Analysis of the Time of Crew Evacuation from the Hazardous Area of Mining Exploitation Using Numerical Simulation

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INTRODUCTION

Hard coal mines are vulnerable to a series of hazards that affect the safety and effectiveness of mining production (An et al., 2019; Brodny and Tutak, 2016; Brodny et al., 2018; Brodny and Tutak, 2018a; Brodny and Tutak, 2018b; Brodny and Tutak, 2019a; Brodny and Tutak, 2019b; Felka and Brodny, 2018; Fernández-Alaiz et al., 2020; Tutak and Brodny, 2017a) One of such hazards is the risk of underground fires that occur as a result of an external cause (the so-called exogenous fires) (An et al., 2019; Fernández-Alaiz et al., 2020). Another threat for the crew and continuity of the production process is also posed by endogenous fires, which are caused by spontaneous combustion of coal (Szurgacz et al., 2019; Tutak and Brodny, 2017b; Tutak and Brodny, 2018). Both types of fires are extremely dangerous for the crew and the ongoing exploitation process. However, the course of exogenous fires is more dynamic. In the event of such a fire, it is therefore necessary to very quickly withdraw the crew from the danger zone. Very often, the time for such withdrawal is very short. It is therefore crucial that this time be determined in as objective a manner as possible. This is because its correct determination may decide about the life and health of the evacuees.

There are numerous causes of exogenous fires in mine headings. Those headings contain a lot of flammable materials that can lead to such fires. One of the more common causes includes the combustion of methane which is released into the headings during coal extraction (Brodny and Tutak, 2019a; Felka and Brodny, 2018). In the Polish hard coal mining industry, there are from a few to a few dozen underground exogenous fires registered each year. In the years 2003-2019, the total number of underground fires was 93, of which more than 22% were the exogenous fires and nearly 78% – endogenous fires (Fig. 1) (Wyższy Urząd Górniczy, 2003-2019).

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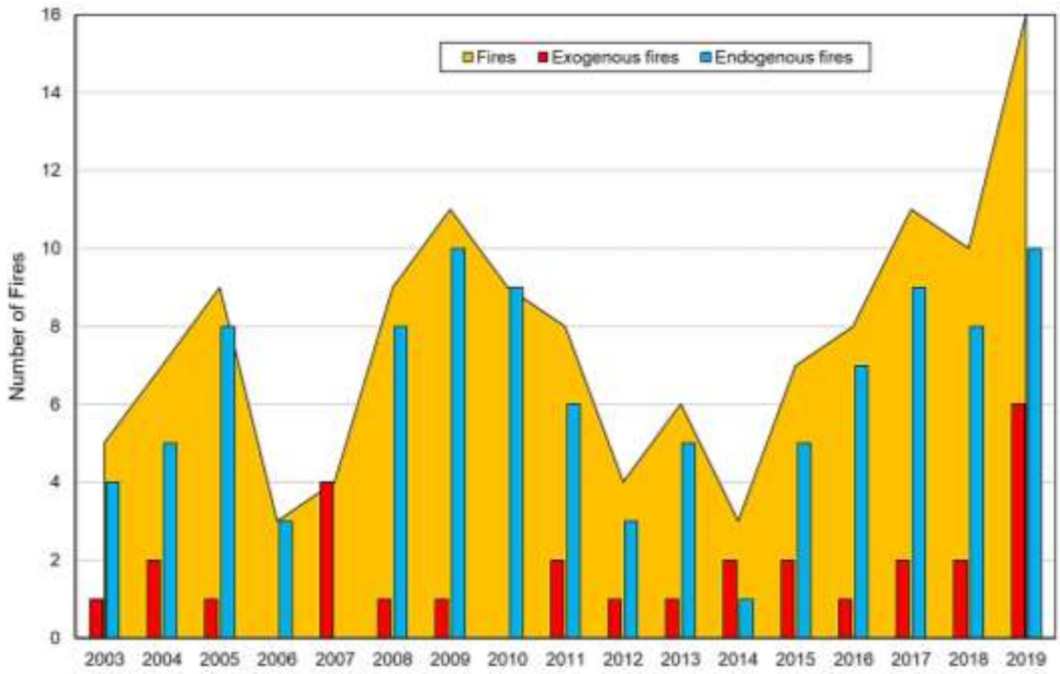

Fig 1 The number of fires in Polish hard coal mines in the years 2003-2019
Source: (Own elaboration based on data from Wyższy Urząd Górniczy, 2003-2019)

The occurrence of an underground fire in a mine heading poses an immediate threat to the life and safety of the crew, as well as disturbs the ventilation process of headings. The stream of ventilation air supplies oxygen that supports the combustion process, as well as carries smoke and gases into further mine workings (Dziurzyński and Krawczyk, 2001). Additionally, the smoke emitted during the combustion of a flammable material/substance considerably obscure visibility.

