Wyznaczanie kierunków ewakuacji do zastosowania w systemach dynamicznego oznakowania dróg ewakuacyjnych

Determining evacuation directions for use in Dynamic Signage System of evacuation routes

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W artykule autorzy przedstawiają wyniki badań modelowych wskazujące na konieczność stosowania systemów kierowania procesem ewakuacji w celu poprawy jej bezpieczeństwa. Architektura dróg komunikacyjnych i wewnętrzny układ przeszkód w budynku powodują, że prowadzenie ewakuacji w sposób bezpieczny nie jest jednoznaczne z prowadzeniem jej najkrótszą możliwą drogą. Jest to szczególnie zauważalne gdy na najkrótszej możliwej dla użytkownika drodze ewakuacyjnej występuje zagrożenie. Analizy dla projektowych pożarów niezależnie od szybkości ich rozwoju wykazały, że zoptymalizowane oznakowanie ewakuacyjne uzależnione od lokalizacji miejsca zagrożenia prowadzi do bardziej bezpiecznego jej prowadzenia, bez zbędnego narażenia użytkowników na niebezpieczne czynniki pożaru. Natomiast wraz ze wzrostem szybkości rozwoju pożaru rośnie poziom bezpieczeństwa przy zastosowaniu zoptymalizowanego oznakowania. W badaniach udowodniono również skuteczność modelu względnej długości drogi ewakuacyjnej do wyjść ewakuacyjnych. Niniejsze badania są rozwinięciem analiz przeprowadzonych przez Choi i Chi, w których wykorzystano teorię grafów oraz ryzyko narażenia na dym użytkowników przemieszczających się poszczególnymi odcinkami drogi ewakuacyjnej.
Słowa kluczowe: instalacje przeciwpożarowe, oświetlenie ewakuacyjne, oznakowanie dróg ewakuacyjnych, kierowanie procesem ewakuacji

In the article, the authors present the results of model tests indicating the need for evacuation guidance systems to improve evacuation safety. The architecture of traffic routes and the internal layout of obstacles in the building mean that conducting evacuation in a safe manner is not synonymous with conducting it by the shortest possible route. This is particularly noticeable when there is a danger on the shortest possible evacuation route for the user. Analyses for design fires regardless of the speed of their development have shown that optimized evacuation signage dependent on the location of the danger leads to a safer way of conducting it, without unnecessarily exposing users to dangerous factors of the fire. On the other hand, as the speed of fire development increases, the level of safety increases with optimized signage. The study also proved the effectiveness of the model of the relative length of the escape route to emergency exits. The present research is an extension of the analysis conducted by Choi and Chi, which used graph theory and the risk of smoke exposure for users moving along different sections of the escape route.
Keywords: fire protection systems, evacuation lighting, evacuation signage, evacuation management

Introduction

According to Polish regulations [1, 2], evacuation safety is mainly ensured by proper design and marking of evacuation routes and exits and by the use of emergency evacuation lighting. A fire safety device such as emergency evacuation lighting is mostly implemented together with illuminated evacuation signage. Current legislation allows the use of static evacuation signage in buildings. They are designed at the stage of creating the construction project and updated during the use of the building. By design, static escape route and exit signage, regardless of the fact that the signs are illuminated, conveys to the building user a single focused message on how to evacuate the building. It is up to the decision of the building user to choose an alternative escape route in case the escape route specified by the escape signs is too dangerous or inaccessible. For users who are very familiar with the facility, this should not pose much of a problem, as opposed to those unfamiliar with its topography. People in the building for the first time may be confused in such a situation and may make wrong decisions during the evacuation process. This problem was noticed a dozen years ago, among other things, when research work was conducted on the possibility of using dynamic (adaptive) evacuation lighting (signage) systems [3]. Due to the wide scale of research around the world related to evacuation safety, there are many solutions, concepts, models that collectively can be referred to as **evacuation guidance**

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systems. Previous analyses have led to the identification of many relationships and conditions under which the use of evacuation management systems can bring tangible and positive effects on the safety of people in the building. The authors of the article address the issue of analyzing the impact of the location of the threat, fire on the appropriate management of the evacuation process. This article will present research on the safety level of the evacuation process for standard and optimized evacuation signage.

Evacuation management systems

When proceeding to analyze the possibilities of guiding the evacuation process, it is necessary to introduce a classification of existing solutions. The proposal for classification is aimed at systematizing the nomenclature of proprietary systems and concepts commonly found in the literature.

