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Article

Risk-Based Approach to the Selection of Fire Exit Strategies for Non-Compliant Buildings

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Abstract

Building law allows the use of a building that is non-compliant with fire safety regulations, provided that enhanced fire exit strategies are implemented to mitigate the negative impact of this non-compliance on fire safety. This article demonstrates the potential of using a probabilistic fire risk analysis method—multisimulation—to increase the efficiency of selecting fire exit strategies. Multisimulation is a quantitative risk analysis method that utilizes, among other things, computer models of fire development and evacuation, as well as modern mathematics and computer science. The main aim of multisimulation is to perform multiple computer simulations (hence the name) for as many fire scenarios as possible in a given building. This article demonstrates the potential of using this method in a practical approach to ensuring fire safety. For this purpose, an existing auditorium building was analyzed, in which numerous non-compliances with applicable regulations were identified. The analysis included 1000 fire and evacuation simulations in a theater auditorium equipped with two emergency exits and 1000 fire and evacuation simulations in a theater auditorium equipped with three emergency exits. In the simulations of both scenarios, the duration of a performance conducted with a full audience and people performing on stage was modelled. The results clearly demonstrated a significant improvement in safety when three emergency exits were available. In terms of both the required safe egress time (RSET) and risk analyses, when three emergency exits were available (instead of the required two), the possibility of having only one functioning exit, which may occur due to a human error, was eliminated. Therefore, it was undoubtedly confirmed that the use of a third emergency exit is justified as an optimal fire exit strategy or a future legislative requirement.

Keywords: risk analysis; evacuation; crowd evacuation; fire

1. Introduction

In Poland, it is legally possible to use buildings with existing fire protection deficiencies [1]. However, this requires a tedious process of agreeing on enhanced fire exit strategies, which are intended to eliminate the negative impact of the existing deficiencies on the building's safety. These strategies, in both form and content, are approved by the Provincial Headquarters of the State Fire Service, which is responsible for the investigated area [2]. Approval of alternative solutions relies on the opinion of a technical expert, such as construction and fire protection experts [3]. Depending on the scale and risks, alternative solutions can be chosen using the expert method or engineering methods. The former uses acceptability criteria derived from the analysis of applicable legal acts [1,4] and is the subject of training, seminars, and conferences [5]. In more complex cases or those requiring detailed analysis, engineering tools such as computer-aided fire development models (CFDs) [6–9] or risk-based methods [10] are used. The optimal acceptability criteria for alternative evacuation solutions have already been discussed in the available literature [3]; they are summarized in this article. The main purpose of this article is to demonstrate the possibility of using modern risk analysis methods to justify the selection of alternative solutions in buildings.

Studies in the literature [11–14] indicate that the quantity of fires and their consequences remain a significant problem. Particular attention should be paid to tragic incidents involving the evacuation of large groups of people from buildings, which have significant social and economic costs [15]. Therefore, among other reasons, this topic remains a research area of interest both in the social sciences and in safety engineering. Due to the current geopolitical situation, threats to places where large groups may be present have intensified recently. In this article, a case study was conducted on an auditorium building, as it is an optimal example to represent the threats related to the evacuation of large groups of people [16–18]. Analyses presented in the literature indicate that auditorium-type buildings exhibit heightened vulnerability in situations where not all emergency exits remain accessible. The present study seeks to develop an evacuation strategy that is robust to human error, particularly in scenarios where emergency exits are inadvertently or improperly closed. This study addresses two aspects of a novel nature. It demonstrates that probabilistic risk analysis can be used to select alternative solutions and objectively demonstrates the impact of using an additional (above-standard) emergency exit on the level of fire safety.

The purpose of the study was to perform a fire safety analysis of the building's current condition and, by analyzing the obtained RSET and risk distributions and fractional effective dose FED inhalation [SE1.1] maps, to select appropriate alternative solutions. Following the modifications to the building, a repeat analysis was planned to assess the effects of the proposed solutions.

The adopted method was quantitative risk analysis using multisimulation [19]. The probability of individual scenarios and their consequences was calculated and summarized as risk. A risk assessment was then performed based on the SFPE manual [20] and PD 7974-7 [21]. In the considered scenario, a fire occurs in one of the rooms within the analyzed area. Because only the auditorium was analyzed, the location of the fire was randomly selected to be within the same room each time. [

2. Background

In practice, the first step in developing enhanced fire exit strategies generally involves employing an expert methodology, which involves intuitively selecting solutions to address existing inconsistencies. Recently, studies that have systematized this process have been published [3]. Below are the objectives guiding the general requirement that are contained in the overarching legal act [1] and detailed in materials available during fire safety engineering training [5].

The purpose of the “ability to evacuate people or save them by other means” is to provide the following:

- (1) Conditions that allow occupants of the building to evacuate (move) to a place of safety by providing the following:
 - a. Adequate evacuation routes;
 - b. Conditions so that they can be rescued by other means (e.g., conditions for surviving a fire).
- (2) Access to the building for rescue teams so that they can search it and, if necessary, take the necessary measures for rescuing people (evacuating the injured) and taking them outside.

Table 1 presents the correlation of possible alternative solutions alongside their impact on five areas (objectives) in the field of fire safety, with the designation of solutions that influence evacuation inconsistencies [3].

Table 1. Relationships between alternative solutions and acceptance criteria (gray color refers to evacuation).

