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Simulation and optimization of evacuation routes in case of fire in underground mines

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ABSTRACT

Risks of fire occurrence in underground mines are known for a long time. Evacuation and rescue plans allow to each underground mine to respond and establish control in case of emergency. The primary goal of this paper is to determine the optimal system for evacuation in case of fire in underground mines and through a process of computer simulation to be presented to all workers that are affected by this issue. In this study is developed a system that allows by using available software to work out the complete evacuation plans that include analysis of fire scenarios and optimal routes for evacuation. With development of database of fire scenarios, it is possible to plan routes for evacuation in all situations. This presented methodology can serve to make effective system for evacuation and rescue in case of fire and to help save lives and protect the financial investment in the mine. This methodology represents the most economical option of making an effective system for evacuation and also can serve as an idea of making a software package that includes all the steps of making a system for evacuation and rescue in case of fire in underground mines. This presented model will have increased accuracy compared to other models presented so far, because of the prepared 3D model of the underground mine which includes the actual dimensions of the mine along with its associated elements from which the fire dynamics and system for evacuation depends.

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1. Introduction

To successfully deal and reduce the consequences that can arise from fires in underground mines, it is necessary to previously prepare plan for evacuation and rescue in emergencies situations which will be presented to all workers in the mine (Conti, Chasko, & Wiehagen, 2005). The main risks for people who are affected by a fire scenario in underground mines are the generated smoke, harmful products of combustion, poor visibility, heat, etc (Derosa, 2004). Appropriate criteria that are needed to be taken in relation to the safety of workers during a fire scenario are the measures taken to deal with toxic gases, smoke, heat, poor visibility, extinguishing the fire, etc. The main focus during the preparation of an optimal system for evacuation from possible fire scenarios, should be determining the spread and movement of smoke and toxic gases through underground mining facilities (Klote, 2002). The systematic

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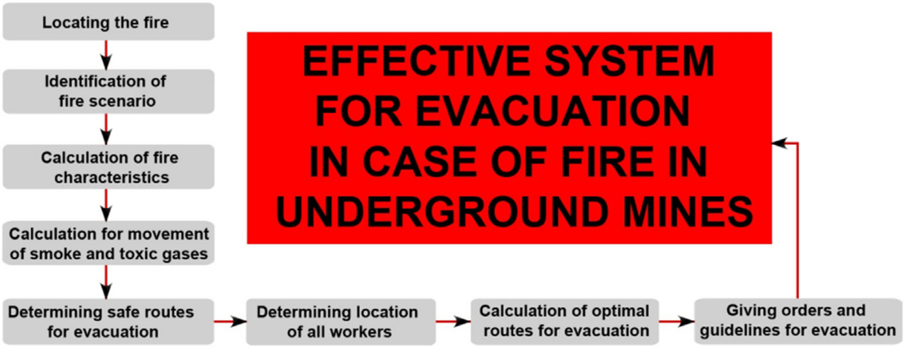

Fig. 1 – Model for evacuation in case of fire in underground mines.

model for evacuation in case of fire in underground mines which will be presented in this paper is described in Fig. 1.

For the purposes of this research paper is used PyroSim and MINEFIRE PRO + software packages.

Computer program PyroSim is a graphical user interface for the Fire Dynamics Simulator (FDS) (PyroSim User Manual, 2012). FDS models can predict smoke, temperature, carbon monoxide, and other substances during fires. The results of these simulations have been used to ensure the safety of buildings before construction, evaluate safety options of existing buildings, reconstruct fires for post-accident investigation, and assist in firefighter training. FDS is a powerful fire simulator which was developed at the National Institute of Standards and Technology (NIST). FDS simulates fire scenarios using computational fluid dynamics (CFD) optimized for low-speed, thermally-driven flow. This approach is very flexible and can be applied to fires ranging from stove-tops to oil storage tanks.

Computer program MINEFIRE PRO + is designed to simulate a mine ventilation system's response to external influences such as fires (MineFire Pro+, 2013). Given data that describes the geometry of the mine network, airway resistances, dimensions, characteristic curves of fans and characteristics of the fire or thermal event, the program will provide tabular representations of various predicted ventilation, contaminant, and temperature parameters as well as graphical representation of the ventilation system and fume front propagation over selected time increments. This information can then be used to show the effects of the thermal event on the system, and modify designs accordingly if engineering judgment deems proper. MINEFIRE PRO+ is designed to assist the mine ventilation practitioner with the prediction of spread of contaminants, heat, or other changes in air density.

2. Methods

2.1. *Modeling and identification of fire scenarios*

The modeled fire scenario is necessary to describe the assumed characteristics of the fire such as: heat release rate, generation of harmful fire gases, smoke, burning rate of the material, generated heat from fire, etc. To determine the characteristics of fire parameters that represent the basic data of modeling a fire scenario, we will be using the computer program Pyrosim (PyroSim User Manual, 2012). Based primarily on the available statistics, the following types of flammable materials in underground mines are identified as those with higher grade of fire risk (Zalosh, 2003):

- Accumulation of flammable liquids (oil, diesel fuel, lubricants, hydraulic fluids);
- Working machinery;
- Conveyors;
- Tires;
- Cables.

Each of these areas where these flammable materials are present must be examined by experts and engineering personnel and the seriousness of each fire scenario are determined by the potential frequency of the hazard, number of people affected, potential spread of contaminants, cost of damage etc. The more formal, team-based risk assessment for identification of potential fire location scenarios, include the following:

- Reviewing an entire work area;
- Reviewing statistical data of past injuries;
- Observing introduction to new working process;
- Implementing of new equipment;
- Reviewing manuals for working processes;
- Observing sources of danger associated to the process' tasks/activities.