As already noted, due to the fact that underground exogenous fires appear suddenly and develop very dynamically, it is very often necessary to evacuate the crew from the danger area. This evacuation is carried out along the previously delineated paths, or the so-called escape routes. These routes are part of the Rescue Plan developed by mining plants and, at the same time, represent one of the elements of the mine's fire-fighting system. An emergency escape route in underground hard coal mines shall be understood as a system of interconnected mine headings used by crews to withdraw from the place where a dangerous incident has occurred or from the danger zone into heading which is free from this hazard. A safe heading is one where the air flow is free from any poisonous and harmful gases and other detrimental substances (emitted, for example, as a result of combustion into the heading's atmosphere), and from which crews can be safely evacuated to the surface.

An ideally determined escape route should make it possible for the crew to leave the danger area to a safe heading within less than 50-60 minutes. This is a time limit within which the operational time of a self-contained self-rescuer (SCSR) has not been exceeded. A SCSR is a device worn by each worker employed underground to be used when the atmosphere becomes unfit for breathing.

The evacuation time along escape routes is commonly determined using analytical methods (Kozdrój, 1964; Walkiewicz, 1983). The evacuation times determined by means of these methods are usually highly underestimated, which may represent a risk to the life and health of a worker when the SCSR stops working. The optimum method for determining the evacuation time, taking into account the insufficient accuracy of analytical methods, is the measurement of evacuation times along escape routes in real-world conditions.

However, it is not always possible to conduct trial rescue operations involving withdrawal of a crew along escape routes in mining conditions. It is also difficult to reproduce the actual conditions that might occur during such operations. Therefore, it becomes reasonable to determine the evacuation time of a crew from the danger area using state-of-the-art calculation methods based on numerical simulations. These methods are currently being increasingly used as research tools in numerous area of science, including the analyses of emergency states. A state of emergency shall be regarded as the occurrence of an underground fire in an underground working environment, which makes it necessary to evacuate a working crew from the danger area.

One of such modern calculation tools used for determining the evacuation times from various facilities is the Pathfinder software. This programme provides a wide range of options to determine the movement (relocation) times for large groups of employees and other individuals from danger areas.

So far, the tools based on numerical simulations have not been used for determining the evacuation times of a crew from the area under the threat of fire in an underground mine heading. For this reason, it was reasonable to conduct a relevant analysis whose results are presented in the paper. The purpose of the analysis was to determine the evacuation time of a 20-member crew from a danger area, along escape routes with the total length of 900 m. The results obtained may constitute an essential source of information for service teams responsible for ensuring the operational safety in a mine. At the same time, they pave the way for estimating the evacuation times of a crew from different regions and for different arrangements of the particular persons. As a result, it is possible to analyse different evacuation variants without interrupting the production process.

METHODOLOGY OF RESEARCH

The numerical analysis, whose purpose was to determine the evacuation time of a crew from a danger area, was conducted using the Pathfinder software . This programme is a tool that uses numerical simulations to analyse the evacuation times of individuals from danger areas. The time needed for safe withdrawal from a danger area can be determined thanks to the use of artificial intelligence (AI) algorithms in the calculations. Pathfinder is a special type of a simulator in which every single predefined individual can be ascribed many individual features that may affect his/her movement speed and decisions during evacuation. Each individual may differ from others in terms of size, appearance,

movement speed and the delay in making decisions about the escape (Pathfinder, 2019).
In the case at hand, it was assumed that the crew must evacuate themselves from the hazardous heading (longwall) where an exogenous fire has occurred. The total length of the headings forming an escape route is 900 m. The assumption was that some of the evacuees moves at the speed of 0.8 m/s, while others at the speed of 0.7 m/s. Such speed rates correspond to the evacuation of a crew under smoke conditions (Chattaraj et al., 2013; Fang et al., 2012; Jeon et al., 2011; Ko et al., 2007; Ma et al., 2012; Yang et al., 2012).
The basic parameters of the calculation model are presented in Table 1.