Solution	Load Capacity	Interior	Outdoors	Evacuation	Rescue Teams
Two directions of evacuation				X	X
Anti-panic devices				X	
Increased width of evacuation routes				X	
Increased height of escape routes				X	X
Improved fire performance of building elements				X	

Activation of devices in first-level alarm				X	
Evacuation lighting with increased intensity				X	
Evacuation luminaires in daylight mode				X	
Rapid response sprinklers	X	X	X	X	X
Increased supervision of sprinkler system	X	X	X	X	X
Separate sprinkler sections	X	X	X	X	X
Two fire pumps	X	X	X	X	X
Two fire tanks	X	X	X	X	X
Fire alarm system		X	X	X	
Increased number of manual call points		X		X	
Increased number of detectors		X		X	
Optical and acoustic signaling devices				X	
Monitoring by Fire Service	X	X	X	X	X
Fire valves on the platforms of the staircases					X
Glazed doors					X
Hydrants 33		X	X		
Computer analysis of structural stability	X	X			X
Preservation of areas without storage	X	X			X
Horizontal evacuation signs				X	
Doors in the same color as evacuation signs				X	
Increased amount of fire extinguishers		X			
More frequent practical evacuation checks				X	
Closed-circuit television system		X	X	X	X

The table above shows that there are at least 22 possible alternative solutions to eliminate the negative impact of evacuation deficiencies. For typical facilities with common discrepancies, a wider range of options makes the task easier for experts. However, in facilities and spaces in which the safety of evacuees is particularly important, the abundance of options limits intuitive perception, and in such cases, fire safety engineering tools should be utilized.

An example of a facility where using such tools to justify the selection of alternative solutions is appropriate is an auditorium building (theater), where a large number of people are concentrated in a single room.

3. Method

An auditorium in an existing theater building in Warsaw was analyzed, the characteristics of which are presented below and shown in Figure 1.

- Internal building area: 1370 m²;
- Stage area: 150 m²;
- Stage volume: 750 m³;
- Auditorium and stage capacity: 246 people;
- Building height: <25 m;
- Number of above-ground floors: 5;
- Number of underground floors: 1.

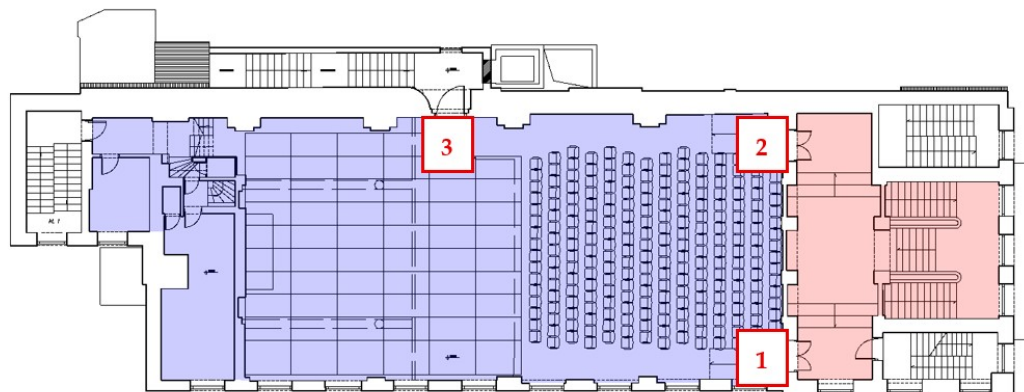


Figure 1. Floor plan of the auditorium and stage with marked emergency exits.

The theater's auditorium, located on the first floor of the building, was analyzed. The auditorium has 14 rows of seats, with a total capacity of 231, and there are three exits from the auditorium. Two double-leaf emergency exits are located at the rear of the auditorium. The third exit (currently not used for emergency evacuation) is a single-leaf door located to the right of the stage. Figure 1 shows a floor plan of the first floor of the building containing the auditorium. Numbers 1 to 3 indicate the emergency exits. For the purposes of the model, 231 people were assumed to be in the audience and 15 actors were assumed to be on stage.

The following evacuation discrepancies were identified in the building:

- (1) No doors separating rooms from the escape route;
- (2) Insufficient width of stairwell flights and landings;
- (3) Excessive step height;
- (4) Lack of fire-resistance-class and non-flammable materials on internal stairs;
- (5) Insufficient width of doors and emergency exits;
- (6) Insufficient height of emergency doors;
- (7) Height of the door to the acoustic cabin is 1.7 m;
- (8) Local reductions in the height of the escape route;
- (9) No emergency exit from staircase K 3 to exit the building;
- (10) No access to the emergency exit to staircase K 1 in the prop warehouse;
- (11) Winder stairs are the only escape route;
- (12) No panic devices on the emergency doors.

For the purposes of the comparative analysis, simulation results were compared for an auditorium equipped with two emergency exits and (after modifications) an auditorium equipped with three emergency exits (where exit number 3 was made available for evacuation). Additionally, a 10% probability of a block to one door was assumed. Next, 1000 simultaneous fire and evacuation simulations were performed for both auditorium models. A risk analysis was conducted based on the results.

Following the multisimulation approach, the Monte Carlo model generated distributions of input parameters for the CFAST fire development model, which was then used to calculate temperature, smoke volume, smoke layer height, and selected gas concentrations. The resulting values were represented as a function of time from the onset of the fire. The location of the fire and other fire parameters were selected randomly in each of the simulations [22]. The model of the auditorium layout used in the simulation is presented in Figure 2, while Figures 3 and 4 show the projections of the models with three and two emergency exits.