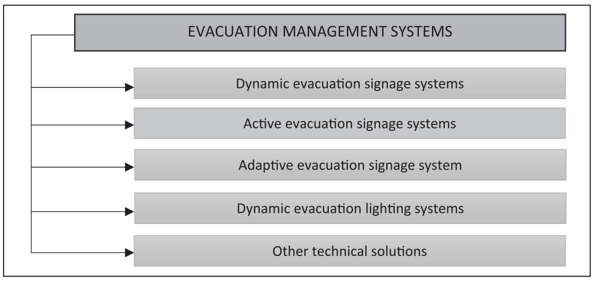


Figure 1: Classification of evacuation management systems. Source: own elaboration based on [3-11]
Rysunek 1. Klasyfikacja systemów kierowania procesem ewakuacji. Źródło: opracowanie własne na podstawie [3-11]

The main purpose of using evacuation management systems is to guide building occupants in such a way that the risk of exposing them to dangerous threat factors is minimized and that they leave the building within the available time for safe evacuation.

Minimum operating time for signage and evacuation lighting

Evacuation signage should function properly outside the immediate area of fire for the available safe evacuation time. The available ASET safe evacuation time ultimately ends when the fire resistance of the building's main supporting structure and the strength of the ASET escape route enclosure is lost$_{FRR}$.

$$RSET + SM \leq ASET_{FRR} \qquad (1)$$

$ASET_{FRR}$ for the most part will be longer than the available safe evacuation time occurring locally in the area of the facility where the fire is developing. The required RSET safe evacuation time should be at least equal to, if not longer than, the sum of the available safe evacuation time and the SM safety margin. When analyzing various evacuation scenarios, it is necessary to move within the limit of at least $ASET_{FRR}$. A significant portion of industrial facilities are made as steel structures. Such structures without adequate fire protection provide a fire resistance of up to 15 min (R 15). The strength of unprotected structures is evaluated using engineering tools such as the SAFIR program. A 10 percent safety margin is necessary when conducting evacuation from such a facility [12]. The adoption of a 10% safety margin applies only to those projects for which the reliability of the input data is very high. For projects with low input reliability, a safety margin of 100% RSET should be adopted.

Initial assumptions

Conducting a proper analysis requires determining the course of many processes. The course of evacuation under different conditions of fire development (hazard) will allow evaluation of the proposed method of guiding the evacuation process.

The study will modify the directions of movement of people in accordance with the proposed evacuation signage, depending on the strength of the fire. Four basic rates of fire development were assumed – slow, medium, fast and very fast. The hazard detection time was determined to be 35.3 s using the DETACT-T2 model [13] according to the parameters specified in Table 1. People directly in the area of the fire outbreak take action in the form of activating the manual call point within 40 s from the onset of the fire. Activation of the manual call point causes the transition of the first-level alarm to the second-level alarm. From the space of the hall from which the resulting danger can be seen, people proceed to evacuate as soon as it is noticed [14]. On the other hand, people outside the immediate area of influence of the fire, from which the fire outbreak is not visible, receive information about the danger in 40 seconds from the onset of the fire. A high level of employee training was assumed, which determines alarm response times in the range of $t_{pre1\%}$ = 0 s to $t_{pre99\%}$ = 40 s, for people near the danger and $t_{pre1\%}$ = 40 s to $t_{pre99\%}$ = 100 s for people outside the fire focus.

Table 1: Assumptions of DETACT-T2 program for calculation of detection time. Source: own study
Tabela 1. Założenia programu DETACT-T2 do obliczenia czasu detekcji. Źródło: opracowanie własne

Parameter	Value
Ambient temperaturę	25 °C
Response Time Index (RTI)	5
Activation temperaturę	30 °C
Room height	3.8 m
Distance between sensing elements	4 m

Considering that industrial facilities have a low density of people distribution, a factor of 30m^2/person was adopted [2]. Taking into account the directly usable area of about 2 500 m^2, the building can accommodate 82 people. For the purpose of the study, a design fire with a maximum power of 2 MW was assumed. The maximum power of 2 MW, depending on the rate of development, is reached by the fire after the time indicated in Table 2.