2.2. *System for evacuation and rescue based on the movement of smoke and fire gases thought underground mining facilities*

Spread and movement of smoke and fire gases in underground mines will determine the security of evacuation and the operation of rescue services. To make an effective system for evacuation it is necessary first to determine and calculate the movement of smoke and fire gases for every predicted and identified fire scenario and to use this information to calculate the optimal routes for evacuation and rescue in the underground mine. For calculation of the movement of smoke and fire gases for specified fire scenario in previously identify location in underground mine will use the computer

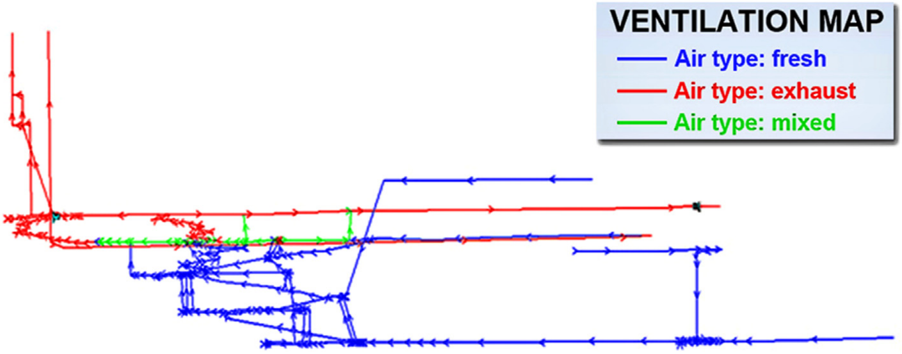

Fig. 2 – Ventilation network of underground mine "Sasa" – R. Macedonia, build in MINEFIRE PRO+.

Table 1 – Values of the coefficient a_h

Thickness of layer smoke and fire gases (m)	Coefficient a_h
>6	0
4–6	0.1
2–4	0.5
1.8–2	1
1.6–1.8	2
1.4–1.6	5
1–1.4	10
<1	100

Table 2 – Values of the coefficient L_r

Visibility distance (m)	Coefficient L_r
>20	1
10–20	1.25
5–10	2.95
3–5	6.25
<3	12.5

program MINEFIRE PRO+ (MineFire Pro+, 2013). For MINEFIRE PRO+ to calculate the movement of smoke and fire gases through the underground mine, it requires the following inputs:

- 3D mine ventilation network which can be prepared in the same software;
- Volume flow of smoke and fire gases generated by the fire, (m^3/s);
- Concentration of carbon monoxide in the volume flow of smoke and fire gases CO, (%);
- Heat flow from fire, (kW);
- Concentration of oxygen in the fire place O_2, (%);
- Volume flow of air in the branch Q, (m^3/s);
- Time for complete development of the fire (min).

All necessary fire input parameters for the computer program MINEFIRE PRO+ will be calculated in the software package for modeling fires Pyrosim (Fig. 2).

2.3. *Optimization of routes for evacuation in case of fire in underground mines*

To calculate the optimal routes for evacuation in case of fire in underground mines, we need more data related to the character of the mine. In case of fire, the factors that affect the evacuation process is complicated and complex. Some of these factors in the underground mines include the following data (Guangwei & Dandan, 2012):

- Mining roadway type;
- Mining roadway slope;
- The impact of smoke and fire gases.

First, in each mining roadway branch is calculated coefficient of influence of each of these factors. These factors influence human escape speed. The influences of these factors to the escape speed are transformed to the mining roadway's equivalent length. Equation (1) gives the calculation method of the mining roadway equivalent lengths and these are used as

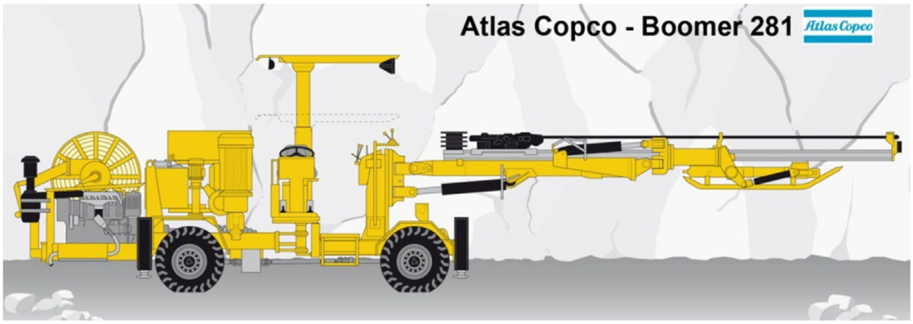

Fig. 3 – Boomer 281.

Table 3 – Properties of hydraulic fluid.

Hydraulic fluid	
Hydraulic fluid in the tank	124 L
Density of hydraulic fluid (Totten, Westbrook, & Shah, 2003)	760 kg/m^3
Simplified chemical hydrocarbon formula of hydraulic fluid	$C_{36}H_{74}$
Heat of combustion	48,544 kJ/kg
Burning rate of material (experimental data) (Roh, Ryou, & Kim, 2007)	0.039 kg/m^2*s

weights of evacuation route. The evacuation route that will have the smallest value of weight will be optimal route for evacuation.

2.3.1. *Calculation of mining roadway weights*

2.3.1.1. Calculation of mining roadway equivalent length. The impact of these factors on the speed of evacuation is transformed into an equivalent length of routes for evacuation and also represent a total weight of evacuation route (Equation (1)) (Guangwei & Dandan, 2012).

$$l_i = (k_{ti}*k_{gi}*k_{vi})*l_{ri} \tag{1}$$

where:

l_i – equivalent length of the mining roadway (weight of evacuation route);

k_{ti} – mining roadway type influence coefficient;

k_{gi} – mining roadway slope influence coefficient;

k_{vi} – smoke concentrations influence coefficient;

l_{ri} – actual length of the mining roadway.

