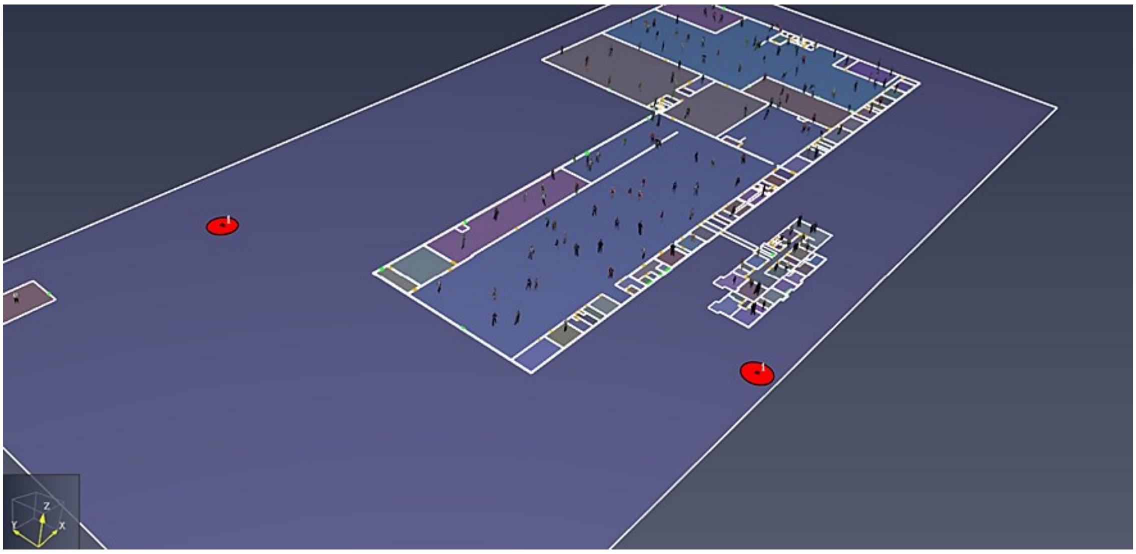

Figure 9. 3D view.

Source: Own elaboration.

Simulation 1 - the standard evacuation course assumes smooth, coordinated actions that ensure the safety of all people in a building or area. It is based on pre-assumed conditions and behaviors, as shown in the 3D view in Figure 9.

Simulation 2 - The scenario assuming that the signage at the plant was incorrect. The reaction of evacuees changes, people went in a direction that deviated from the planned evacuation route. In order for the assumptions to be reflected in the program, two destination points were added as in Figure 10, where evacuees had to be located, after which they went to the already designated destination.

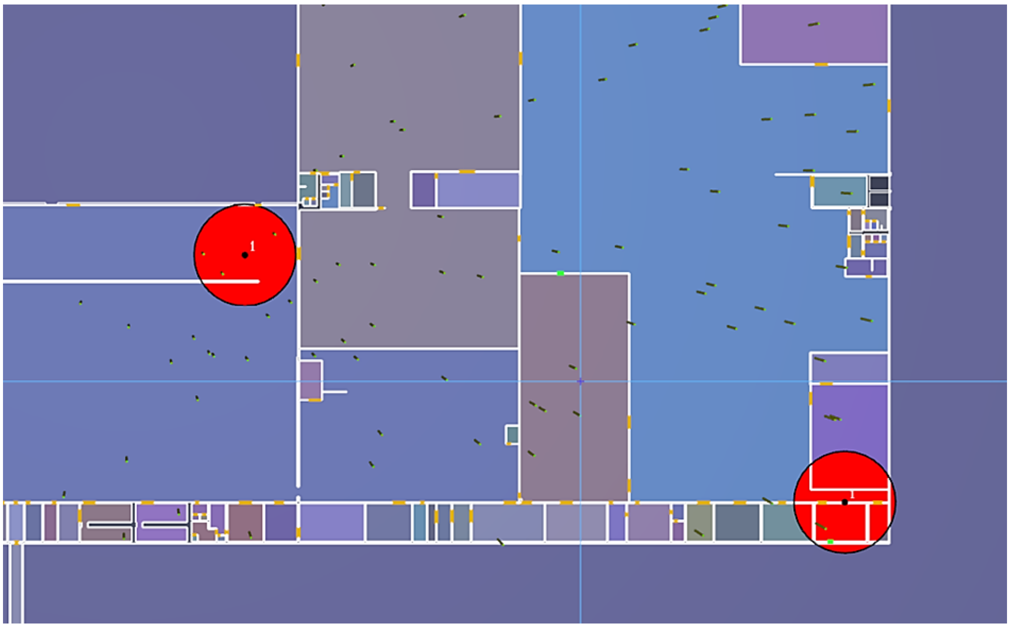

Figure 10. Places of incorrect evacuation.