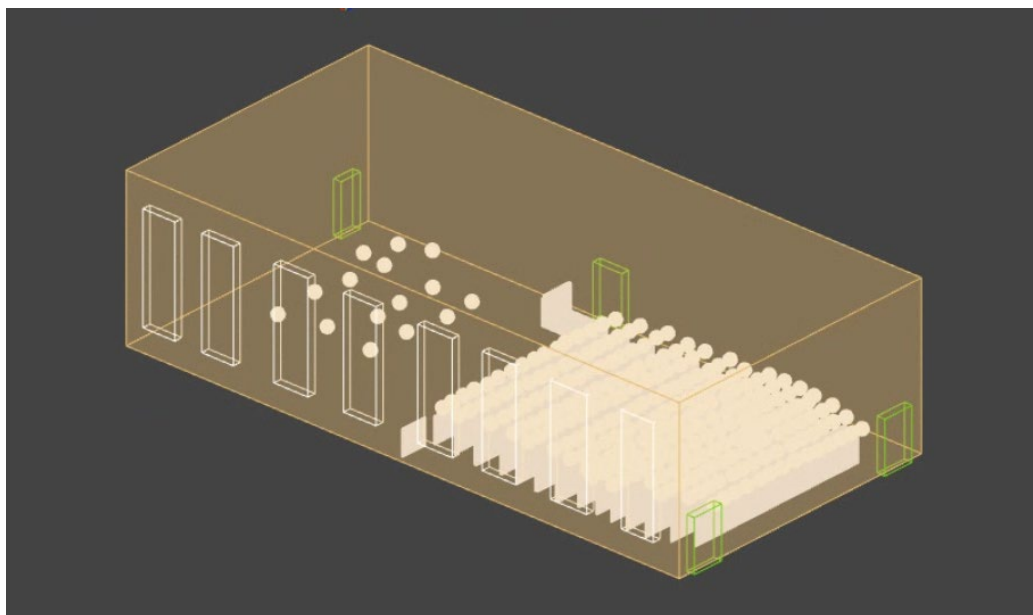


Figure 2. Floor plan model (auditorium with stage) used in this study.

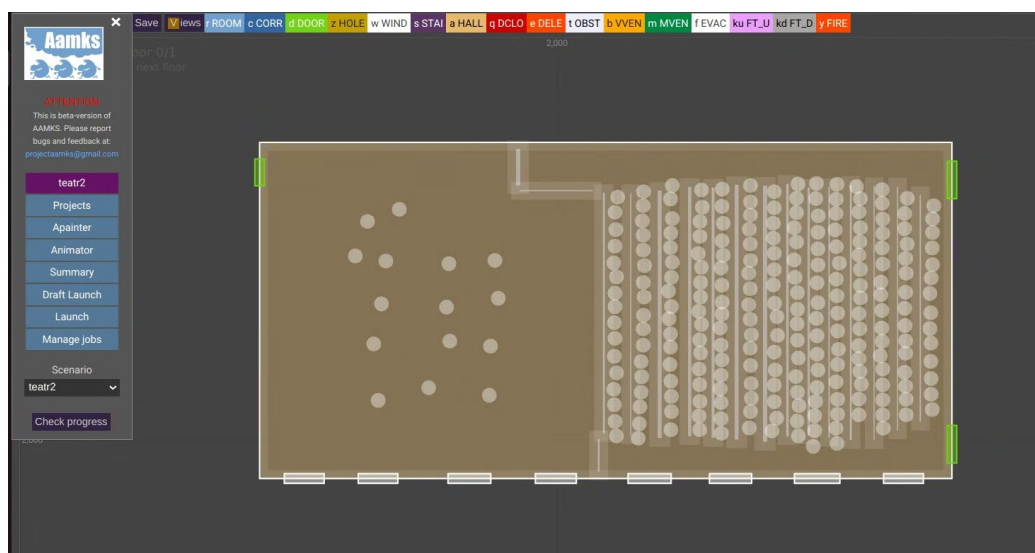


Figure 3. A projection of the auditorium model equipped with two emergency exits.

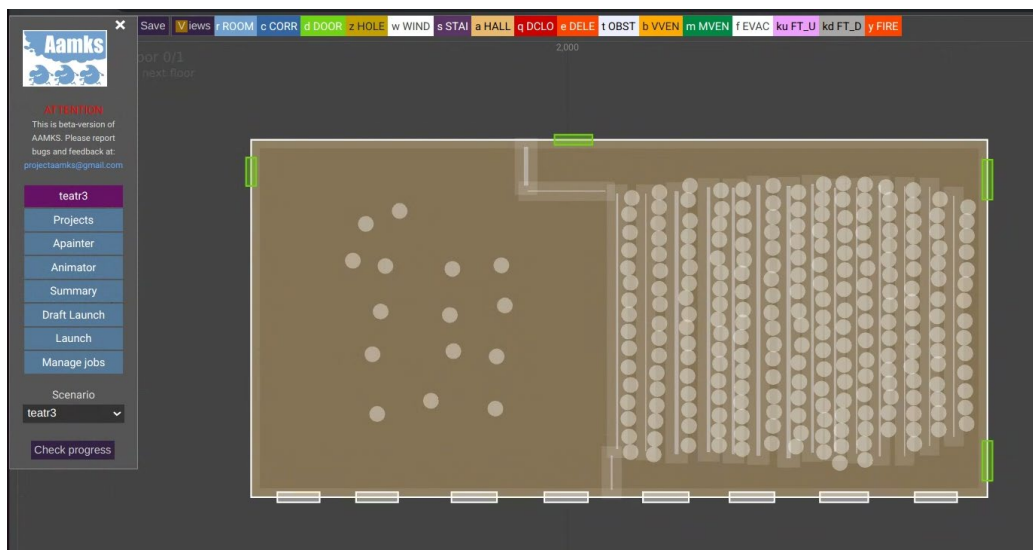


Figure 4. A projection of the auditorium model equipped with three emergency exits.