We denote the human normal walking speed by v_0. Under the influence of the mining roadway type coefficient k_{ti}, the human escape speed is equals to $v = \frac{v_0}{k_{ti}}$. These above coefficients are previously defined, and under their common influence, the escape speed is equals to:

$$v = \frac{v_0}{k_{ti}*k_{gi}*k_{vi}} \tag{2}$$

Through Equation (1), we can calculate the escape time $t = \frac{l_{ri}}{v}$, or as $t = \frac{l_i}{v_0}$.

2.3.1.2. Mining roadway type influence coefficient. The type of underground mining facility can affect the speed of evacuation in case of emergency situation. For example if people faced with an emergency situation are in a mining facility where is transportation systems, then the speed of evacuation will be equal to the speed of the available transportation

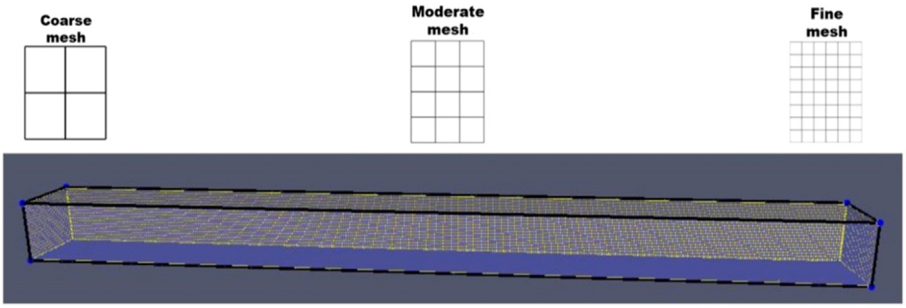

Fig. 4 – Process of modeling moderate mesh in computer program PyroSim.

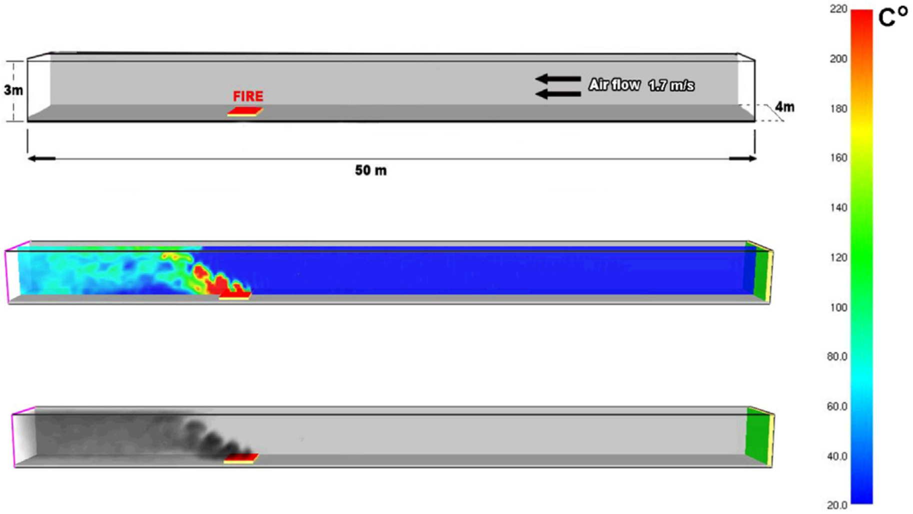

Fig. 5 – CFD simulation of selected fire scenario in computer program PyroSim.

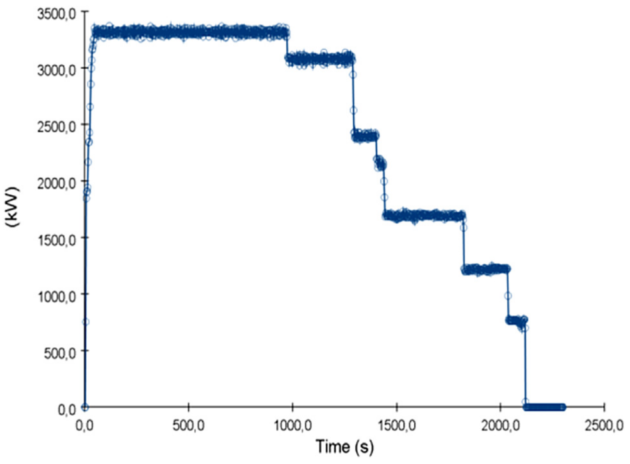

Fig. 6 – Heat release rate.

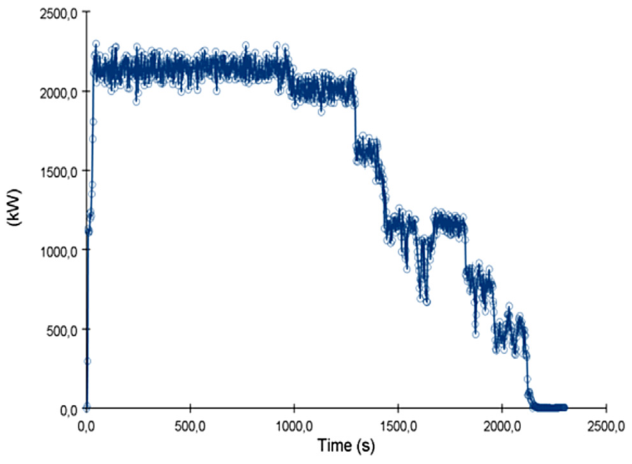

Fig. 8 – Heat flow.

system. Mining roadway type influence coefficient can be calculated as (Guangwei & Dandan, 2012):

$$k_{ti} = \frac{\upsilon_0}{\upsilon_t} \tag{3}$$

where:
υ_0 – speed of normal movement of human, m/s;
υ_t – speed of the transportation system, m/s.

