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Methodology for Optimal Fire Evacuations in Underground Mines Based on Simulated Scenarios

Vancho Adjiski and Zoran Despodov

Abstract

The purpose of this chapter is to develop a methodology that will contribute in locating optimal evacuation routes in case of fire that are based on minimal carbon monoxide (CO) exposure during the evacuation procedures. The proposed methodology is tested using simulated fire scenarios from which CO concentration over time curve is extracted from all available evacuation routes and presented in a weighted form based on the accumulating effect of CO inhalation in the form of fractional effective dose (FED). The safety limits of the FED model on which the optimization process is based are determined using a model for the prediction of carboxyhemoglobin (COHb) levels in human blood. The COHb model is associated with predicted clinical symptoms that are the basis for determining the level of incapacitation at which the mineworkers are incapable of completing their evacuation. Also in the process of improving the fire risk analysis, the proposed methodology enables the development of evacuation plans that are based on the results of modeled fire scenarios combined together with the results of the anticipated hazards generated by CO inhalation. The results presented in this chapter indicate a more precise approach in the process of planning the evacuation system inside the underground mines.

Keywords: underground mines, fire, safety, evacuation, optimization, simulation, modeling

1. Introduction

Fires are one of the most serious accidents that can occur in underground mines due to the restricted ability to evacuate quickly from the confined excavations that can be filled quickly with smoke and noxious fumes [1]. The behavior of underground mine fires is difficult to predict due to their dependence on multiple factors that are closely related to the amount of flammable material, ignition location, ventilation system arrangement, time of occurrence, etc. [2]. These uncertainties associated with mine fire scenarios can have unexpected impacts on the evacuation process, firefighting, and rescue strategies and also further complicate the process of design and implementation of fire protection systems.

Developing effective evacuation plans in case of fire in underground mine is the most important and sometimes the only option for safe evacuation of all involved in the fire scenario. The wide range of possibilities in the process of improving the evacuation plans in case of fire has motivated many researchers to make new or to modify the existing methodologies or procedures for developing effective and optimal evacuation plans.

Ji et al. [3] developed a visual model to simulate the evacuation process of miners to determine the evacuation time, exit flow rate, and evacuation path and show that simulation is effective technology to establish safe evacuation system. Chen et al. [4] developed 3D CFD model to reconstruct the laneway conveyor belt fire scenes under two ventilating conditions to investigate the influence of smoke movement on miner evacuation behaviors. Wang et al. [5] through example demonstrated the use of their proposed framework for human error risk analysis of coal mine emergency evacuation and also the method to evaluate the reliability of human safety barriers. Wu et al. [6] conducted emergency evacuation simulation and visualized analysis of underground mine water bursting disaster scene, to achieve the simulation of the dynamic process of individual or group behavior and to provide platform for rational evacuation under the situation of mine disaster. Adjiski et al. [7–9] completed many different manuscripts and projects in the field of simulation and modeling of fire scenarios and evacuation plans in underground mines.

To the authors' best knowledge and the extensive search of literature, a lack of methodologies and systems that focus on developing evacuation plans in case of fire in underground mines is shown. Due to the large number of factors from which the effective evacuation process depends, this field of research requires continuous upgrading to address all challenges and also to provide optimal evacuation routes that sometimes represent the only option for preventing loss of human lives.

This chapter is an extension and upgrade of the previously published works from the same author and hopefully will contribute to the process that will improve the methodologies and systems for optimal fire evacuations in underground mines.

2. Methodology for developing underground mine fire scenarios

In underground mines, a fire can occur wherever flammable material is found, but predicting it at all possible locations is practically impossible. So by analyzing this list of fire locations that have potential flammable materials, it is down to those places that have the highest risk of fire occurrence [10]. The process of conducting fire risk assessment is very straightforward and does not need to be considered in any further detail in this research.

What is new in this study is the proposal of methodology for quickly and efficiently locating and generating fire scenarios ready for simulation on the basis of which optimal evacuation plans will be developed.

To identify possible locations for fire scenarios in underground mines, different approaches can be used, such as [2, 9]:

- Fire risk assessment
- Historical records of fire incidents in the mine

- Analysis of production plans
- Analysis of work processes and mechanization, etc.

The dynamics of mining activities to increase and fulfill production capacity generates a constant shift in production sites generally associated with mechanization that is likely to trigger a fire scenario. Due to this fact as a relevant indicator that realistically reflects and constantly updates, the list of possible fire locations would be a detailed analysis of daily or monthly production plans. This step involves a thorough analysis of the daily/monthly production plans that will detect any flammable materials mostly associated with the mechanization needed to achieve the required production capacity.

A case study of the “SASA”-R.N. Macedonia mine was used in order to conduct the necessary steps presented on **Figure 1**.

The steps shown in **Figure 1** are based on a simple analysis of the production plans that can detect all workplaces with the appropriate work cycle together with the related mechanization which is often associated with fire scenarios.

To demonstrate the presented methodology, a 3D model of the underground ventilation network of the mine “SASA”-R.N. Macedonia is prepared on which all the necessary analysis and simulations will be performed (**Figure 2**). On the ventilation map, the possible fire locations along with the group of mineworkers identified using the proposed methodology on **Figure 1** and also the possible exits from the underground mine are also marked.

The process of modeling fire scenarios is closely related to the degree of uncertainty when it comes to the input data, which largely depends on the size of the fire itself [11, 12]. Examples of such input parameters that affect the fire models in underground mines are fire load, fire location, burn rate of materials, heat release rate, ventilation parameters, etc. Due to the stochastic nature of the input parameters related to the fire models, the appropriate results should be treated with caution.

From the large list of stochastic input parameters, the authors decided to elaborate only on the process of obtaining fire load inputs, which largely depends on

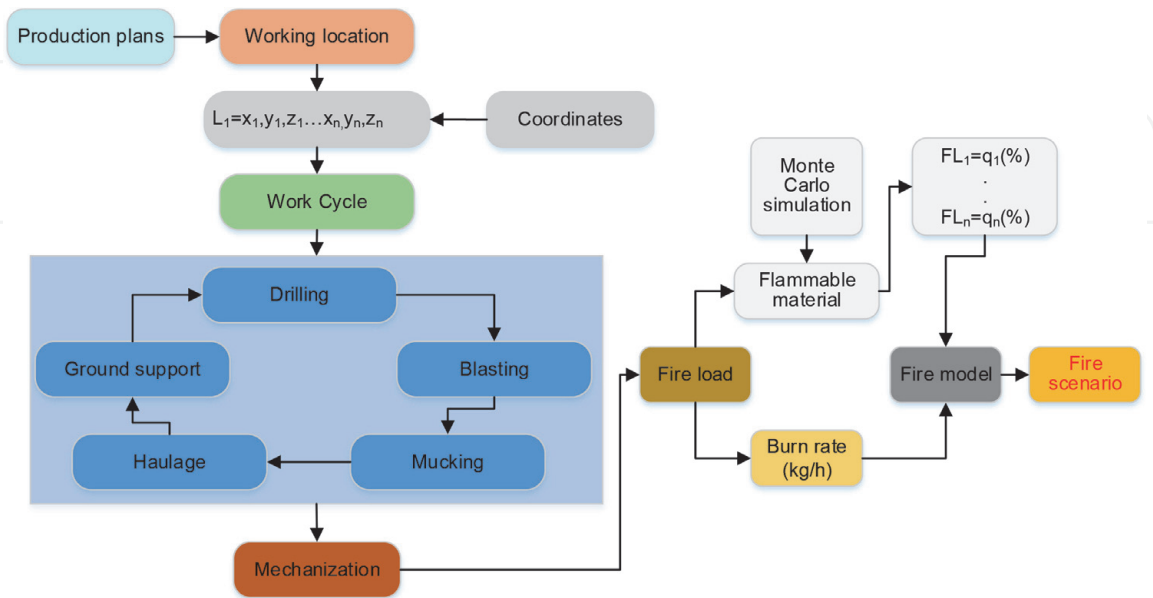


Figure 1.
Methodology for developing and locating fire scenarios in underground mines.