Multisimulation is a quantitative risk analysis method. In this approach, computer models of fire development and evacuation, among other things, are utilized, drawing on modern mathematics and computer science to optimize the calculation process. The main aim of multisimulation is to perform multiple computer simulations (hence the name) for as many fire scenarios as possible in a given building. Probability distributions for individual scenarios and their consequences are then determined. The analysis of all possible scenarios in multisimulations is possible thanks to the Monte Carlo method, developed by Stanislaw Ulam (1909–1984), a Polish–American mathematician [23]. This method generates the following input parameters for the models embedded in the multisimulations (Figure 5): fire intensity, fire development rate, fire protection equipment status, ventilation conditions in the building, fire location, etc. Each parameter is input with a specific variability range (e.g., fire speed can be set from slow through to medium, fast, or ultra-fast), which allows for the entire set of possible events to be probed.

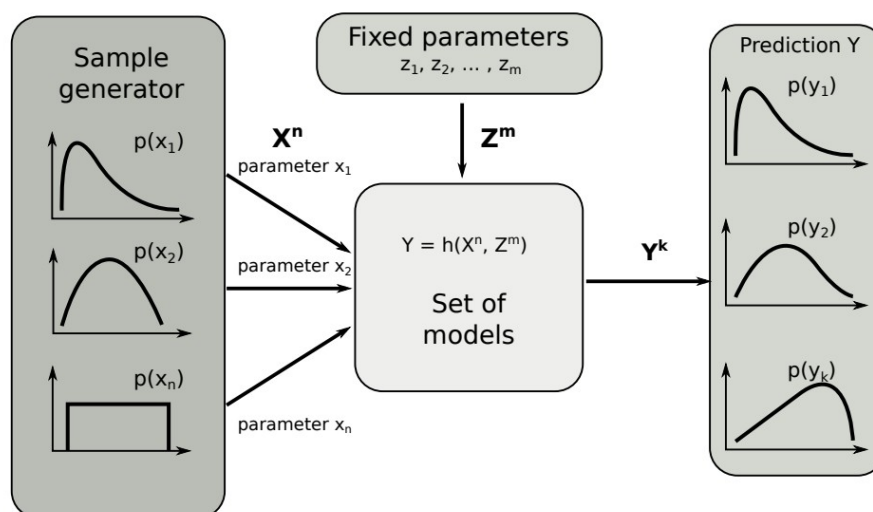


Figure 5. The construction principle of the multisimulation. X^n is a vector length n of independent copies of random variable X providing the input for the models, Z^m is a vector length m of fixed parameters providing the input for the models, Y^k is a vector length k predicted output parameters.

In the multisimulations, it is assumed that the fire in a building, peoples' responses, and the safety systems are constant and can assume different values. Therefore, if fire parameters are not

constant but rather take on values within a certain range, simulations should be run for each value within that range. Some values within this range are more probable; others are less probable. For fire development simulations and evacuation models, so-called input parameter distributions are introduced; i.e., a set of values for a given parameter, along with the probability of its occurrence. Multisimulations are well-established in both science and normative studies. The formal basis for this method is provided by the NFPA 551 [24], NFPA 101 [25], and ISO/TS 16733 [26] standards; the technical knowledge principles of the SFPE Engineering Guide to Performance-Based Fire Protection 2nd Edition [27]; and the SFPE Handbook of Fire Protection Engineering [20]. In most cases, comparative analysis is used according to the method specified in British Standard PD 7974 [21]. The input parameters for the multisimulation were determined based on analysis of the SWD-ST database and numerous published experimental results.

Both the model and the multisimulation methodology may seem inaccessible for independent implementation. In practical situations (such as those involving a fire safety engineer), there is no need for a thorough understanding of the mathematical principles involved. Applying the multisimulation method involves using a suitable computer program and defining parameters for the analyzed facility. Available free software include PFS (<https://github.com/atpaajan/pfs>, accessed on 16 November 2025), a tool developed by VTT Finland [28], and B-RISK, developed by the University of Canterbury in New Zealand [29], while the Fire Academy is developing software called Aamks [22].

The fundamental parameter determining the safety of a given facility is risk. In safety engineering, risk is defined as the product of the probability of a specific event occurring and its consequences. By performing multisimulation, we obtain the probability of a given risk, which is determined from the frequency of specific effects occurring in all simulations. The effects are assessed as the impact of smoke, temperature, and thermal radiation on evacuating individuals. An evacuation model was implemented in the multisimulation program to evaluate the consequences of individual scenarios. The number of people in the facility and their location, alarm response time, and movement speed within the office space and on escape routes are randomly selected. The position of each person at each simulation step is plotted against the fire environment, calculated using a fire development model. This allows us to determine whether and how much a given person inhaled fire gases, and to assess the effects of this inhalation.

4. Risk Indicators and Analysis Parameters

Risk assessment methods can be classified as qualitative or quantitative methods. Qualitative analysis relies on expert experience in a given field, which allows for the estimation of the risk level associated with a given job position or technological process. Due to its nature, the qualitative approach can be perceived as subjective. Through the quantitative approach, risk is estimated based on numerical values obtained from historical data, equipment reliability statistics, and probabilistic models. The quantitative approach is more precise, reliable, and perceived as objective. Quantitative risk assessment is more difficult to implement due to the complexity of the calculations and the availability of data and models. This case study utilized multisimulation as a quantitative risk assessment method.

The following risk indicator was analyzed:

- The probability that people being evacuated will inhale fire gases in an amount that threatens their life.