2.3.1.3. *Mining roadway slope influence*. Gradient of the mining roadway, greatly influences the human walking speed. Greater the value of slope, greater the resistance of movement. To calculate the impact ratio of the mining roadway slope influence coefficient we use the following equation (Guangwei & Dandan, 2012):

$$k_{gi} = \frac{mg\upsilon_0 sin\theta_i}{P_0} + cos\theta_i \tag{4}$$

where:

m – standard human mass, kg (we will assume m = 80 kg);
g – gravitational acceleration, m/s^2;
υ_0 – human normal walking speed, m/s;
θ_i – mining roadway angle of slope, degrees;
P_0 – human's walking power, W (we will assume $P_0 = 200$ W).

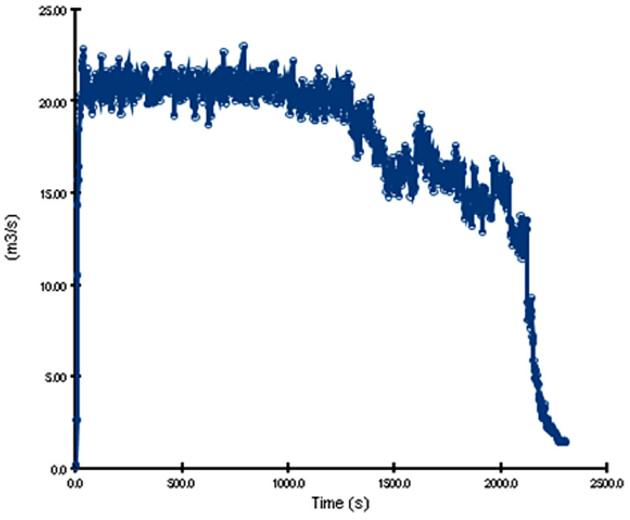

Fig. 7 – Volume flow of smoke and fire gases generated by the fire.

When workers move to down slope and horizontal mining roadways, we assume normal speed of movement of human, and the coefficient is. $k_{gi} = 1$.

2.3.1.4. *Impact of smoke and fire gasses*. Harmful and toxic properties of the smoke has long been known and defined as one of the main causes of death consequences in case of fire. The concentration of smoke and fire gases have a major impact in the safe evacuation and the speed of withdrawal. Coefficient of the impact of smoke and fire gases are calculated using the following equation (Guangwei & Dandan, 2012):

$$k_{\upsilon i} = (1 + a_h + L_r) \tag{5}$$

where:

a_h – effecting coefficient of the thickness of layer smoke and fire gases (Table 1)
L_r – affecting coefficient of visibility (Table 2).

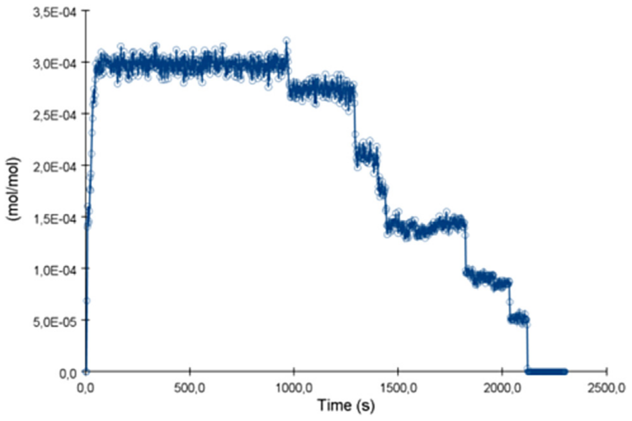

Fig. 9 – Generation of carbon monoxide from fire.

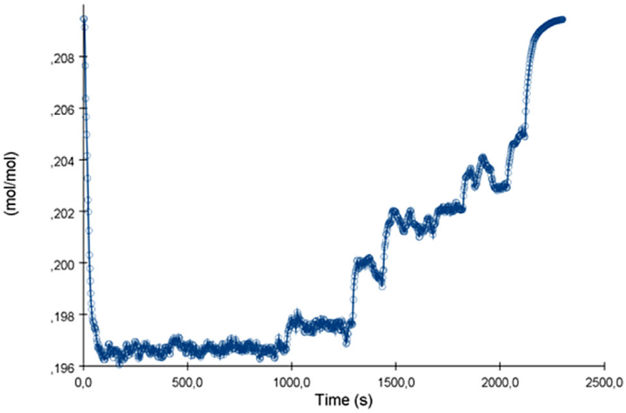

Fig. 10 – Oxygen in fire place.

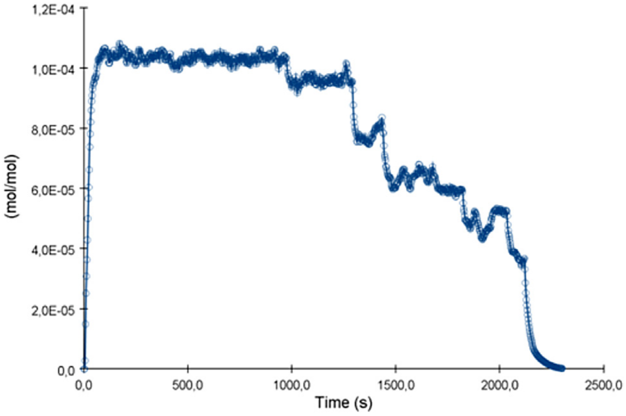

Fig. 11 – Generating soot from fire.