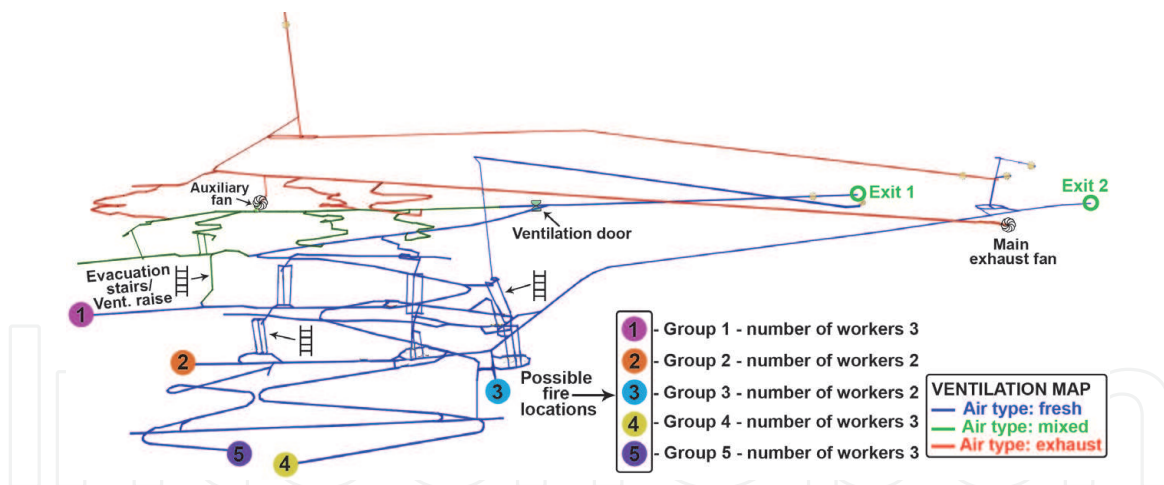


Figure 2.
Ventilation map of the “SASA” mine with marked possible fire locations, group of mineworkers, and exits.

the severity of the fire scenario itself. The process of modeling fire load inputs that are closely related to the inability to accurately determine the type and quantity of flammable material covered by a fire scenario is done using the Monte Carlo simulation technique. The reason for selecting and analyzing the fire load parameter is because of its immense contribution in generating the amount of toxic gases from which the complexity of the evacuation process depends. The reason for choosing the Monte Carlo simulation technique is because of its speed and simplicity of implementation and also the ability to generate a large amount of input data sampled randomly from their respective distributions [13–15].

The process of developing this model that incorporates the Monte Carlo simulation technique associated with the normal distribution defined by mean = 50, and standard deviation = 15, has been previously explained by the same author, and the entire methodology and reasons for selecting the highlighted parameters can be found here [16].

What is new in this research is the development of a database that includes all fire scenarios in a predetermined location using the abovementioned methodology on **Figure 1**.

All fire scenarios are analyzed in terms of impact from the fire load input parameters on the evacuation process, that is, how different distribution of combustible materials from the same mechanization (or other composition of combustible materials) will impact the evacuation process.

The introduction of this database aims to select fire scenarios of the same type but with different fire load distribution, from which we can analyze the effects on the evacuation process. The results of this analysis can be used to improve the design of fire systems and evacuation plans and to test them for their effectiveness in different conditions.

From the simple analysis of the monthly production plan of “SASA” mine, we have extracted all work sites for ore exploitation and development of mining facilities with the appropriate work cycle together with the related mechanization. To present the methodology, we will only analyze fire scenarios generated by only one mechanization and present the optimal evacuation route for only one group of workers.

For the purposes of this analysis, we will present the results of the fire scenarios generated by the mechanization Scooptram ST7, located at the possible fire location 3, from where we will simulate the fire scenarios and calculate the optimal evacuation route for group 1 (**Figure 2**).

	Tire [kg]	Diesel fuel [L]	Hydraulic fluid [L]
Scooptram ST7	238 * 4 (tires) = 952	190	111

Table 1.
Approximate fire load calculation for the fire scenario from Scooptram ST7.

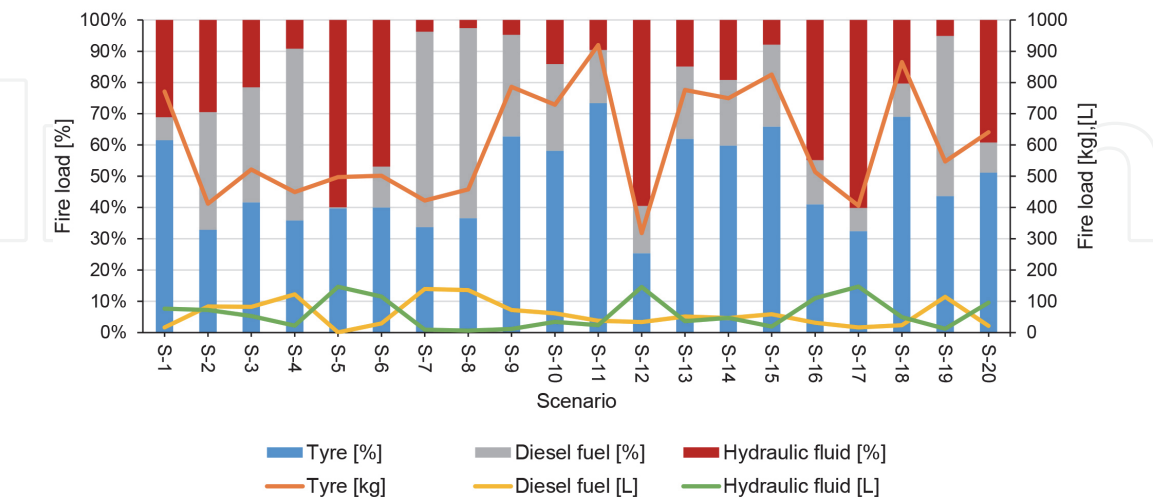


Figure 3.
Generated scenarios along with the corresponding fire load distribution obtained from the Monte Carlo simulation model.