Source: Own elaboration.

Simulation 3 - Scenario assuming obstacles on escape routes. A fire was assumed to occur in the southern part of the production hall. As a result of the rapid spread of the fire and the increase in temperature, the load-bearing capacity of the ceiling was significantly weakened. The structure could not withstand the load under fire conditions and there was a partial collapse of the ceiling. Falling structural elements and concrete fragments blocked three of the nine emergency exits for production workers. On the other side of the building, in the office section, which was separated from the production hall by a communication connecting passageway, there was damage to the ceiling in the main lobby, where one of the emergency exits was located. The structure in this part did not collapse completely, but detached fragments of suspended ceilings, falling elements of the ceiling installation and intense smoke made this exit considered impassable and out of service.

In order to best represent the conditions, the selected doorway was treated as a section of the building wall as in Figure 11.

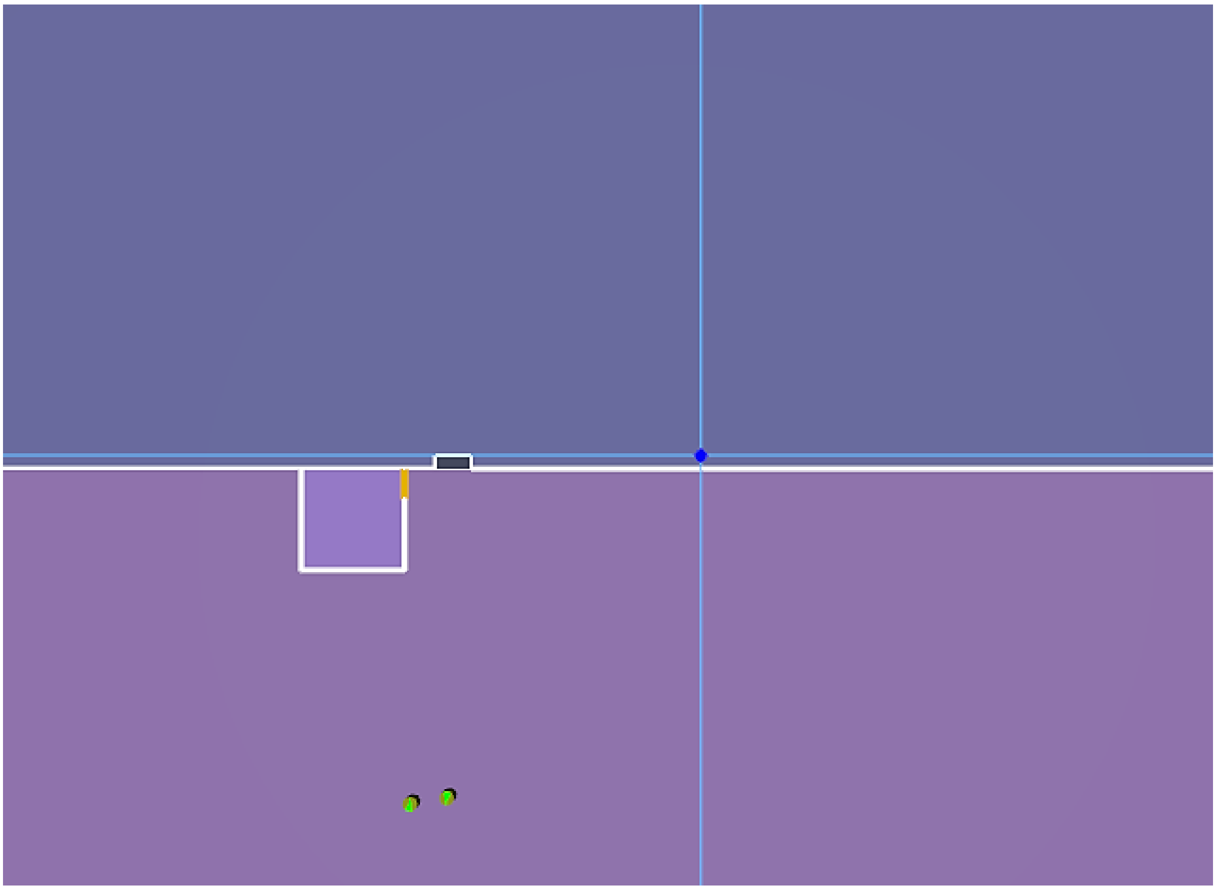

Figure 11. Blocked doorways.

Source: Own elaboration.

3. Discussion

The first simulation resulted (Figure 12) in an evacuation duration of 5 minutes and 5 seconds. Thanks to the possibility of comparing the time of the simulation carried out with the time of the last trial evacuation at the plant, for which the evacuation time was 5 minutes and 37 seconds, it can be concluded that the program reproduces in a very good way the conditions that accompany the occurrence of a threat to life and property.