3. Results and discussion

3.1. *Modeling fire scenario caused by working machinery*

Fire models describes the fire characteristics, such as for example (Hansen, 2010): heat release rate, heat flow, burning rate of material, generating toxic gases, smoke, etc. In this paper we will model fire scenario in which we will assume a mechanical problem of the working machinery Boomer 281 (Fig. 3), from which the hydraulic fluid will leak from the tank and will ignite (Table 3).

For the purposes of this research paper, in computer program PyroSim is prepared 3D computer underground mining drift with the following dimensions: width of 4 m, height of 3 m and length of 50 m, in which is simulated fire scenario from mechanical problem of the working machinery Boomer 281 (Fig. 3), from which the hydraulic fluid will leak from the tank and will ignite. In the analysis and calculations made in computer program Pyrosim also is included the actual ventilation air speed of 1.7 m/s that corresponding to the selected fire location. In this large eddy simulation (LES), the grid size is an important factor to be considered. A smaller gird size gives more detailed information of the turbulent flow but needs more computation resource and longer computing time. For this simulation, we take into account a moderate cell size (dx) of 14.88 cm (Fig. 4). The mesh line for FDS is as follows:

- actual (dx) size is 0.148(x), 0.139(y) 0.15(z), m;
- distances are 4(x), 50(y), 3(z), m;
- total number of cells is 194,400.

At low air velocity in case of fire in underground mines, the effect of smoke rollback is often present (Adjiski, 2014). The process of smoke rollback can be dangerous and potentially fatal threat to miners and mine rescue teams. A smoke rollback effect usually occurs when the air velocity (ventilation) is too low in dependence of fire intensity. Results from computer program PyroSim show that for the specified fire scenario there is no smoke rollback effect in the opposite direction from the ventilation (Fig. 5).

From the computer program for modeling fires Pyrosim (Hansen & Ingason, 2013; Ingason, 2006, 2008, 2009), for burning 124 L of hydraulic fluid and the above mentioned chemical and physical characteristics of the hydraulic fluid we get the following experimental software results: Fig. 6, Fig. 7, Fig. 8, Fig. 9, Fig. 10, Fig. 11.

From the analyzes and calculations from computer program Pyrosim, for complete combustion of 124 L of hydraulic fluid we get fire time length of 36.8 min. To calculate the movement of smoke and fire gases in previously specified location in underground mine, we used the computer program MINEFIRE PRO+ (MineFire Pro+, 2013). For the purposes of this research paper, in computer program MINEFIRE PRO+ a 3D computer underground mining ventilation system of underground mine “Sasa” – R. Macedonia is build which correspond to the actual ventilation system of the mine (Fig. 2). In MINEFIRE PRO+ we are entering previously calculated fire characteristics from computer program Pyrosim, for fire pool caused by leakage and ignition of 124 L of hydraulic fluid from working machinery Boomer 281 (Table 4).

From the analysis and calculations of this fire scenario 1, in computer program MINEFIRE PRO+, for movement and spread of smoke and fire gases, we get the following results: Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16, Fig. 17, Fig. 18.

Table 4 – Input fire parameters in computer program MINEFIRE PRO+.

Volume flow of smoke and fire gases generated by the fire (m^3/s)	Concentration of carbon monoxide in the volume flow of smoke and fire gases CO (%)	Heat flow from fire (kW)	Concentration of oxygen in the fire place O_2 (%)	Volume flow of air in the branch Q (m^3/s)	Time for complete development of the fire (min)
14.9	0.0176	1446.2	20	9.7	1

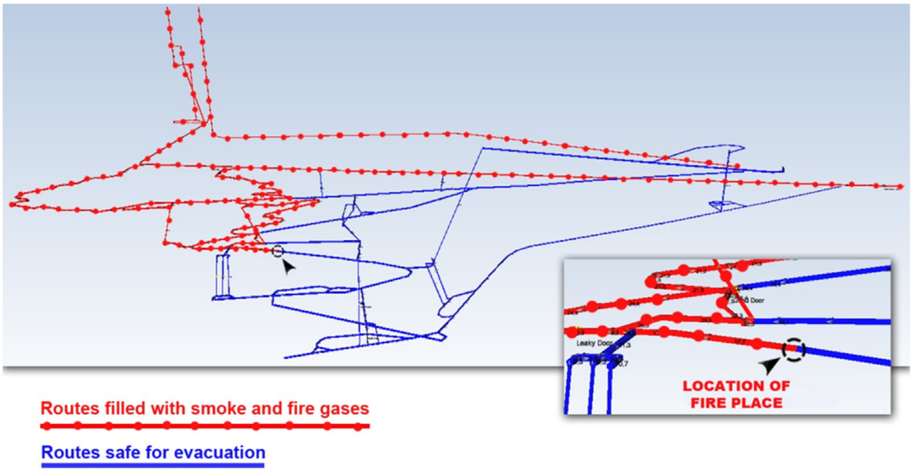

Fig. 12 – Calculations for movement of smoke and fire gases made in computer program MINEFIRE PRO+ for fire scenario 1, in underground mine "Sasa" – R. Macedonia.