Table 2 Fire development parameters. Source: own study
Tabela 2. Parametry rozwoju pożarów. Źródło: opracowanie własne

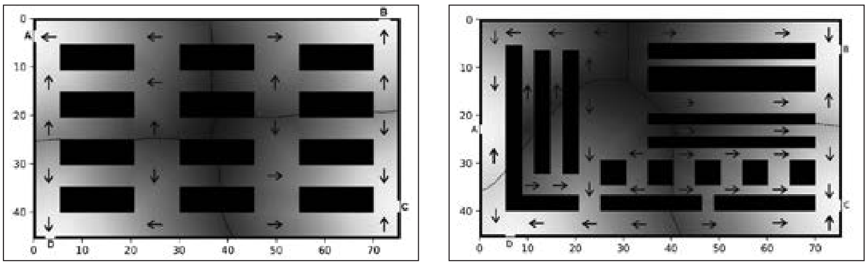
The rate of fire development	α	Time to reach maximum power of 2 MW
Slow	0.00293	826 s
Medium	0.01172	441 s
Fast	0.04689	225 s
Ultra fast	0.18760	121 s

Research

Modeling of fire development and the evacuation process was carried out for two scenarios of evacuation signage: S1 – static signage leading by the shortest route to the nearest emergency exit and S2 – dynamic signage. A model proposed in the publication [15] using the relative length of the evacuation route was used to determine the optimal evacuation directions. Implementation of the model using elements of cellular automata was realized using the Python programming language. The development of algorithms used the Numpy and Matplotlib programming library. The analysis was carried out for two arrangements of the interior of the 76 x 46 m facility. Arrangement A1 inspired by the facility proposed in the publication [16], and arrangement A2 prepared for this publication. The analyses were carried out for different room heights: 3.8 m, 4.8 m and 6.8 m.

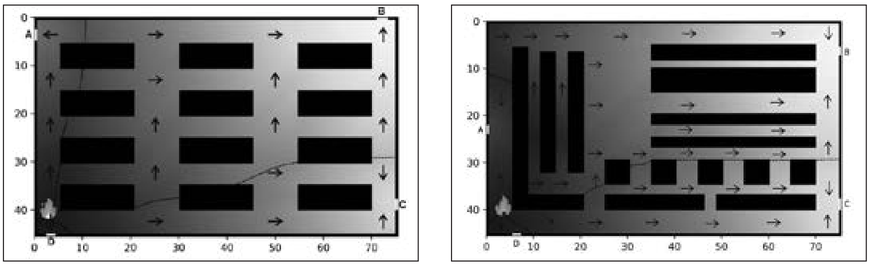
In the basic scenario S1 taking into account the static marking of the escape routes leads people according to the shortest escape route – Figure 2. Static marking is implemented at the stage of commissioning the facility for use and does not reflect the actual location of the danger that may occur in the facility. It is up to the users of the facility to decide whether to change the direction of evacuation. Such a change may be dictated by the conditions of fire development in the place to which the evacuation marking leads.

In the S2 optimized scenario, which takes into account the location of the fire at evacuation exit D, the method of evacuation is



a) b)

Figure 2.
Plan of the facility with standard (static) evacuation signage: a) interior arrangement A1, b) interior arrangement A2. Source: own study
Rysunek 2. Rzut obiektu ze standardowym (statycznym) oznakowaniem ewakuacyjnym: a) aranżacja wnętrza A1, b) aranżacja wnętrza A2. Źródło: opracowanie własne



a) b)

Figure 3.
The floor plan of the facility with optimized evacuation signage: a) interior arrangement A1, b) interior arrangement A2. Source: own study
Rysunek 3. Rzut obiektu z zoptymalizowanym oznakowaniem ewakuacyjnym: a) aranżacja wnętrza A1, b) aranżacja wnętrza A2. Źródło: opracowanie własne

shown in Figure 3. The determination of evacuation directions according to the model [15] is possible only if we know the location of the hazard present.