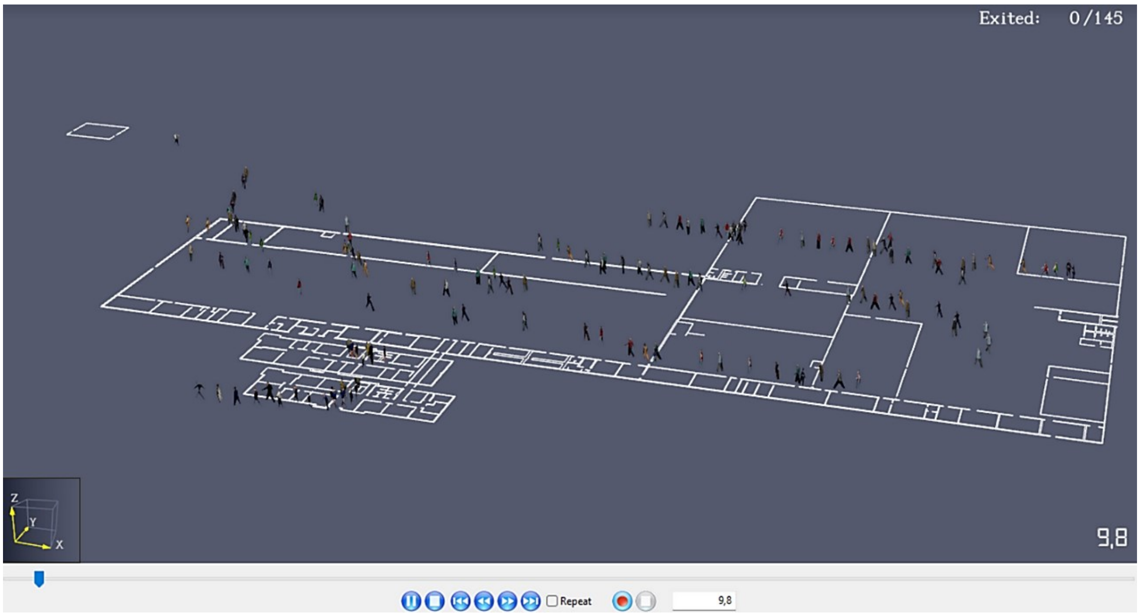

Figure 12. Simulation 1 – standard evacuation procedure.

Source: Own elaboration.

The evacuation time in the second scenario was 6 minutes and 57 seconds, which differed significantly from the time expected for a correctly marked route. Due to incorrect signage, the evacuation participants had to cover a route that was more than 60 metres longer (Figure 13).