The inputs in the next steps of the proposed methodology are the approximate values of the total fire load for the selected mechanization. To simplify the process of determining this data, we used the technical manual of the Scooptram ST7, from which we approximated the quantities for the tire, hydraulic fluid, and diesel fuel which will be threatened as total fire load (**Table 1**). Regardless of the fact that the amount of diesel fuel is stochastic in nature, and is dependent on a number of factors, to simplify the model, we will consider it a known value, and we will treat it in a further expansion of the research.

Following the analysis of the approximate amount of fire load, the next step is to model them using the previously mentioned Monte Carlo simulation technique, along with the necessary data for its normal distribution defined by mean and standard deviation [16].

For the purpose of this study using the Monte Carlo simulation model, we have generated 20 scenarios with different fire load distribution, which will give variations in the results from the fire scenarios, and we will analyze their impact on the evacuation process (**Figure 3**).

3. Modeling and simulation of fire scenarios in underground mines

The purpose of fire models is to describe fire characteristics, such as heat release rate, the burning rate of material, smoke, generating toxic gases, etc., and the results of simulating these models will be as good as the inputs [9, 17]. In order to create a relevant fire model in underground mines, it must be based on an accurate ventilation model. This interconnection and accuracy of the fire and ventilation models will depend on the movement of smoke and toxic gases through the mine facilities from which the evacuation process is based.

Various case studies previously published from the same author are based on the modeling of fire scenarios in a number of different mine ventilation layouts [7–9].

For this study, i.e., for simulating fire models across the 3D ventilation network, we used the VentSim software along with VentFIRE™ module that are interconnected because they belong to the same software package. With the help of VentSim software a 3D ventilation network with all working parameters is developed, while the VentFIRE™ module is used for simulation and calculation of the fire scenarios previously generated with the Monte Carlo simulation model.

The theoretical and the working principle of the VentSim software together with the VentFIRE™ module can be found here [18]. Fire models in some cases are analyzed by CFD software for the purpose of comparison between the results obtained from simpler computational methods. Due to the size and complexity of the underground mines, it should be emphasized that CFD analysis can only be used to represent a small section of the mine. The results of such CFD analyses that require a large number of computations which will generate only results related to the immediate proximity of the fire scenario cannot realistically represent the full image generated by the fire model [8, 19]. The functionality of the methodology presented in this chapter is based on the modeling and simulation of fire scenarios whose results can fully represent each time interval of the movement of smoke and fire gases through the whole ventilation network from which the evacuation process entirely depends.

In the process of modeling fire scenarios in VentFIRE™ module in addition to the fire load data presented in **Figure 3**, which was generated with the Monte Carlo simulation model, specific data are also required for each material which is presented in **Table 2**. For the purpose of providing this data, laboratory tests or fire databases containing such information may be used [20, 21].

The results of the fire models obtained by the VentFIRE™ module are in the form of a dynamic representation of the real-time fire progression and utilize a graphic visualization of the spread and concentration of combustion products and all the fire-related data throughout the ventilation system (**Figure 4**).

Monitoring points that are strategically placed throughout the ventilation network allow the extraction of data in the form of concentrations over time for all fire-related data. In this study, for the evaluation of the evacuation plans, only the CO concentration over time curve will be analyzed throughout the ventilation network. The results from the monitoring points will serve for realistic mapping of the CO inhalation throughout the evacuation route for anyone affected by the fire scenario. **Figure 5** shows the CO concentration measured from the monitoring point at the location for the fire scenario S-1.

	Tire	Diesel fuel	Hydraulic fluid
Density [kg/m ³]	1150	832	760
Simplified chemical hydrocarbon formula	C ₄ H ₆	C ₁₂ H ₂₃	C ₃₆ H ₇₄
Heat of combustion [MJ/kg]	44	45	48
Burning rate of material [kg/m ² * s]	0.062	0.045	0.039
O ₂ consumed [kg/kg]	3.62	3.33	3.57
Yield CO ₂ [kg/kg]	0.9	3.2	3.3
Yield CO min [kg/kg]	0.13	0.019	0.1
Yield CO max [kg/kg]	0.23	0.21	0.24
Yield soot [kg/kg]	0.1	0.059	0.1

Table 2.
Input fire characteristics data for the fire load.

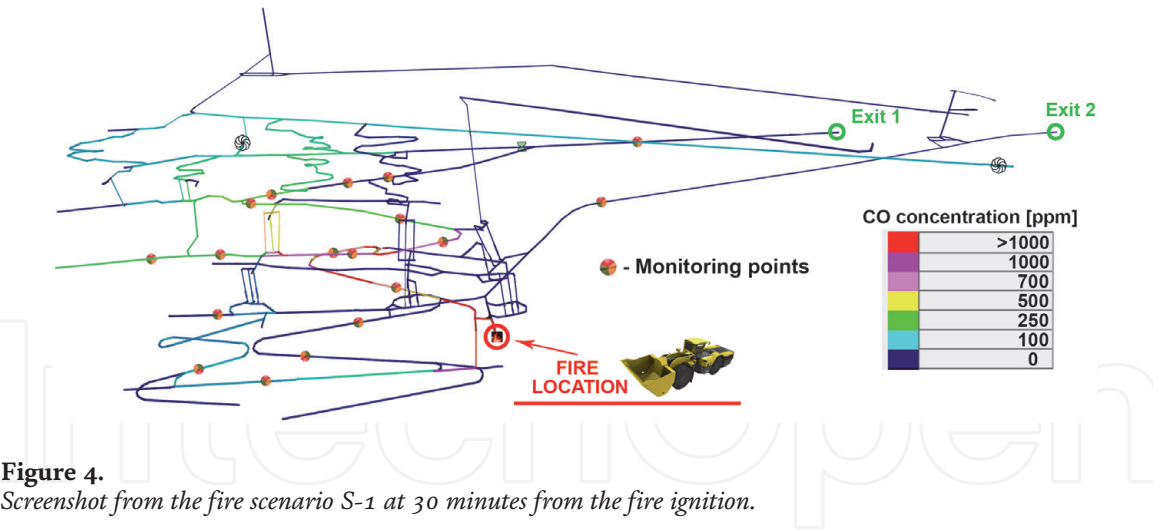


Figure 4.
Screenshot from the fire scenario S-1 at 30 minutes from the fire ignition.