The location of the fire was selected as the most unfavorable at one of the emergency exits, taking into account the C/VM2 guidelines [17]. Determining the location of fire origin in an actual facility is made possible by fire alarm systems with point addressable detection elements. The fire alarm system is necessary to implement an appropriate evacuation scenario. The evacuation scenario can be activated, already at the stage of the first-level alarm, even before the announcement of a general fire alarm (second-level alarm). Information about the location of activation of the manual call point should not provide information to guide the evacuation process, since its activation is not necessarily correlated with the location of the fire. A pressed manual call point at a location other than the fire origin could lead to the selection of an incorrect evacuation scenario. On the other hand, the use of a manual call point together with fire detection by addressable detectors could lead to a general alarm and an evacuation scenario according to the location of the detection element. Activation of the fire alarm can take place in case of fire detection by two detectors or by a detector and a manual call point. The entry of the fire alarm system into the state of the second level alarm allows alerting all persons outside the immediate area of the fire. The evacuation process was analyzed using FDS 6.7.5 and EVAC 2.5.2 software.

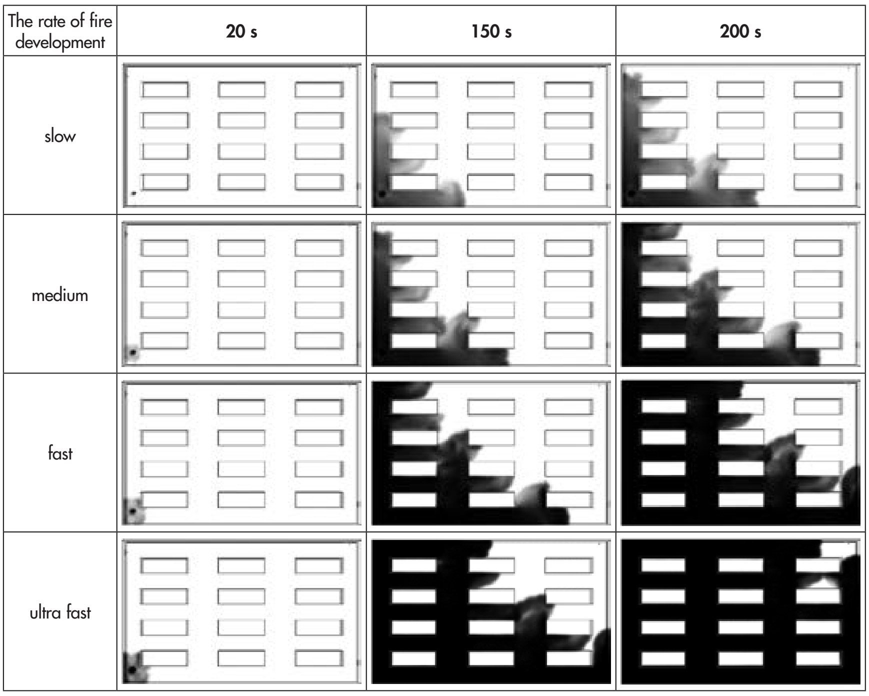


Figure 4:
Visualization of the spread of smoke in the facility depending on the rate of fire development for interior arrangement A1. Source: own development
Rysunek 4. Wizualizacja rozprzestrzeniania się dymu w obiekcie w zależności od szybkości rozwoju pożaru dla aranżacji wnętrza A1. Źródło: opracowanie własne

Depending on the rate of fire development, fire gases and smoke spread through the facility at different rates. The process of smoke spread depending on the rate of fire development is shown in Figures 4 and 5.

The main factor affecting evacuating people outside the fire focus is smoke containing toxic, suffocating and irritating gases. Only within the fire focus can evacuees be exposed to elevated environmental temperatures and thermal radiation. Depending on the speed of fire development, smoke and fire gases spread at different speeds. In a very fast fire, smoke in the ceiling layer spreads faster than people move.

The research conducted showed that in the S1 scenario, the process of leaving the building starts faster, as more people reach the nearest emergency exits. On the other hand, in the S2 scenario, leaving the facility by evacuees is prolonged by about 10-20 seconds. This is due to the need to travel a much longer evacuation route leading to safe emergency exits. Regardless of the height of the analyzed room, the evacuation process is very similar. The evacuation process is influenced only by the adopted evacuation scenario and the speed of fire development.