In the final stage of the analysis, the risks were estimated and the calculated values were compared to the SFPE standards [20] and PD 7974-7 [21] in order to categorize the obtained results. However, more importantly for the purpose of this publication, the risk distributions in the absence and presence of the proposed solution (a super-standard evacuation exit) were compared. The variable analysis parameters adopted in the multisimulation are presented in Table 2.

Table 2. Input parameters to the risk assessment model.

Parameter	Value
Fire Growth Rate	Triangular distribution α z min = 0.00293, max = 0.01172, mod = 0.1876
Fire Power Density	Triangular distribution q_A z min = 300, max = 500, mod = 1300 kW/m ²
Fire Location Coordinates 1	Fire randomized only in the auditorium
Fire Location Coordinates 2	Random positioning within the room or zone: uniform distribution 0 to the width and length of the zone
Fire Location Height	Logarithmic transformation of the continuous uniform distribution from 0 to H
Heat of Combustion	Depending on the type of material, modeled with a uniform distribution, min = 12,400 kJ/kg max = 28,000 kJ/kg
Carbon Monoxide Mass Fraction	Uniform distribution min = 0.01, max = 0.023
Radiation Coefficient	Triangular distribution min = 0.2, max = 0.4, mod = 0.35
Smoke Particle Mass Fraction	Uniform distribution min = 0.01, max = 0.17
Probability of Fire Alarm Activation	Binomial distribution p = 0.98
Pre-evacuation Time	Logarithmic distribution; normal mean = 3.95 σ = 0.236
Speed of Movement on the Horizontal Escape Route	Normal distribution μ = 1.2, σ = 0.2
Speed of Movement on the Vertical Escape Route	Normal distribution μ = 0.8, σ = 0.2
Influence of Smoke on Speed of Movement	Pursuer relationship, alfa μ = 0.706, σ = 0.069, beta μ = -0.057, σ = 0.015
Temperature Outside the Building	Normal distribution μ = 10.7, σ = 20 °C

To address the impact of smoke toxicity on evacuees, the fractional effective dose (FED) method was used. This method allows for determining the dose of fire gases ingested by individual evacuees and the consequences of this dose. According to the method presented in [20,30], the FED can be estimated according to the following relationship:

$$FED_{tot} = FED_{CO} \cdot HV_{CO_2} + FED_{O_2}$$

The individual components of FED_{tot} are calculated as follows:

$$FED_{CO} = 4.607 \cdot 10^{-7} \cdot (C_{CO})^{1.036} \cdot t,$$

where

C_{CO} – carbon dioxide concentration measured in ppm, obtained from the fire development model;

t – transit time through the hazardous zone.

$$FED_{O_2} = \frac{t}{60 \cdot \exp [8.13 - 0.54(20.9 - C_{O_2})]}$$

where

C_{O_2} – oxygen concentration expressed in %, obtained from the fire development model;

t – transit time through the hazardous zone.

$$HV_{CO_2} = \frac{\exp (0.193 \cdot C_{CO_2} + 2.0004)}{7.1},$$

where

C_{CO_2} – carbon dioxide concentration expressed in %, obtained from the fire development model.

A lethal dose is defined as an FED value greater than or equal to 1 [30]. The remaining consequences of exposure to gases below 1 were estimated using a logarithmic scale, allowing for a possible synergistic effect on smoke toxicity. The effects of different FED_{tot} values are shown in Table 3.

Table 3. The magnitude of effects depending on the FED [31].

Min FED _{tot}	Max FED _{tot}	Consequences
0	0.0099	none or minor injuries
0.01	0.29	minor injuries with no lasting symptoms
0.3	0.99	serious injuries, prolonged hospitalization
1	+∞	fatal outcome

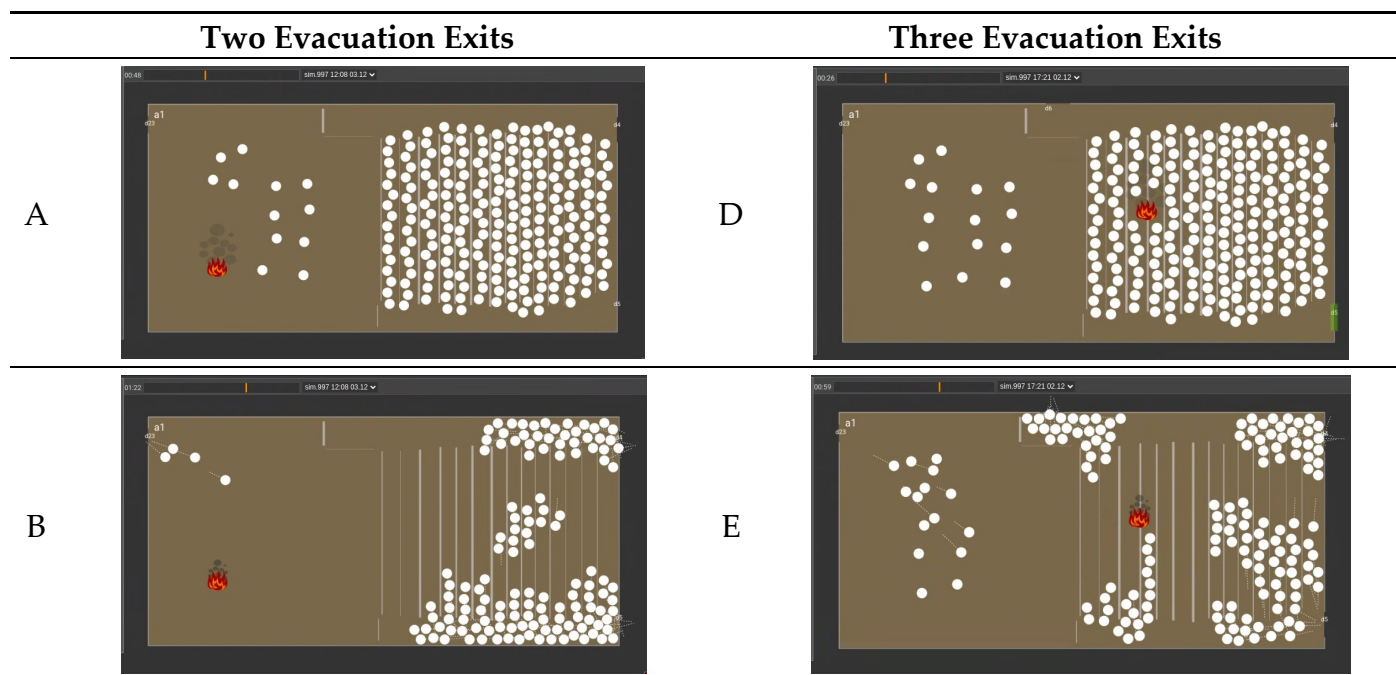
The above methodology allows for a risk assessment of individual scenarios. The influences of temperature and thermal radiation flux are defined as limit values. It was assumed that evacuation is possible if the smoke temperature does not exceed 60 °C at a height of 1.8 m and the thermal radiation flux does not exceed 2.5 kW/m². The thermal radiation flux criterion is sometimes expressed alternatively as a smoke layer temperature at a height of 2.5 m not exceeding 200 °C, which approximately corresponds to a radiation of 2.5 kW/m².