Table 1 The basic parameters of the calculation model

Parameters	Value
The total length of the headings, m	900.0
The width of the longwall, m	4.0
The width of the other excavations, m	5.0
The number of individuals present in the intersection area between the longwall and the tailgate	20
Average walking speed, m/s	0.8 (10 people), 0.7 (10 people)

Source: (Own elaboration)

Figure 2, on the other hand, presents the geometric model of the escape route under analysis, whereas Figure 3 – a fragment of the intersection between the longwall and the tailgate (of the danger area), along with the distribution of the crew members (top view). The model thus developed was subjected to numerical analysis.

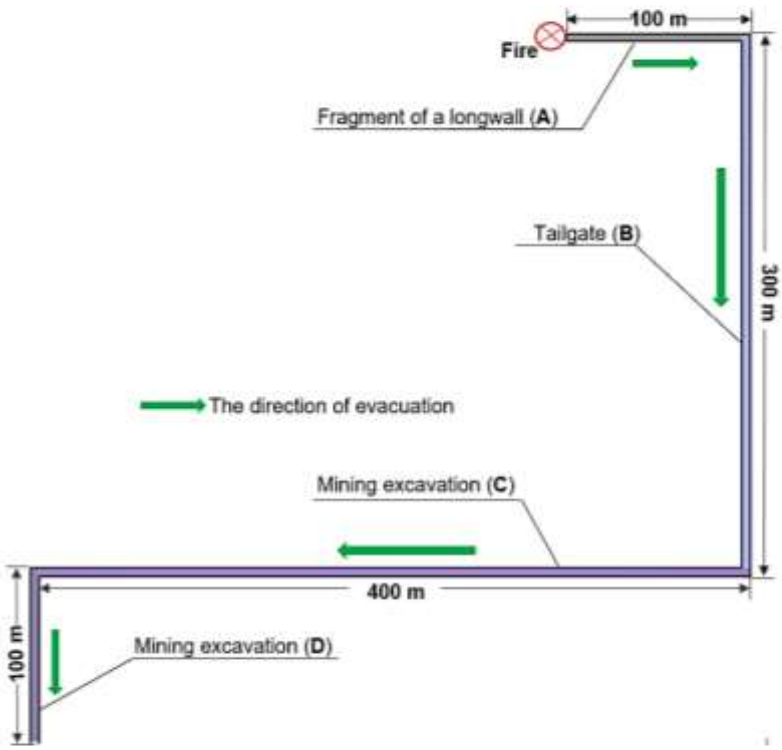

Fig. 2 The geometric scheme of the heading under analysis (a top view)
Source: (Own elaboration)