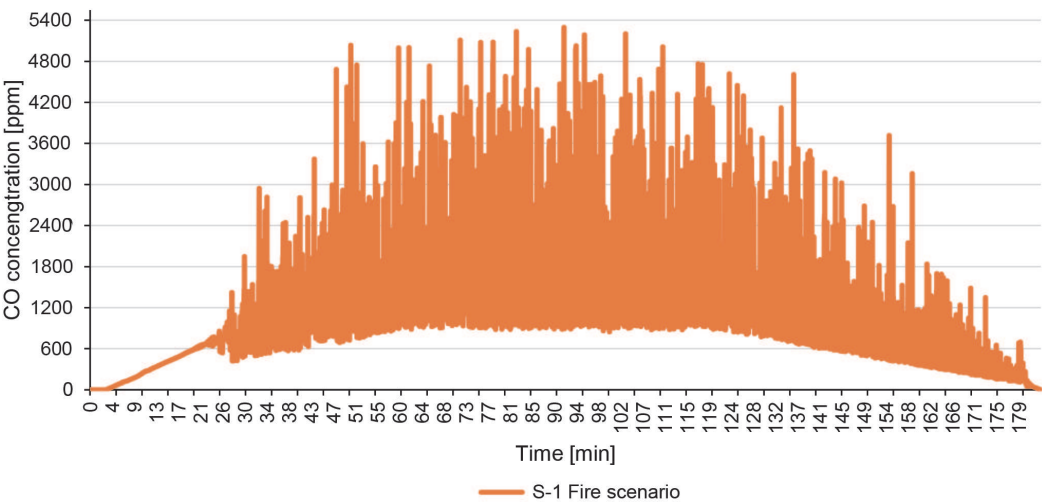


Figure 5.
CO concentration over time curve at the fire scenario S-1 location.

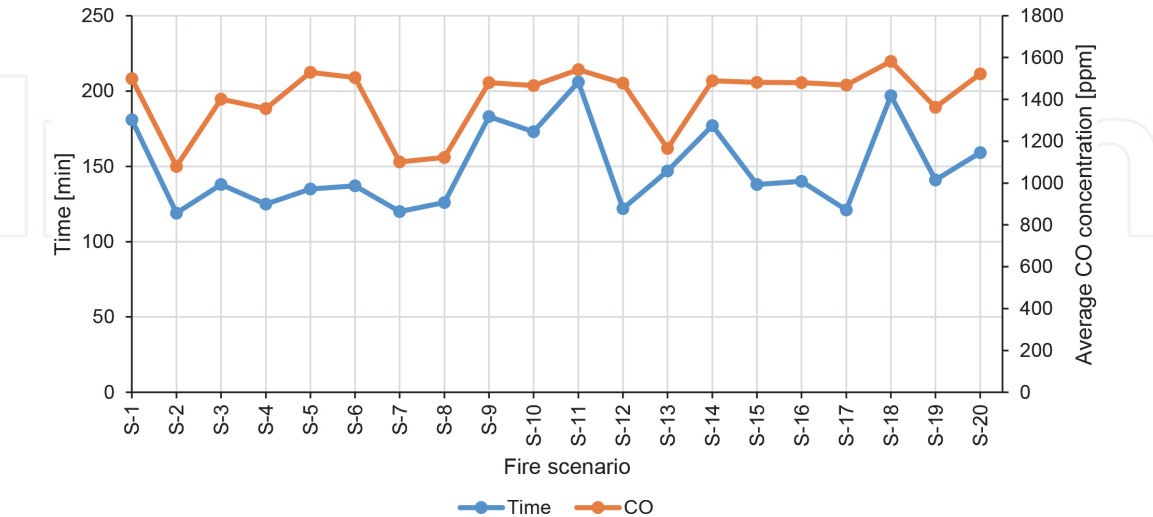


Figure 6.
Average values of CO concentration at fire location and total time duration of the fire for all scenarios generated by the Monte Carlo simulation model.

Figure 6 shows the average values of CO concentration vs. total duration time for all fire scenario variants generated by the Monte Carlo simulation model, measured from the fire location.

These results highlight the impact of different fire load distribution, thus providing additional data for analysis during the process for determining the optimal evacuation routes.

4. Methodology for determining the optimal evacuation routes based on simulated fire scenarios

4.1 Life safety assessment during evacuation based on fractional effective dose (FED) from CO inhalation

Statistical underground mine fire evidence shows that most injuries and deaths are not caused by direct contact with the fire but by way of smoke and toxic gases inhalation [22].

While the fire scenario may be confined to a localized underground mine area, the smoke produced will rise and with the help of the ventilation system may spread rapidly through the mine.

The spread of smoke and toxic gases through the underground mine network will cause difficulties in the evacuation process, and therefore, there is a need for an effective methodology for planning and developing of optimal evacuation routes.

Purser [23] gives extensive review of smoke and toxic gases hazards, including exposure thresholds that can cause incapacitation and even death.

In underground mine fires, the most common asphyxiate is CO, and its effects of incapacitation depend from the gas concentrations and the durations of exposure.

The evacuation management system must be designed and evaluated against a set of criteria to ensure safe evacuation of the mineworkers, which can be achieved by analyzing the fire environments using modeling and simulation.

The proposed method in this book chapter involves the determination of accumulating exposure effect at regular discrete time increments to get the cumulative dosage in terms of FED for the total period of exposure. The exposure doses are calculated as a fraction of incapacitation at every time increment, and the value of FED = 1.0 represents the state of incapacitation in which mineworkers are incapable of completing their own evacuation.

Purser [24] suggests mathematical model for estimating toxic hazard from inhalation of CO from fire scenario in terms of time to incapacitation or death in form of FED and is given as follows:

$$FED_{Toxicity} = FED_{CO} * V_{CO_2} + FED_{O_2} \quad (1)$$

$$FED_{CO} = \sum_{t_1}^{t_2} \frac{K * [CO]^{1,036}}{D} \Delta t \quad (2)$$

$$V_{CO_2} = \frac{\exp(0,1903 * \%CO_2 + 2,0004)}{7,1} \quad (3)$$

$$FED_{O_2} = \sum_{t_1}^{t_2} \frac{1}{\exp(8,13 - 0,54(20,9\% - \%O_2))} \Delta t \quad (4)$$

where CO (carbon monoxide) is the average concentration (ppm) over the time increment Δt in minutes, K and D are constants which depend on the activity of the person (**Table 3**), $\%CO_2$ is the carbon dioxide concentration, and $(20,9 - \%O_2)$ is the oxygen vitiation over the time increment Δt .

Activity	K	D
At rest	$2,81945 * 10^{-4}$	40
Light work	$8,2925 * 10^{-4}$	30
Heavy work	$1,6585 * 10^{-4}$	20

Table 3.
Values for different activity levels for the constants K and D.

COHb (%)	Clinical symptoms
0,4–1	Normal value for nonsmokers
2,5–4	Decreased exercise performance in patients with angina
5–10	Shortness of breath on vigorous exertion, possible tightness across forehead, statistically significant diminution of visual perception, manual dexterity, or ability to learn
11–20	Atypical dyspnea, throbbing headache, dizziness, nausea, confusion and decreased exercise tolerance, dilatation of skin vessels
21–30	Severe headache, pulsation in sides of head, impaired thinking, disturbed vision, fainting, easy fatigability, disturbed judgment
31–40	Severe headache, dizziness, respiratory failure, coma, intermittent convulsions
41–50	Brain damage, lethargy, seizures, syncope, death from severe cellular hypoxia if exposure is prolonged
51–60	Same as above, coma, convulsions, Cheyne-Stokes respiration
>70	Slowing and stopping of respiration and death within short period

Table 4.
Approximate clinical symptoms associated with the blood COHb (%) level [26].

One of the limitations of this model is the lack of a clear safety margin between the values of the FED in which the transition in the evacuation process from safe to unsafe zone begins. As previously stated, for the evacuation to be considered safe, the FED value should be <1 . The question here is how much less than 1?