5. Results

In both scenarios, a fire occurred during a performance. The number of people in the audience was determined based on the number of seats available, and these people were placed in the model according to the submitted seating arrangement. A total of 15 actors were assumed to be on stage.

Table 4 presents the evacuation process for one of the randomly selected simulations for scenarios with two and three accessible emergency exits. To assess the safety of the proposed layout, a total of 1000 computer simulations of fire development and evacuation were conducted for both scenarios. Figure 6 presents the distributions of RSET times for both scenarios.

Table 4. Evacuation process (A—beginning of evacuation, two emergency exits; B—during evacuation, two emergency exits; C—final phase of evacuation, two emergency exits; D—beginning of evacuation, three emergency exits; E—during evacuation, three emergency exits; F—final phase of evacuation, three emergency exits).



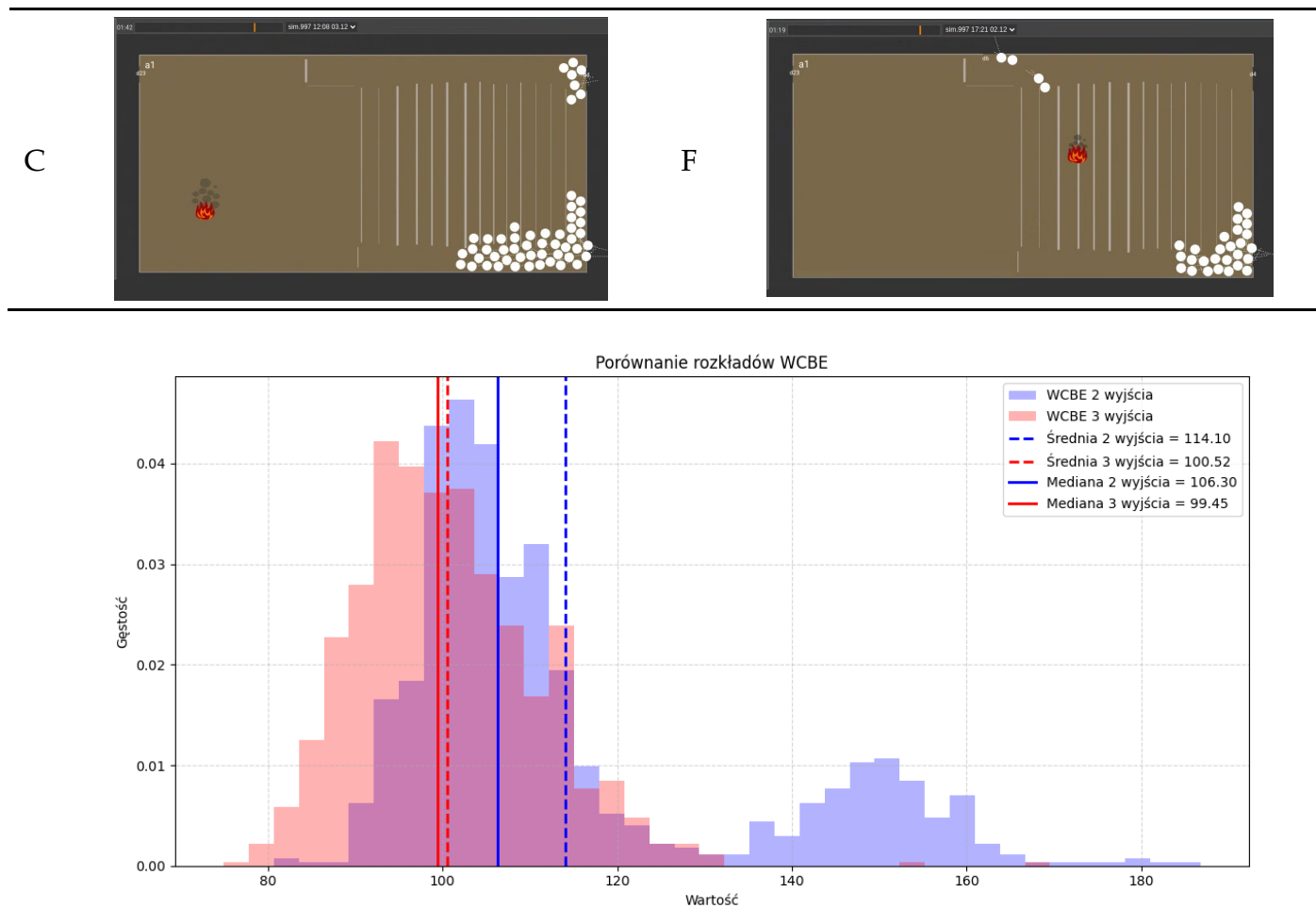


Figure 6. Distributions of RSETs for the two analyzed event scenarios.