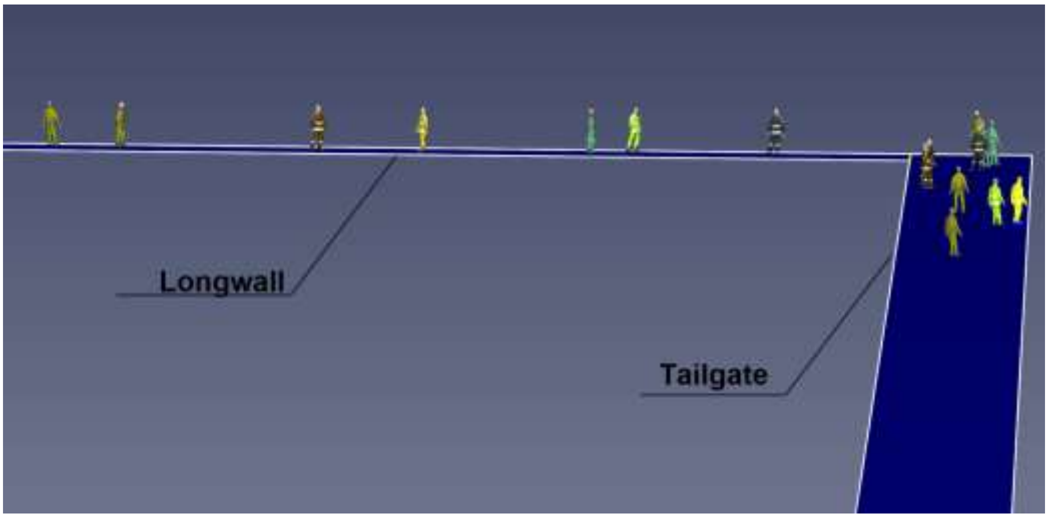

Fig. 3 A fragment of the intersection area between the longwall and the tailgate, with the distribution of a 20-member crew

Source: (Own elaboration)

RESULTS AND DISCUSSION

The calculations performed served as the basis for determining the total evacuation time of a mining crew from the danger area. The fundamental information on the results obtained in terms of the evacuation time for the variants in question are presented in Table 2, whereas Figure 4 shows the number of crew members evacuated from a heading as a function of analysis time.

Table 2 General results from the research conducted

Number of people in the mining crew	First person evacuation time	Evacuation time of the last person	Average evacuation time	Standard deviation
	s			
20	958.8	1236.3	1077.4	76.7

Source: (Own elaboration)

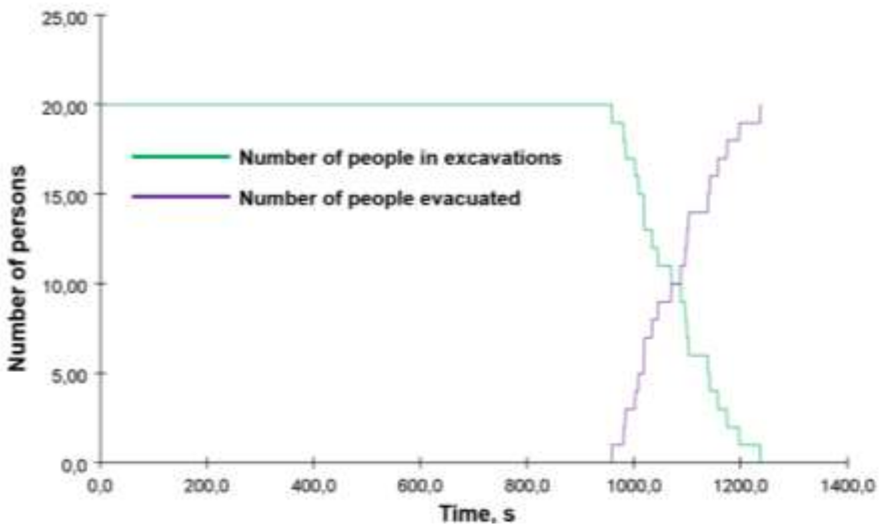

Fig. 4 The number of crew members evacuated from headings as a function of analysis time

Source: (Own elaboration)

Table 3, on the other hand, summarises the basic information about the distances that had to be covered by the evacuated crew.

Table 3 General results from the research conducted

The minimum distance to be covered	The maximum distance to be covered	The average distance to be covered	Standard deviation
m			
748.6	876.4	810.2	34.2

Source: (Own elaboration)

The calculations performed indicate that the total time needed by the last worker (of a 20-member crew) to cover the escape route amounted to 1,236.3 seconds (nearly 21 minutes). The last worker leaving the danger area had to cover the distance of approx. 876.4 m. The worker who took the shortest time to evacuate himself from the danger area covered the escape route in 958.8 seconds along the distance of 748.6 m.

Table 4 presents the times necessary for all the crew members to cover the subsequent headings comprising the escape route (illustrated in Figure 2), while Figure 5 shows the flow of the crew through the individual headings as a function of time.