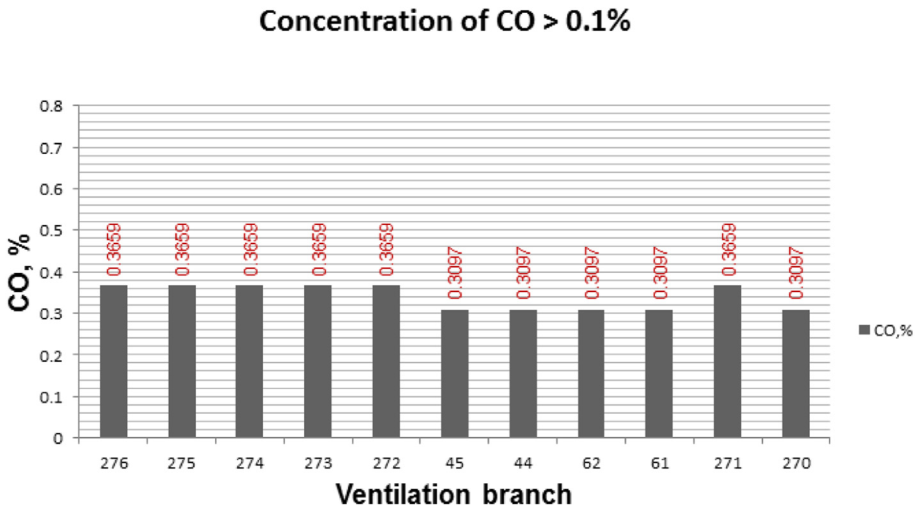

Fig. 13 – Critical conditions in fire scenario 1, with CO>0.1%, 90 s after fire event.

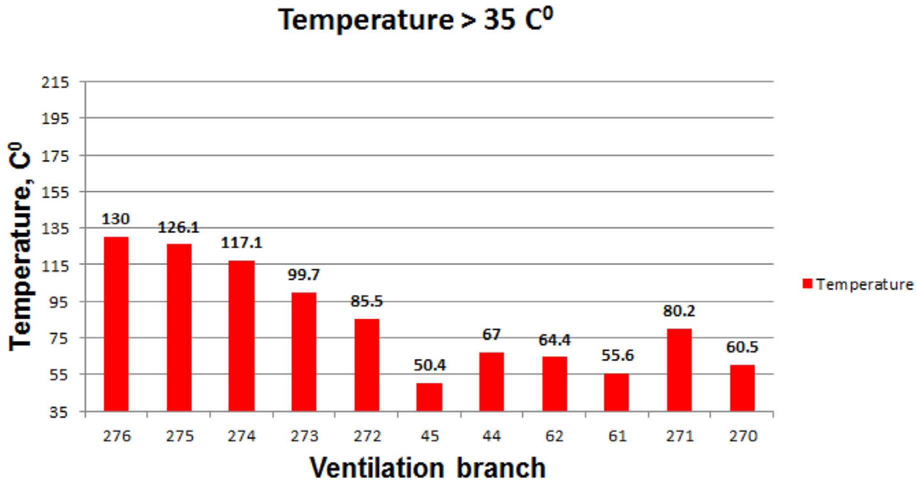

Fig. 14 – Critical conditions in fire scenario 1, with temperature >35 °C, 90 s after fire event.

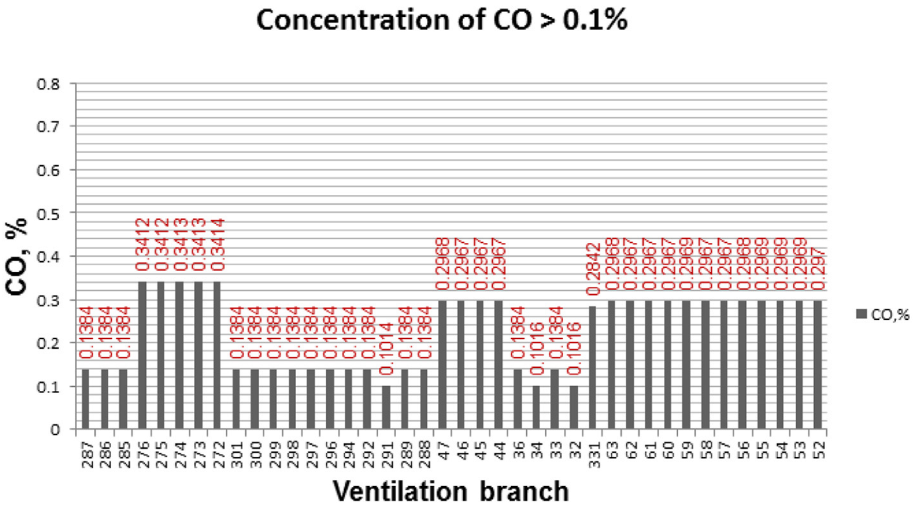

Fig. 15 – Critical conditions in fire scenario 1, with CO>0.1%, 1080 s after fire event.

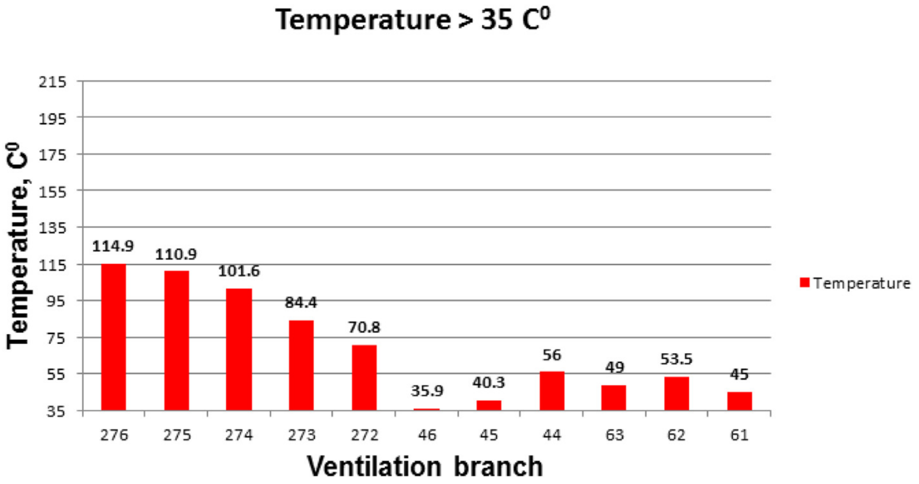

Fig. 16 – Critical conditions in fire scenario 1, with temperature >35 °C, 1080 s after fire event.