To improve the methodology in this regard, additional model is introduced that will allow to link the entire evacuation timeline with another parameter in the form of COHb prediction in the blood as a result of the CO inhalation generated by the fire scenario.

4.2 Model for predicting carboxyhemoglobin (COHb) concentration as a result of CO inhalation

The overwhelming hazard in fires is the COHb buildup in the blood as a result of exposures to CO. Inhaled CO acts on the human body by competing with oxygen to combine with hemoglobin molecules in the blood, forming COHb rather than normal oxyhemoglobin (O₂Hb) [25]. Exposure to a large concentration of CO is lethal, and the signs and symptoms produced are directly related to the percentage of COHb in the blood (**Table 4**).

The most widely used mathematical model (Coburn-Forster-Kane (CFK)) was implemented in order to predict COHb (%) blood level from CO exposure on mineworkers during the underground mine fire scenario.

Previous research by several authors validated both linear and nonlinear CFK model against observations made on subjects exposed to variable CO concentrations, and the consensus is that the model predictions works quite well. The CFK nonlinear model is given by the following Equation [27]:

$$[\text{COHb}]_t = \frac{1}{A \left(\frac{AC}{[\text{COHb}]_0} \right)} + (1 - C)V_{\text{CO}}B + (1 - C)P_{1,\text{CO}} \quad (5)$$

$$A = \frac{PO_2}{M[\text{O}_2\text{Hb}]} \quad (6)$$

$$B = \frac{1}{D} + \frac{P}{V_a} \quad (7)$$

$$C = e^{\left(-\frac{tA}{V_b B} \right)} \quad (8)$$

where:

M—Haldane constant, ratio of the affinity of Hb for CO to that of O₂ = 240.

[O₂Hb]—oxyhemoglobin concentration = 0,2 ml ml⁻¹ blood.

[COHb]_t—carboxyhemoglobin concentration at time t in ml CO per ml blood.

[COHb]₀—initial concentration of carboxyhaemoglobin in blood

(%COHb = 0,5% for nonsmokers; %COHb >2% for 80% of smokers; %COHb = 10% for heavy smokers).

PO₂—partial pressure of oxygen in lung capillaries = 13,3 kPa.

V_{CO}—endogenous CO production rate = 0,007 ml min⁻¹.

D—diffusion capacity of the lungs for CO = 225 ml min⁻¹ kPa (in reality this is not a constant but is altered by a number of factors including exercise).

P—Barometric pressure - saturated vapor pressure of water at 37°C = 95,1 kPa.

V_b—blood volume 5500 ml.

P_{1,CO}—partial pressure of CO in inspired air = 0,0101 kPa (adopted for the purposes of this model).

V_a—alveolar ventilation rate = 6000 ml min⁻¹.

t—duration of exposure [min].

The limitations in the CFK model are located with the physiological variables needed as input to the model which are difficult to measure, such as blood volume, endogenous production of CO, and the pulmonary diffusing capacity [28].

For the purpose of this study, an Excel model based on the CFK equation is built to predict the individual's COHb formation (%), as a result from CO inhalation. For simplification purposes the abovementioned physiological variables are set as default values (as defined in the equation).

The proposed model for predicting COHb (%) with appropriate clinical symptoms (**Table 4**) connected with the FED model can better determine the threshold in which the evacuation will be considered safe.

4.3 Model for the conversion of the factors that influence the speed of evacuation

To be able to calculate the optimal evacuation routes in underground mines, details about the tunnels' parameters should be provided. Each fire scenario generates factors that influence the complexity and the speed of the evacuation itself.

Based on extensive literature review, two factors are located that have most influence on the evacuation speed, and these factors are generalized in the form of tunnel slope and smoke visibility [7, 29–31]. The model framework is shown in **Figure 7**.

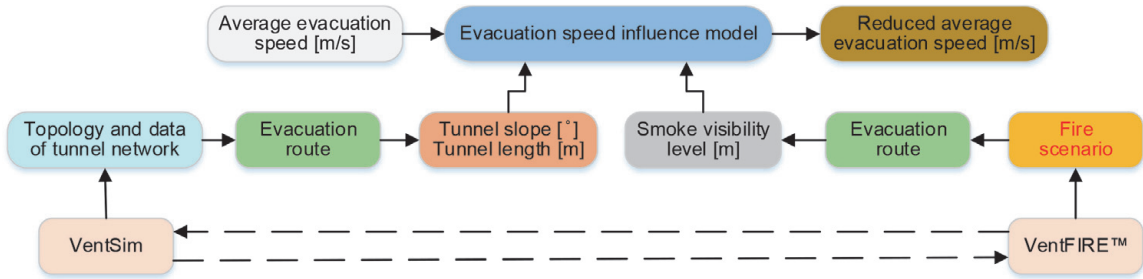


Figure 7.
Methodology for implementation of the evacuation speed influence model.

These factors that influence mineworkers' escape speed can increase the exposure time from the fire scenario and thus present very important factors to be considered in the process of determining optimal evacuation routes.

We defined the mineworkers' normal evacuation speed by v_0 , and under the influence of the above factors, the evacuation speed will be v_f .

The tunnel slope influences the mineworkers' evacuation (and also walking) speed, and the greater the slope the more influence it will have on the process.

The tunnel slope influence under climbing situation is given by the following Equation [31]:

$$k_{ts} = \frac{mgv_0 \sin \theta_s}{P_0} + \cos \theta_s \tag{9}$$

where m is the standard human mass [kg], g is the gravity acceleration [m/s^2], and θ_s is the tunnel's angle of slope in degrees.

When mineworkers pass down slope tunnels, we will assume no influence on their speed, and the model will treat this as normal evacuation speed v_0 (i.e., $k_{ts} = 1$).

The smoke generated by the fire scenario is a major factor in determining tunnel visibility. This visibility factor has important effects on the evacuation speed of the mineworkers who are escaping.

Based on the reviewed literature, two threshold values hold a central function during an evacuation in a smoke-filled environment [30, 32]. The first threshold value is the visibility level at which evacuees in general can be expected to start reducing their evacuation speed. This value based on the reviewed experiments of the data presented from the literature was set to 3 meters as corresponding visibility threshold value [30, 33, 34].

The second threshold value is the visibility level at which the mineworkers can be assumed to be evacuating with their slowest speed. Based on the reviewed literature, the slowest speed during an evacuation in a smoke-filled environment is similar to movement in complete darkness which can be expected to be about 0,2 m/s [30]. In this analysis, the value for the slowest speed of evacuation will also be applied when the mineworkers will move through the evacuation stairs in the ventilation raise.