Analyzing the course of movement of people depending on the speed of fire development, there are no major differences in the way people move in the initial stage of the process. However, evacuation is definitely prolonged in its final stage in the case of scenario S1 (static marking) for fast and very fast fires. This is due to the fact that after 150 s from the onset of the fire, smoke for fast and very fast fires covers at least half of the facility's space. The last evacuees are forced to change the direction of evacuation due to increasing smoke on the marked evacuation route. It takes considerably longer to cover the new route, and sometimes leads to wandering around the facility and staying there. From the perspective of analyzing the number of people in the facility, one might assume that the

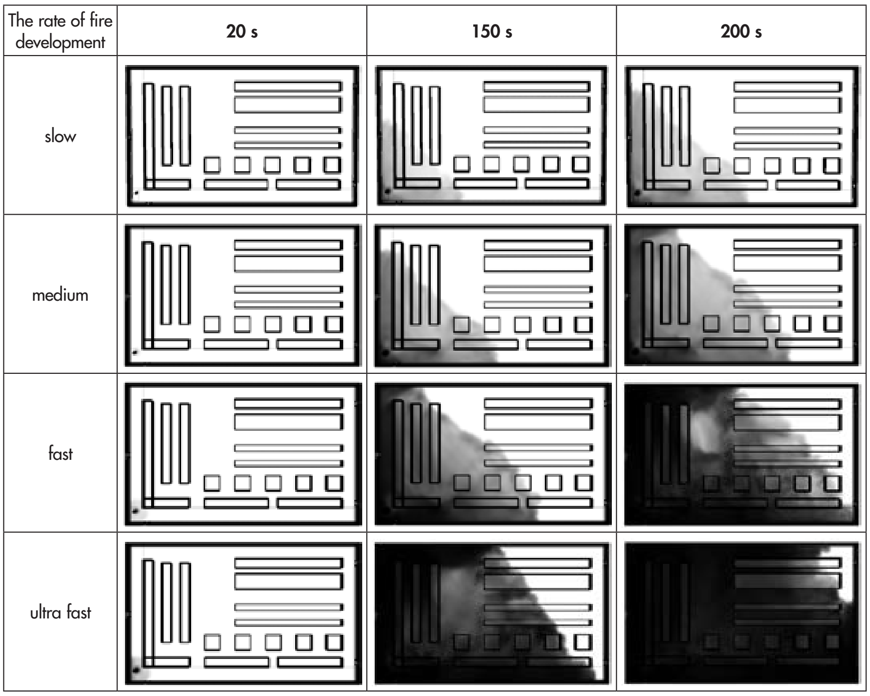


Figure 5:
Visualization of the spread of smoke in the facility depending on the rate of fire development for the A2 interior arrangement. Source: own development
Rysunek 5. Wizualizacja rozprzestrzeniania się dymu w obiekcie w zależności od szybkości rozwoju pożaru dla aranżacji wnętrza A2. Źródło: opracowanie własne

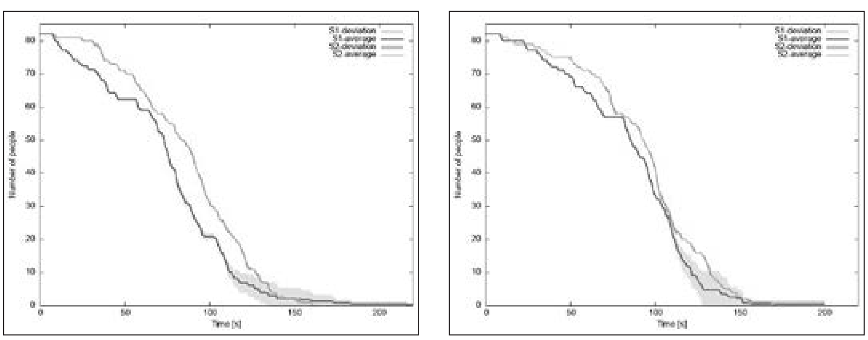


Figure 6.
Average number of people in the facility and standard deviation: a) arrangement A1, b) arrangement A2. Source: own study
Rysunek 6. Średnia liczba osób w obiekcie oraz odchylenie standardowe: a) aranżacja A1, b) aranżacja A2. Źródło: opracowanie własne

Table 3. Evacuation time depending on the evacuation scenario, the rate of fire development and the height of the building for arrangements A1 and A2. Source: own study
Tabela 3. Czas ewakuacji w zależności od scenariusza ewakuacji, szybkości rozwoju pożaru i wysokości obiektu dla aranżacji A1 i A2. Źródło: opracowanie własne