Table 4 Summary of the times necessary for crew members to cover the subsequent headings comprising the escape route

Section of the escape route (heading)	The average time needed to cover the section of the escape route, s
A	92.6
B	428.9
C	572.1
D	142.4

Source: (Own elaboration)

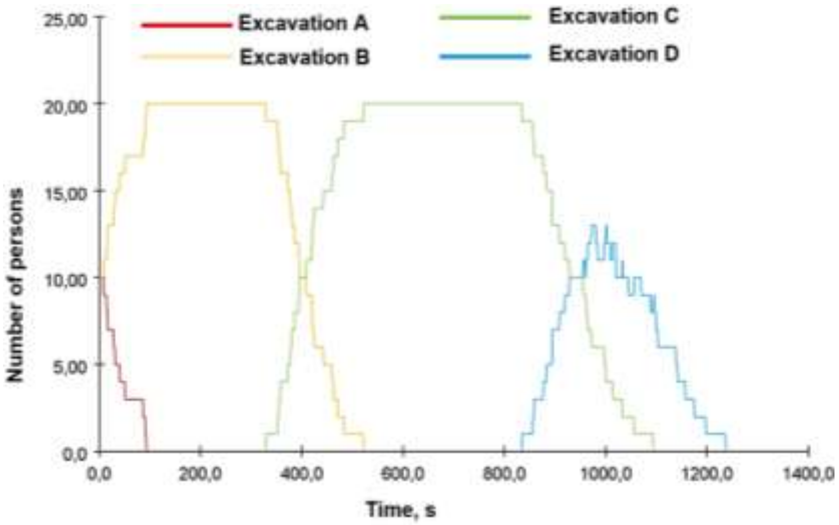

Fig. 5 The movement of crew members along the particular headings as a function of time

Source: (Own elaboration)

The calculations performed also allowed for determining the evacuation times of the last worker from the particular headings that comprise the escape route. The “A” heading (the longwall), where a fire has occurred, is left by the last crew member after 92.6 seconds from the beginning of the evacuation process. The time needed by the last evacuee to cover the distance of the subsequent headings is 428.9 seconds (the “B” heading), 572.1 seconds (the “C” heading) and 142.4 (the “D” heading) respectively.

CONCLUSION

The basic goal in the event hazard activation in hard coal mines, including the fire hazard, is to ensure safety for the crew working in the danger area. In the case of a hazardous situation, the crew must leave the danger area along the previously designated evacuation route leading to the assembly point. For the evacuation process to run smoothly, the workers must be familiar with the escape route and the time needed to cover its distance. From the perspective of work safety, it is one of the most significant responsibilities of the safety teams in mines.

The paper refers to this issue, presenting the results of model-based tests of the crew evacuation from a longwall. The purpose of the tests was to determine the evacuation time of a 20-member crew from a danger area of a longwall. The analysis encompassed an escape route with a length of 900 m, which is very close to the most common distances occurring in practice. The analysis also encompassed four different headings intersected by the evacuation route under analysis.

The results revealed that the total evacuation time for workers moving with the speed corresponding to the movement speed in a heading filled with smoke (with considerably reduced visibility) amounts to approx. 21 minutes. The time needed to cover the designated escape route depends on the place where a given worker is at the beginning of the evacuation process. The closer to the assembly point he is at the beginning of evacuation, the shorter the time to cover the escape route.

The model developed and the tool used offer great opportunities in terms of analysing emergencies and the related necessity to evacuate the workers. There is no doubt that the results obtained should be used for the development of safety procedures in the process of mining exploitation

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Abstract: Hard coal mines are vulnerable to a series of hazards that affect the safety and effectiveness of mining production. One of such hazards is the risk of underground fires. As the exogenous underground fires appear suddenly and have a highly dynamic course, it is very often necessary to quickly evacuate the crew from the danger area. The time needed to evacuate the crew from the danger area is most commonly determined by means of analytical methods, which provide a very general calculation. Therefore, it becomes necessary to also make use of other methods and tools for determining this time. Undoubtedly, such characteristics are offered by modern calculation methods based on the artificial intelligence (AI) algorithm and characterised by high accuracy. The paper presents a sample application of such a method for evacuating a 20-member crew from the heading under threat. In order to determine the evacuation time for those individuals, a calculation model was built for the total length of the escape routes equal to 900 m. The results revealed that the total evacuation time for workers moving with the speed corresponding to the movement speed in a heading filled with smoke (with considerably reduced visibility) will amount to approx. 21 minutes. The results obtained may constitute an essential source of information for service teams responsible for ensuring the operational safety in mine headings. At the same time, the model developed allows for broader application to the estimation of crew evacuation times from danger areas.

Keywords: fire hazard, evacuation, mining operations, escape routes