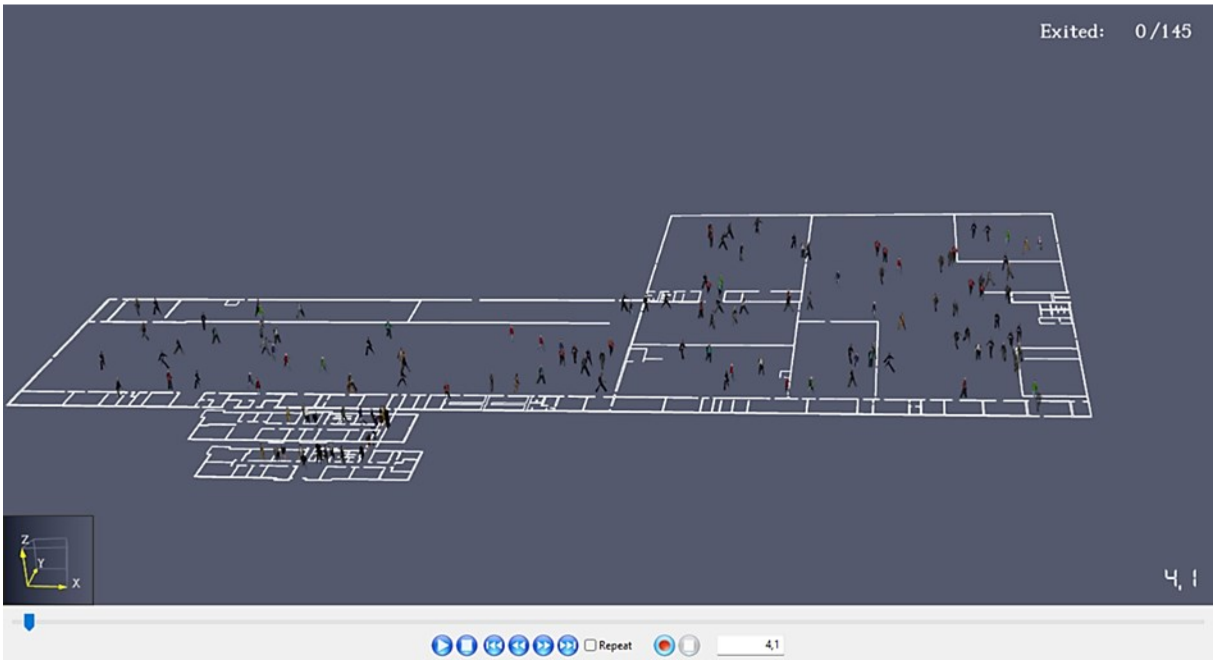

Figure 13. Simulation 2 – evacuation in incorrect direction.

Source: Own elaboration.

In scenario three due to the limitation of available exits, workers had fewer evacuation options, resulting in an increase in evacuation time by 33 seconds compared to the standard scenario - to 5 minutes and 38 seconds (Figure 14).

Figure 14. Simulation 3 – evacuation with some emergency exits unavailable.

Source: Own elaboration.

Data of the times from the conducted scenarios are shown in the table (Table 2).

Table 2.
Evacuation times

Scenario	Time
Sample evacuation at the plant	5 minutes and 37 seconds
Scenario 1	5 minutes and 5 seconds
Scenario 2	6 minutes and 57 seconds
Scenario 3	5 minutes and 38 seconds

The differences in evacuation times presented in the table above may not seem significant, but they should be considered in relation to the conditions that threaten the life and health of employees during fires and emergencies, when every minute of delay in leaving the danger zone is of great importance, especially in a situation where the threat is spreading, for example, a fire spreading and blocking or closing of subsequent zones or rooms in the building affected by the fire.

The strength of using computer simulations to analyse the employees' behaviour and their choice of escape routes during emergency situations is the ability to build various scenarios and then, based on the results obtained, modify the designation and marking of escape routes. The above activities are possible without incurring losses for the entrepreneur associated with the need to suspend production, which occurs during an actual evacuation of employees. The disadvantages include the need for a very detailed analysis of the construction documentation and a complete reflection of the building's structure when mapping it to the computer programme used, which requires knowledge of both the software and aspects related to fire protection.

The research identified the elements that require special attention when designating material storage areas in a company so that key escape routes are not blocked. It also identified the importance of training employees on these escape routes and properly marking all elements related to the evacuation of employees from the building. The results also confirmed that the simulation of employee evacuation times from the building, carried out using a computer application, accurately reflected the actual conditions that occurred during the physical evacuation of employees.

In further research, computer simulations will be carried out on other buildings, where tests will also be conducted assuming various scenarios of emergency situations, such as fires and, for example, toxic substance leaks requiring the evacuation of employees from the building.

4. Conclusions

The main difference between a trial evacuation and an evacuation at the time of a potential emergency is that a trial is designed to evaluate and refine procedures under controlled conditions, while an evacuation in an actual emergency takes place under stress and uncertainty, where speed of response, clarity of communication and adherence to procedures are crucial.

The program effectively replicated the behavior of employees during an evacuation. The difference in times between the trial evacuation and the assumed scenario 1 was only 32 seconds. Such a result demonstrates the high precision of the simulation, which largely corresponds to actual evacuation conditions.

Simulation 2 showed that erroneous signage has a significant impact on increasing the total evacuation time, and can also lead to dangerous confusion for some employees, especially those unfamiliar with the current organization of the space. This scenario clearly indicates the need for regular review and verification of the compatibility of evacuation signage with the actual spatial layout of the building, as well as the need for training and refresher exercises that consolidate the patterns of correct action in emergency situations.

The blocking of most of the emergency exits in the production section and the cutting off of one of the exits in the office section, as shown in Scenario 3, severely overloaded the remaining available routes. As a result, evacuation times were significantly increased, and local congestion and slowdowns were created at some points in the facility, which could pose a real threat to the life and health of evacuees.

The preventive measures implemented at the plant are yielding positive results, as no fires have been reported so far. And carrying out trial evacuations eliminates the possibility of unforeseen situations as well as allows verification of the current state and the introduction of possible additional solutions.

A computer program can help plan, model and simulate the evacuation process, but it is not a substitute for a physical evacuation. Computer simulations can show how people will move in different evacuation scenarios, allowing optimization of evacuation routes and identification of potential problems, such as narrow corridors, congestion or improper exit placement.

It is worth noting that prevention is often much cheaper than repairing damage.

Maintaining fire protection systems and regularly training employees are investments that save money in the long run. With effective prevention, it is possible not only to reduce the risk of fire, but also to protect life, property and the environment, ultimately benefiting society as a whole.

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