	A1						A2					
	3.8 m		4.8 m		6.8 m		3.8 m		4.8 m		6.8 m	
α	*S1*	*S2*	*S1*	*S2*	*S1*	*S2*	*S1*	*S2*	*S1*	*S2*	*S1*	*S2*
slow	140 s	162 s	137 s	162 s	137 s	162 s	152 s	169 s	153 s	170 s	153 s	169 s
medium	140 s	161 s	138 s	161 s	137 s	161 s	152 s	170 s	151 s	171 s	153 s	169 s
fast	217 s	161 s	150 s	161 s	135 s	161 s	152 s	170 s	150 s	170 s	153 s	170 s
ufast	∞	162 s	149 s	161 s	143 s	162 s	∞	171 s	151 s	169 s	152 s	169 s

S1 scenario is better, as leaving the facility is much faster than in the S2 scenario. However, this is an erroneous observation if one does not take into account the degree of exposure of evacuees to the spreading smoke. Moving people along shorter evacuation routes leads to the need to traverse often already smoky sections of it and a higher degree of exposure to dangerous fire factors – Figure 9.

From the analysis of the exposure of evacuees to fractional effective dose (FED), it is easy to see that the most exposed person takes many times higher dose for scenario S1 than for scenario S2. The degree of exposure to the fractional effective dose coincides with the health of the person after the evacuation process.

The study shows that conducting evacuations in accordance with signage determined by the location of the hazard always leads to less exposure to the effects of fire. Definitely better effects are noticeable for rooms with greater height and for fires developing at slow, medium and fast rates. For fires developing very quickly, the difference is small. This is due to the fact that the products of combustion spread at a speed similar to that of moving people.

As exposure to the partial effective dose increases, the risk of the effects of combustion products, temperature and thermal radiation on evacuating people increases. The likelihood of first aid services, such as oxygen therapy, burn cooling, among others, also increases. Exposure to dangerous thermal decomposition products can also contribute to the onset of conditions later on, such as respiratory problems, asthma, allergies or even cancer [18, 19]. Therefore, it should be important in the evacuation process to limit its participants' exposure to fire gases.

Static evacuation signage guides people to the nearest emergency exits. Users who are outside the focus of the fire are notified of the danger only at the stage of the second-level alarm. Taking into account the reaction time to the sounded alarm, they start moving along evacuation routes when the fire is already developed. People moving toward the nearest emergency exit may encounter conditions that limit visibility or even prevent evacuation to the outside. Inhaling irritating and suffocating smoke, they become disoriented and, in uncoordinated movements, may become stuck in the smoky and dangerous space of the facility.

Studies have shown that guiding the evacuation process is necessary to ensure a higher, and sometimes necessary, level of safety. The concept of using evacuation guidance systems is becoming essential in the face of intensive construction development.

Discussion

The study clearly shows that proper management of the evacuation process reduces the risk of exposing people to the dangerous effects of the fire environment. The coexistence of a fire alarm system and dynamic evacuation signage can help improve evacuation safety. Actions are needed to make designers and then facility managers aware of the benefits of using a fire alarm system and dynamic evacuation signage to significantly improve the safety level of a facility. The public and legislators should be made aware that current legislation has not kept pace with progress. Ongoing studies in the field of evacuation management capabilities show that this is the right direction to improve the safety of facilities. However, the proper design of systems for directing the evacuation process requires a lot of analysis, so as not to lead to a situation of worsening conditions in the case of very fast-developing fires.

Studies conducted on the basis of the algorithm [15] show without doubt that when smoke spreads at a speed less than or equal to the speed of human movement, the model

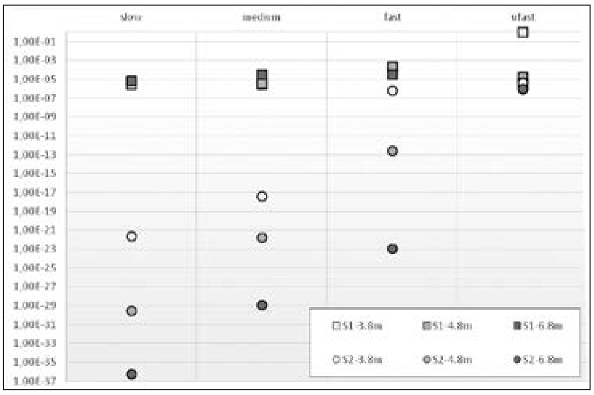


Figure 7:
Maximum value of the partial effective dose (FED) depending on the scenario and height of the facility for the A1 arrangement. Source: own study
Rysunek 7. Maksymalna wartość cząstkowej dawki skutecznej (FED) w zależności od scenariusza i wysokości obiektu dla aranżacji A1. Źródło: opracowanie własne