Practically, in the process of calculating the reduction of evacuation speed based on the smoke visibility level, the model is set in the following way:

- All individuals in the group are assumed to be evacuating with the same speed.
- Visibility levels >3 m: mineworkers' evacuation speed is represented by 1,2 m/s

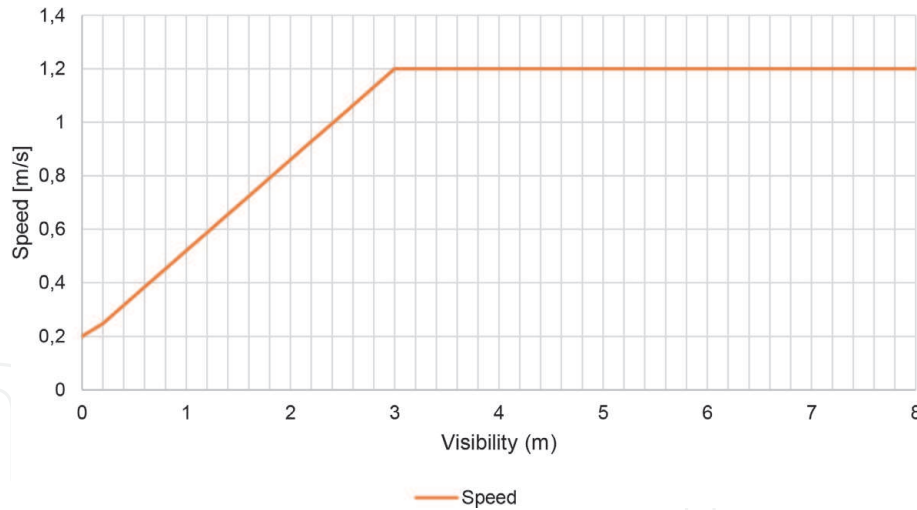


Figure 8.
Representation of relative reduction of speed in a smoke-filled environment according to the model.

- Visibility levels ≤ 3 m: mineworkers' evacuation speed is represented by a relative reduction of 0,34 m/s per meter visibility in a smoke-filled environment down to the previously defined minimum speed of 0,2 m/s.

The correlation in this model is described by the following equation and by **Figure 8** [30]:

$$w = \min(1; \max(0, 2; 1, 2 - 0, 34 * (3 - V))) \quad (10)$$

where w is the evacuation speed [m/s] and V the visibility [m].

5. Results and discussion

Determining the optimal routes for evacuation in the case of underground mine fire makes the difference between life and death. In this book chapter, we established a methodology for calculating the optimal routes for evacuation in case of underground mine fire based on simulated scenarios. The methodology shown in **Figure 9** provides the necessary steps to assess the potential fire scenarios and to generate the necessary data on the basis of which all evacuation routes will be evaluated and the optimization process implemented.

The methodology consists of three parts, i.e., developing underground mine fire scenarios, modeling and simulation of fire scenarios, and determining the optimal evacuation routes based on the generated results. The parts of the presented methodology and the procedures for their implementation are presented in detail above.

For the purpose of this study, a case study of the “SASA”-R.N. Macedonia mine was used for determining the optimal routes for evacuations.

To present all the steps that the methodology is consists of, we will present the results obtained from only one fire location from which we will calculate the optimal evacuation routes for only one group of workers for all of the 20 fire scenarios generated by the Monte Carlo simulation model.

The results from the Monte Carlo simulation (**Figure 3**) are used as input fire load data for modeling and simulating fire scenarios in the VentFIRE™ module through the mine ventilation network (**Figure 2**). Following the simulation of all 20 fire scenarios from the same fire location, all possible evacuation routes for group 1 have been identified (**Figure 10**).

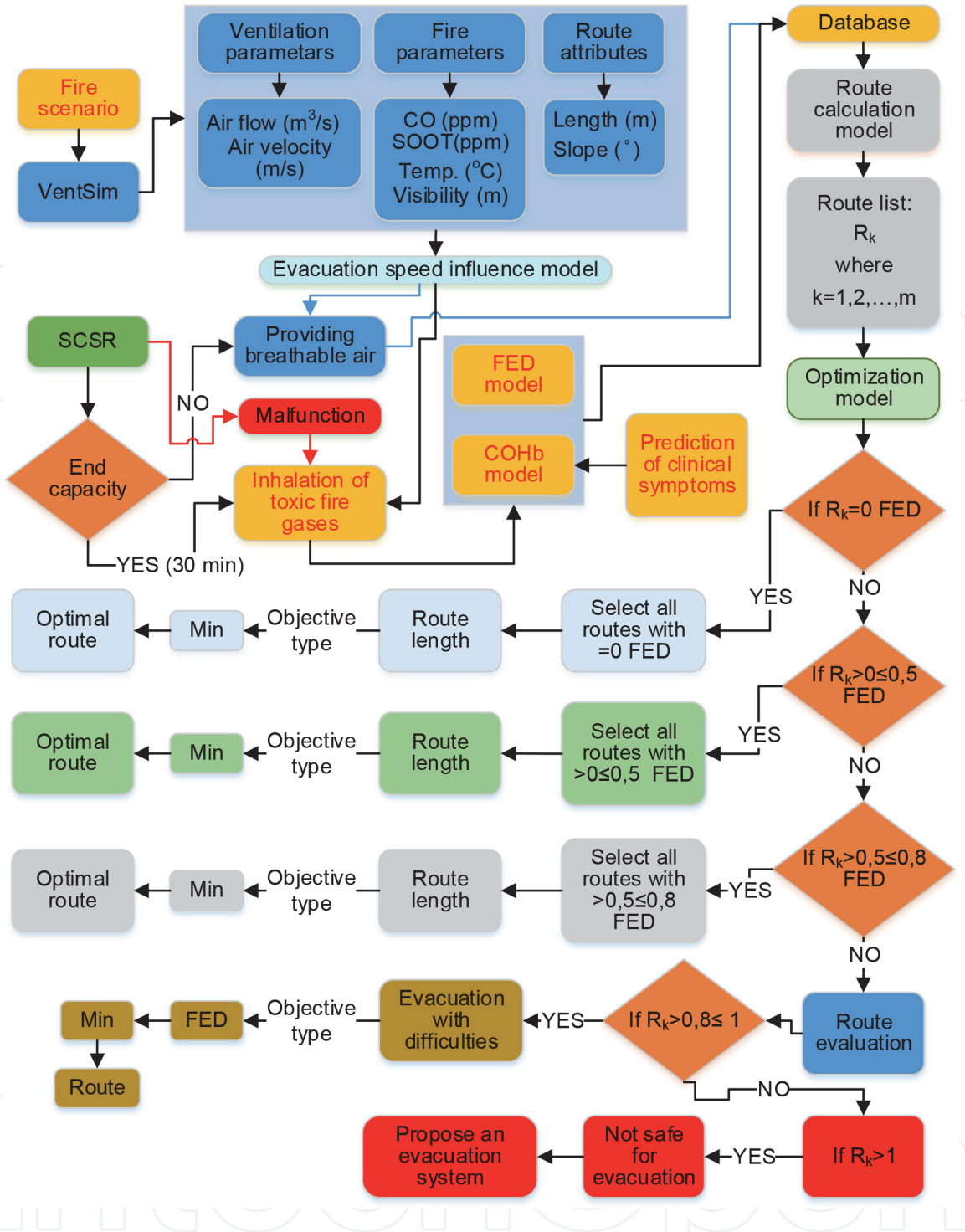


Figure 9.
Proposed methodology implementation framework.