A wide range of fire parameters were analyzed, taking into account various combustion materials, fire growth rates, fire intensities and locations, and the response of people and safety systems. In Figure 6, blue indicates the distribution for scenarios with two emergency exits, while orange indicates the distribution for scenarios with three emergency exits. A certain aberration can be observed, visible around 140–160 s and occurring only for the scenario with two emergency exits. For the scenario with three emergency exits, the RSET distribution falls between 80 and 120 s.

The main aim of the proposed alternative solution and the amendments to the existing regulations is to reduce the risk of human error (one of the two available doors being blocked). The above analysis clearly demonstrates that the use of at least three emergency exits does not significantly increase the time it takes for the audience to leave the auditorium, even if one is blocked. Due to the presence of alternative exits from the auditorium, no deaths caused by excessive FED_{tot} exposure were observed in the 2000 simulations of fire development and evacuation. In each simulation, the ASET was longer than the RSET.

Despite the absence of fatal scenarios, the increase in RSETs in the scenario with two emergency exits compared to that with three emergency exits is significant. A significantly higher risk was also confirmed by the increased mean increases in the FED_{tot} coefficient in the former scenario (Figure 7) compared to the latter (Figure 8). The increased dose is primarily due to the increased evacuation time in the scenario with two emergency exits, caused by longer queues at the auditorium exits.

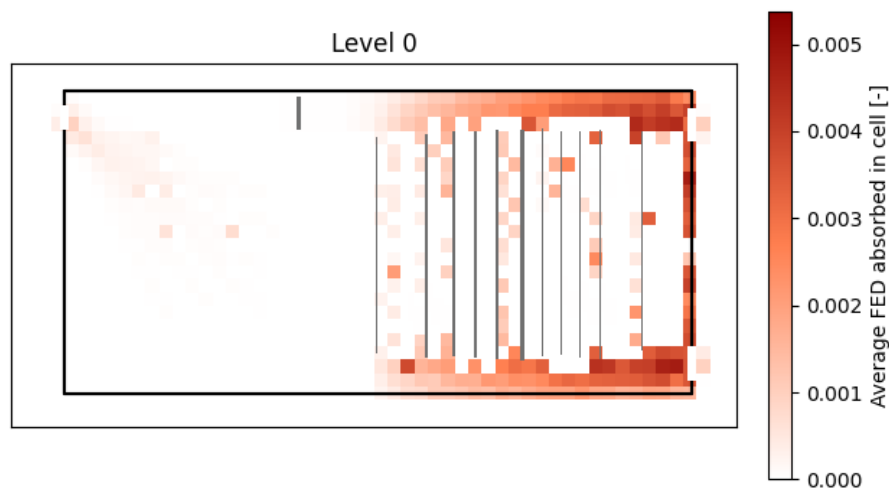


Figure 7. Heatmap showing average FED_{tot} increases in the two-exit scenario.

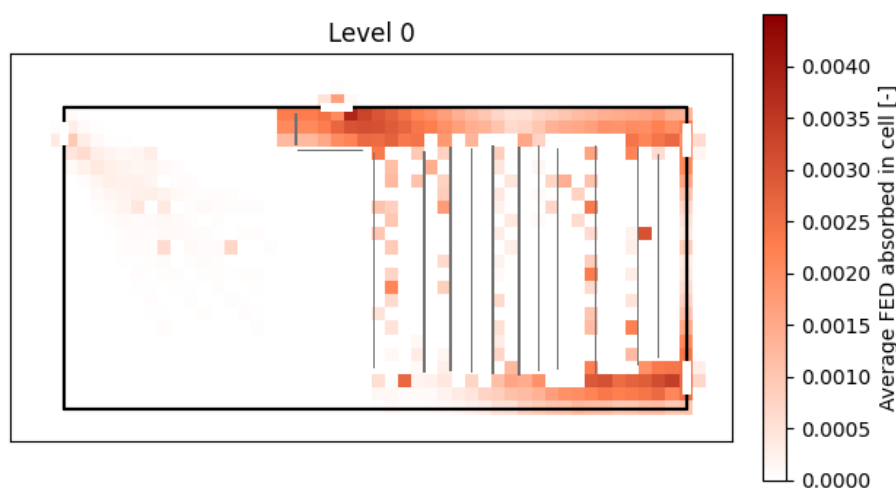


Figure 8. Heatmap showing average FED_{tot} increases in the three-exit scenario.

Figure 9 presents the distribution of fire effects calculated based on the inhaled FED_{tot} . Note that the negative effects calculated for the auditorium with two emergency exits are greater than those of the scenario with three emergency exits. The relative differences are greater than the relative differences in the distribution of RSET times, which results from the higher concentrations of toxic gases in the later stages of the fire. The graph also shows that in the scenario with two emergency exits, at values of 0.65, 0.85, 1.0, 1.15, and 1.4, there are few high-risk cases, which occur in situations where the fire occurred at the only available emergency exit. Similarly to the analysis of RSET distributions, these disruptions did not occur with three available emergency exits.