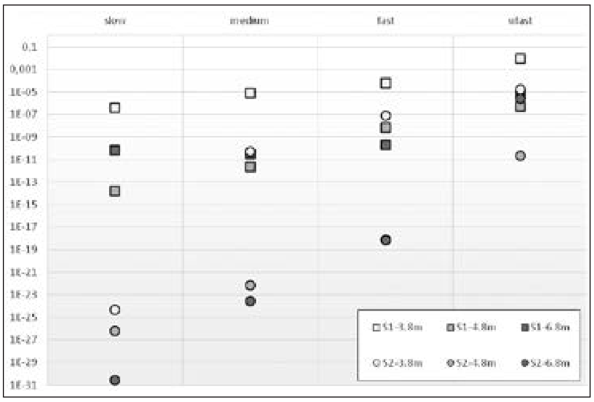


Figure 8:
Maximum value of the partial effective dose (FED) depending on the scenario and height of the facility for the A1 arrangement. Source: own study
Rysunek 8. Maksymalna wartość cząstkowej dawki skutecznej (FED) w zależności od scenariusza i wysokości obiektu dla aranżacji A1. Źródło: opracowanie własne

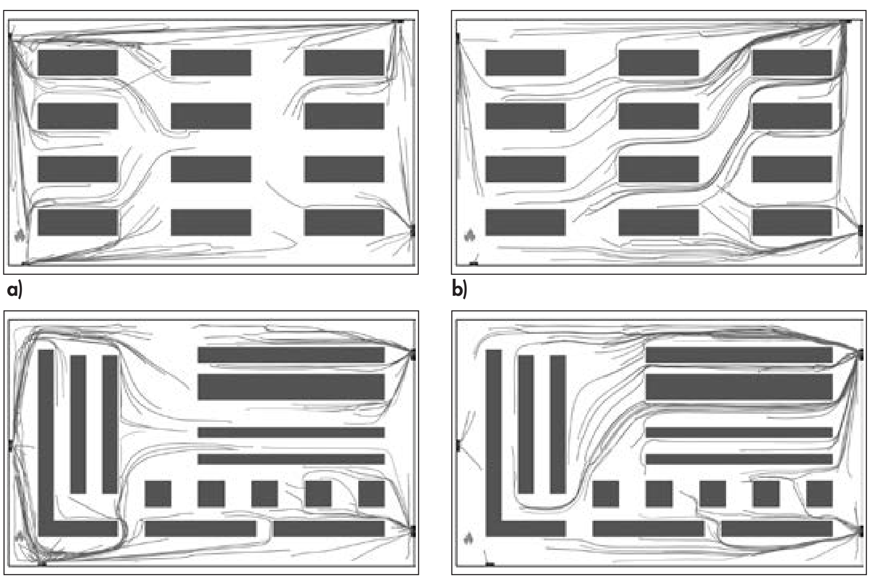


Figure 9:
Passage routes of evacuees depending on the arrangement and evacuation scenario for a very fast fire: a) A1-S1, b) A1-S2, c) A2-S1, d) A2-S2. Source: own study
Rysunek 9. Trasy przejścia ewakuujących się osób w zależności od aranżacji i scenariusza ewakuacji dla pożaru bardzo szybkiego: a) A1-S1, b) A1-S2, c) A2-S1, d) A2-S2. Źródło: opracowanie własne

provides the highest level of safety, while increasing the duration of evacuation. However, the increase in evacuation duration by 10-20 s, which is equivalent to having to travel about 10-20 m more of the evacuation route, is small compared to the benefits that accrue from repeatedly reducing the probability of exposure to hazardous fire factors.

The study also proves that for a proper assessment of evacuation safety, it is not enough just to determine the time for people to leave the facility. It is necessary to confront this with the degree of their exposure to dangerous factors of fire. It can be noted that for static marking of evacuation routes, the time to leave the facility in slow and medium fires is very optimistic because it is within 145 s. In contrast, this marking does not work at all when the speed of fire development increases. It can even lead to people remaining in the danger zone and their death.

Fire alarm system installations and evacuation signage should be designed in such a way as to ensure that their potential can be used to improve the safety of facilities.

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