In the process of calculating all the parameters needed to determine the optimal evacuation routes, we will take into account the self-contained self-rescuer (SCSR). The use of SCSR in underground mining is a legal obligation in almost all countries around the world, so its introduction into the process of determining the optimal evacuation routes is a very important factor. The SCSR is a portable device that is used in underground mines to provide breathable air for the mineworkers when the surrounding atmosphere is filled with contaminants after emergency situation.

Extensive research on fire reports provides the fact that sometimes this first line of defense from smoke inhalation in the form of SCSR fails to function properly due to technical problems or due to insufficient training of the mineworkers [35]. Because of this fact in this study, we will make two parallel analyses to calculate the

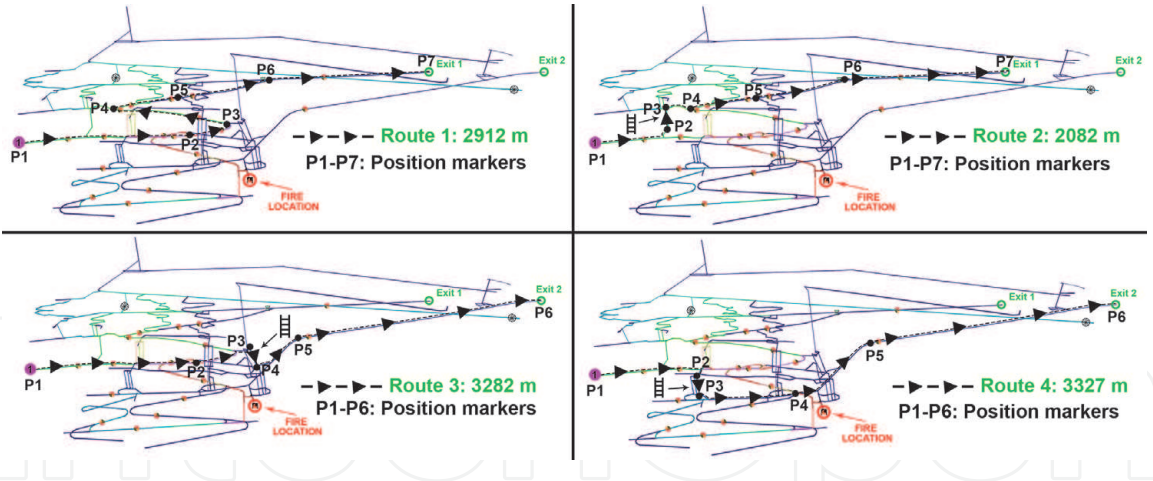


Figure 10.
Identification of possible evacuation routes for group 1 for all generated fire scenarios.

Position	Section length [m]	Visibility [m]	Slope [°]	Reduction of evacuation speed (from visibility and slope) [m/s]	Average CO (ppm)	Evacuation time in section [s]	Cumulative time [s]
P1-P2	667	5	0	1,2	448	556	556
P2-P3	232	2	6	0,4	881	580	1136
P3-P4	495	4,6	6,1	0,3	514	1650	2786
P4-P5	524	12	5,71	0,29	480	1807	4593
P5-P6	199	25	5,8	0,55	0	362	4955
P6-P7	792	25	1	0,66	0	1200	6155

Table 5.
Results for group 1, evacuated along route 1 for scenario S-1.

optimal evacuation routes in which we will introduce the use of a SCSR with a capacity of 30 minutes and the possibility of its non-functionality. By introducing this parameter in the form of functionality and non-functionality of SCSR, we can provide a detailed analysis that can predict the evacuation routes under different conditions.

To elaborate on the proposed methodology, we will present in details the results of scenario S-1.

After the development of the underground mine fire scenarios and their modeling and simulation inside the VentFIRE™ module, all the necessary data for the optimization process is gathered.

For the purpose of this analysis, an average evacuation speed of 1,2 m/s is assumed. The average evacuation speed will be affected by the tunnel slope and smoke visibility.

To calculate the impact on the average speed inside the evacuation process, An Excel model was built based on Eqs. 9 and 10. The results from the simulated fire scenario S-1, which are required as inputs for the FED, COHb, and route calculation models, are shown in **Tables 5–8**.

In the calculation process for the CO exposure over the entire evacuation route, we will include the SCSR in its two previously mentioned forms. To calculate the exposure from CO for each of the possible evacuation routes, the results shown in **Tables 5–8** are used as inputs to the FED and the COHb model. The results from the CO exposure based on FED and COHb models build inside Excel are shown in **Figures 11–14**.

Position	Section length [m]	Visibility [m]	Slope [°]	Reduction of evacuation speed (from visibility and slope) [m/s]	Average CO (ppm)	Evacuation time in section [s]	Cumulative time [s]
P1-P2	347	5,1	0	1,2	448	289	289
P2-P3	80	5,3	75	0,2	450	400	689
P3-P4	135	4,7	1,4	1	524	135	824
P4-P5	524	12	5,71	0,29	480	1807	2631
P5-P6	199	25	5,8	0,55	0	362	2993
P6-P7	797	25	1	0,65	0	1226	4219

Table 6.
Results for group 1, evacuated along route 2 for scenario S-1.

Position	Section length [m]	Visibility [m]	Slope [°]	Reduction of evacuation speed (from visibility and slope) [m/s]	Average CO (ppm)	Evacuation time in section [s]	Cumulative time [s]
P1-P2	667	5	0	1,2	448	556	556
P2-P3	340	2	6	0,34	881	1000	1556
P3-P4	80	25	75	0,2	0	400	1956
P4-P5	462	25	0	1,2	0	385	2341
P5-P6	1689	25	0	1,2	0	1408	3748

Table 7.
Results for group 1, evacuated along route 3 for scenario S-1.

Position	Section length [m]	Visibility [m]	Slope [°]	Reduction of evacuation speed (from visibility and slope) [m/s]	Average CO (ppm)	Evacuation time in section [s]	Cumulative time [s]
P1-P2	461	5,1	0	1,2	448	384	384
P2-P3	80	14	75	0,2	344	400	784
P3-P4	426	22	0	1,2	0	355	1139
P4-P5	671	25	0	1,2	0	559	1698
P5-P6	1689	25	0	1,2	0	1408	3106

Table 8.
Results for group 1, evacuated along route 4 for scenario S-1.

All of the gathered results from the models are stored and arranged in the database. The next step of the proposed methodology is to filter the results inside the database through a route calculation model that will sort out all the evacuation routes according to the level of CO exposure, i.e., the results obtained from the FED and COHb model.

The purpose of the route calculation model is to generate a list of all evacuation routes, which will include the data for route length and cumulative CO exposure in the form of a FED through the evacuation process.