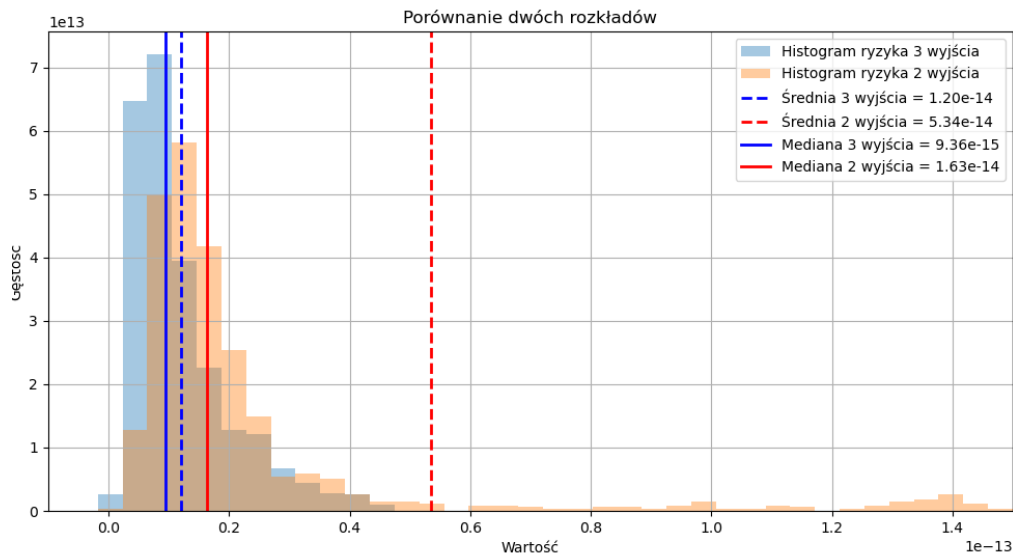


Figure 9. Distribution of average fire effects calculated on the basis of FED_{tot} .

To calculate the absolute risk of death due to fire in this scenario, the values obtained from the simulation (the average value of fire consequences determined based on the average FED coefficient) were multiplied by the probability of fire occurrence. According to the standard [21], the probability of fire occurrence in an assembly entertainment building is 0.7×10^{-2} [1/year]. Table 5 presents the absolute values of the risk of death due to a fire in the building in both scenarios.

Table 5. Calculated values for the risk of death due to fire.

Parameter	Value
Individual risk, two emergency exits	$3.74 \cdot 10^{-15}$
Individual risk, three emergency exits	$8.4 \cdot 10^{-16}$

Based on the data presented in the figures and Table 4, the risks for each scenario and their consequences were calculated. The risk value was calculated as the product of probability multiplied by consequences [21,32]:

$$R_i = P_i \cdot S_i$$

Next, based on international guidelines [20,33–35], risks were assessed and entered into a risk matrix with the aim of determining negligible and acceptable risks and risks requiring mitigation. Figure 10 presents the risk matrix for the building section under consideration; symbols are detailed in Table 6.

Table 6. Description of risk calculated.

Risk	Description	Value
R2	Two exits—risk of inhaling a dose of gases that would result in death	$3.74 \cdot 10^{-15}$
R3	Three exits—risk of inhaling a dose of gases that would result in death	$8.4 \cdot 10^{-16}$

S \ P	P			
	$\leq 10^{-6}$	$10^{-6} - 10^{-4}$	$10^{-4} - 10^{-2}$	$> 10^{-2}$
High		7	4	1
Medium	10	8	5	2
Low		9	6	3
Negligible	11	12		

R2
R3

RYZYKO
 wysokie
 średnie
 niskie
 nieistotne

Figure 10. Risk matrix for the analysis performed.

The value of fire effects is a function of the absorbed FED_{tot} . Low effect values (order of magnitude: 10^{-14}) indicate that a statistically very small amount of toxic gases was ingested by individuals, which does not have any significant negative health effects and is classified as negligible in the risk matrix.

In the adopted model and analysis, a situation in which all doors or escape routes were blocked, or other planned sabotage, was not considered. Unusual, unpredictable human behavior, such as someone remaining unconscious in the auditorium, was also not considered. The fire development rates of regulation-compliant elements typically used in the auditorium's interior design were considered, and the analysis was limited to evacuation from the auditorium itself. Fires located in other parts of the building, including the routes leading from the auditorium to the exterior, were not considered.[]

6. Conclusions

We analyzed 1000 fire and evacuation simulations each for the studied theater auditorium equipped with either two or three emergency exits. The simulations analyzed in each of the two scenarios covered the duration of the performance, meaning that they were conducted with a full audience and while people were on stage.

The results clearly demonstrated a significant improvement in safety when introducing a third emergency exit. In analyses of both the RSET and risk, when three emergency exits were available (instead of the required two), the possibility of the presence of only one exit, which may occur in the event of a human error, was eliminated. Therefore, it was undoubtedly confirmed that the use of a third emergency exit is justified as an alternative solution or a future legislative requirement.

Regardless of the above, in absolute criteria, the risk fell within the negligible category under both studied scenarios in the analyzed facility. This risk was determined based on the assumption that at least one emergency exit was available in each fire simulation, ensuring that no fatalities occurred in any simulation, and the negative consequences were limited to the ingestion of toxic gases.

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Conflicts of Interest: The author declares no conflicts of interest.

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