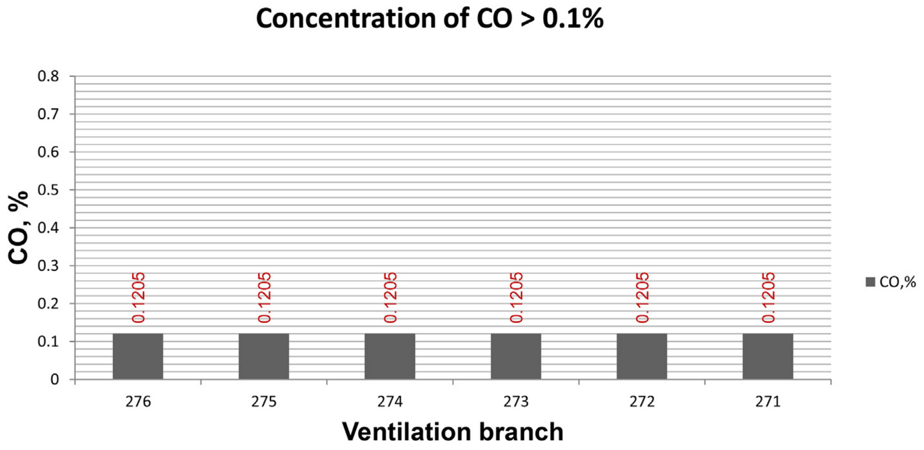

Fig. 17 – Critical conditions in fire scenario 1, with CO>0.1%, 2210 s after fire event.

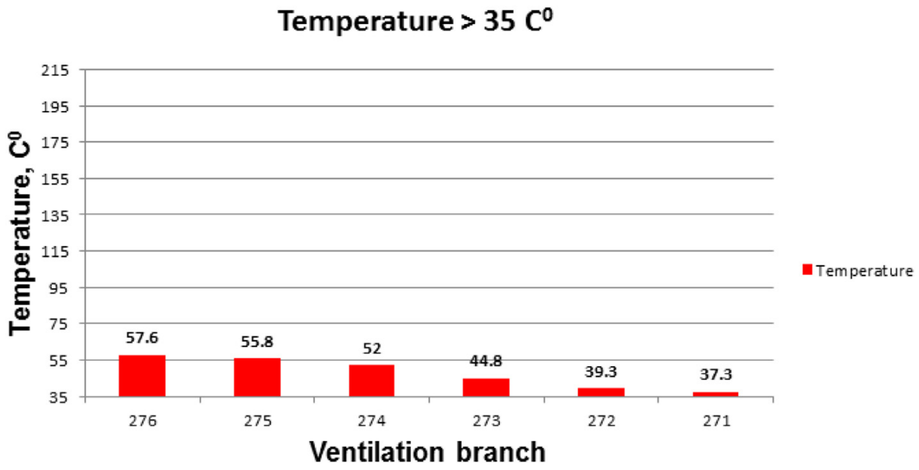

Fig. 18 – Critical conditions in fire scenario 1, with temperature >35 °C, 2210 s after fire event.

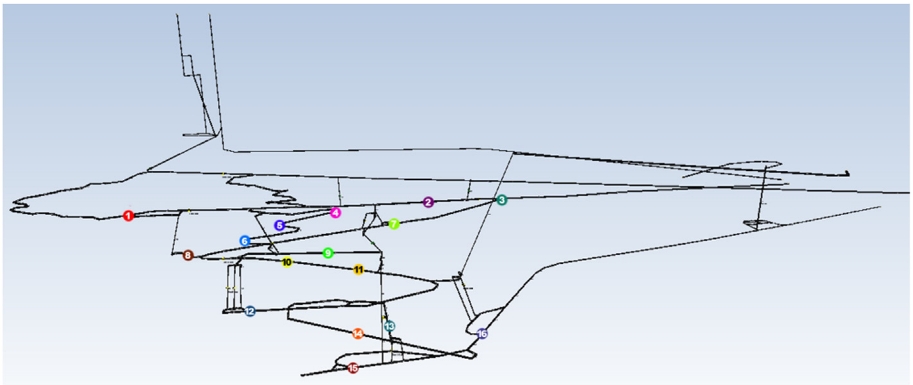

Fig. 19 – Locating the position of all workers in the underground mine.

After the analysis and calculations for the movement of smoke and fire gases generated by the fire scenario 1, next process is locating the position of all workers in the underground mine "Sasa" – R. Macedonia (Fig. 19) and giving them orders and guidelines form previously calculated safe routes for evacuation (Fig. 12).

3.2. *Optimization of evacuation routes for fire scenario 1*

To calculate the time required for evacuation, we will assume an average speed for normal movement of workers in all horizontal corridors and down slopes in the underground mine of 1.19 m/s. For movement through shaft using skip

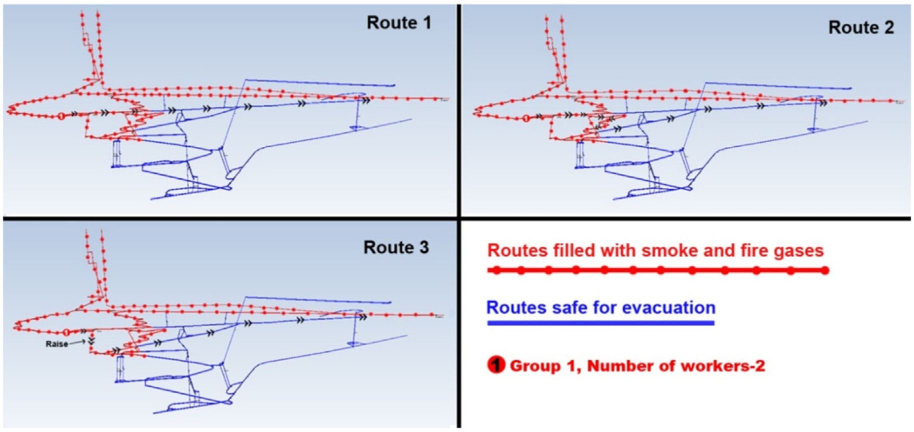

Fig. 20 – Possible routes for evacuation of group 1, considered to the third rank.

Table 5 – Total weight of evacuation routes of Group 1 (considered to the third rank).

Rank	Routes for evacuation of group 1	Total weight of the route for evacuation (m)	Time for evacuation (min)
1	Route 1	2074	29.1
2	Route 2	3631	50.8
3	Route 3	3478	48.7

hoist we will assume average speed of 10 m/s and for movement through raise we will assume average speed of 0.3 m/s. According to the analysis and calculations for the movement of smoke and fire gases made in computer program MINEFIRE PRO+, for fire scenario 1 (Fig. 12), we located the possible routes for evacuation of group 1 (we will consider routes for evacuation to the third rank). Next step is choosing the optimal route for evacuation of group 1 (Fig. 20).

The impacts of the previously defined factors for optimization will affect the speed of evacuation and those factors are transformed into an equivalent length of routes and represent a total weight of evacuation route. One evacuation route that will have the smallest weight calculated by previously mentioned methodology, will be the optimal route for evacuation (Jalali & Noroozi, 2009).

Analyzing and calculating (Table 5), we choose the optimal route 1, for evacuation of group 1, with the evacuation time of 29.1 min (Fig. 21, Table 6).

Disadvantage of this system is that it is constantly exposed to changes due to the rapid advancement and opening of new underground mining facilities that directly affect the ventilation system and also require introduction of new working activities that introduce new and different fire scenarios. Due to constant changes in the underground mining layout if we want this system to be efficient and accurate we need to constantly modify and customize this system, depending on

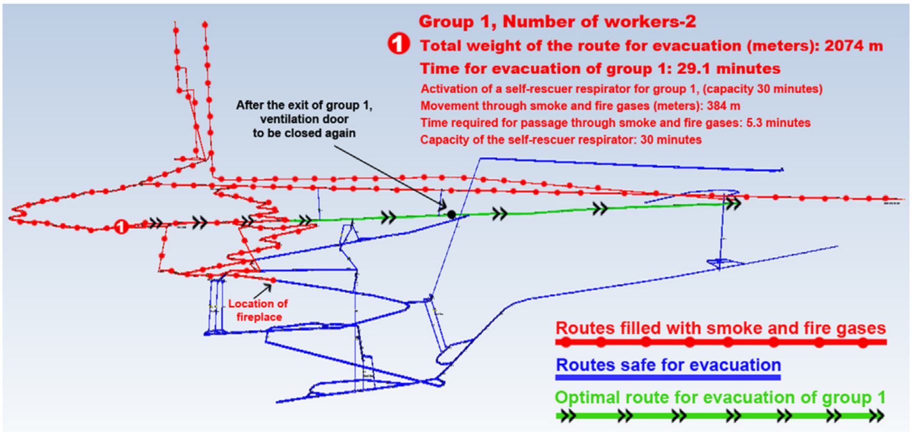

Fig. 21 – Optimal route for the evacuation of group 1.

Table 6 – Optimal routes for evacuation of all workers in the underground mine generated by fire scenario 1.

Evacuation of a group of workers	Number of workers	Total weight of the route for evacuation (m)	Time required for evacuation through the selected route (min)	Activation of a self-rescuer respirator (capacity 30 min)	Movement through smoke and fire gases (m)	Time required for passage through smoke and fire gases (min)
Group 1	2	2074	29.1	Yes	384	5.3
Group 2	3	1027	14.3	No	0	0
Group 3	2	810	11.3	No	0	0
Group 4	3	1615	22.6	Yes	346	4.8
Group 5	2	1621	22.7	Yes	260	3.6
Group 6	2	1445	20.2	Yes	85.3	1.1
Group 7	2	1084	15.1	No	0	0
Group 8	2	1577	22	Yes	213	2.9
Group 9	3	2377	33.2	No	0	0
Group 10	2	2434	34	No	0	0
Group 11	2	2285	32	No	0	0
Group 12	2	2557	35.8	No	0	0
Group 13	3	2590	36.2	No	0	0
Group 14	2	2254	31.5	No	0	0
Group 15	2	2280	31.9	No	0	0
Group 16	2	1969	27.5	No	0	0

the progress of mining activities as well as with introduction of new machinery and new work processes.

4. Conclusion

The risks of fire occurrence in underground mines have been known for a long time. Fires that occur in underground mines can pose a considerable threat and cause a number of problems, both for people who are affected by the fire and for rescue teams. Plans for evacuation and rescue in case of fire scenario in underground mines outline the procedures and preventive measures that are necessary for effective handling of this emergency situation. In this research paper is developed a model for modern approach of the planning system for evacuation and rescue in case of fire in underground mines, and this model can be used for training, research and practical purposes. This methodology represents the most economical option of making an effective system for evacuation and rescue in case of fire in underground mines. The main objective of this research paper is using this quick actions and precautions concerning this kind of emergency is to help save lives and protect the financial investment in the mine.

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