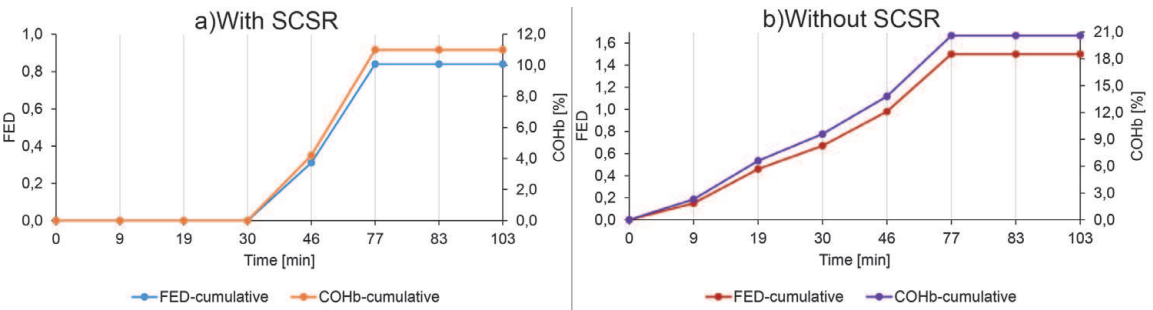


Figure 11.
Results from the FED and COHb models, for inhalation of CO during evacuation along the route 1.

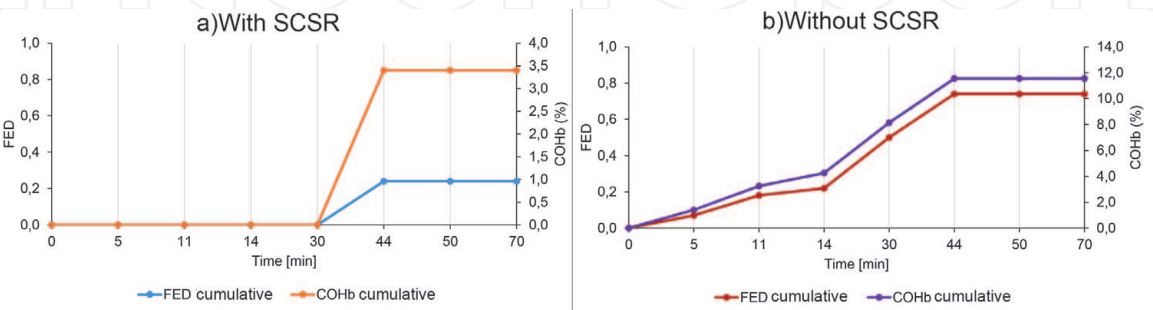


Figure 12.
Results from the FED and COHb models, for inhalation of CO during evacuation along the route 2.

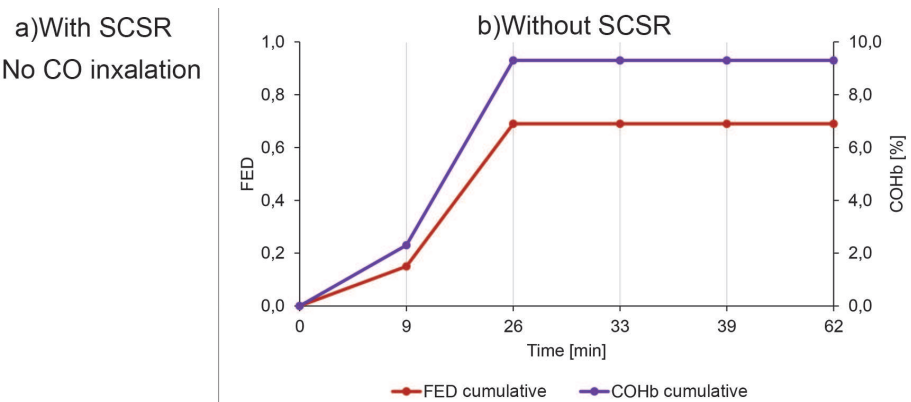


Figure 13.
Results from the FED and COHb models, for inhalation of CO during evacuation along the route 3.

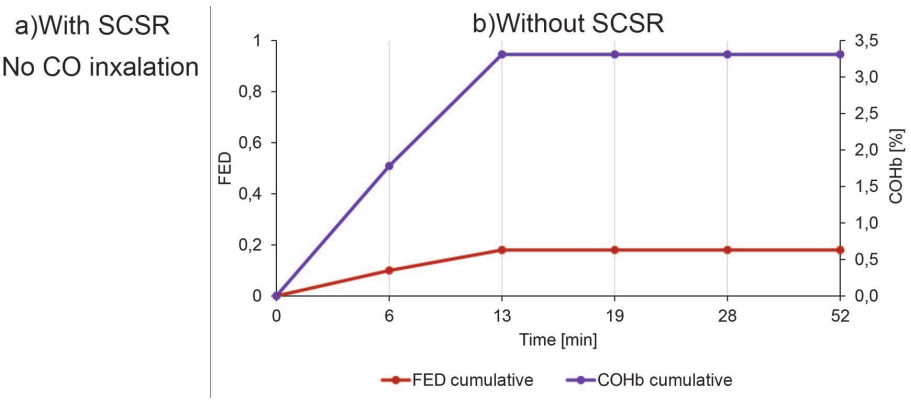


Figure 14.
Results from the FED and COHb models, for inhalation of CO during evacuation along the route 4.

The first step in the optimization model is to group the evacuation routes into five categories:

1. Group 1 of evacuation routes with a value of $FED = 0$
2. Group 2 of evacuation routes with a value of $FED > 0 \leq 0,5$
3. Group 3 of evacuation routes with a value of $FED > 0,5 \leq 0,8$
4. Group 4 of evacuation routes with a value of $FED > 0,8 \leq 1$
5. Group 5 of evacuation routes with a value of $FED > 1$

The values of the FED parameter on which the grouping is based are determined using the COHb model from which COHb (%) concentrations in the blood are predicted for the same CO exposure which in turn are related to the clinical symptoms presented in the **Table 4**.

After grouping the routes into the abovementioned categories, they are filtered through a decision support process that applies the parameter optimization objectives. The optimization model is set so that there is no data in the first group to continue to the next one until the last group is reached.

For the routes in the first group in which the level is set to $FED = 0$, the model will select the shortest route in length which will represent the optimal evacuation route.

The same optimization process is also set for the second and the third group in which the level is set to $FED > 0 \leq 0,5$ and $FED > 0,5 \leq 0,8$ accordingly. The reason why this three groups are separated is to give an advantage in the optimization process to the routes with less CO exposure than on those with shorter lengths.

For the routes in the fourth group in which the level is set to $FED > 0,8 \leq 1$, the model will select the route with the minimum CO exposure presented in the form of FED. In this group, clinical symptoms of CO exposure predict conditions that can cause difficulties during the evacuation process, and because of this, the optimization is set based on the FED parameter with minimal value. The evacuation routes selected in this group should be treated with caution, and they should be thoroughly analyzed for opportunities to install additional evacuation support systems in certain critical locations.

For the routes in the fifth group in which the level is set to $FED > 1$, the model will treat all routes as unsafe for evacuation. If the proposed methodology in this study does not generate data which will fall into the first four groups, then an additional analysis should be performed using the developed ventilation model that shows the movement of smoke and toxic gases through the underground mining facilities. These results could serve to plan the action strategy for the rescue teams

	FED	Route length [m]
Route 3 (rank 1)	0	3282
Route 4 (rank 2)	0	3327
Route 2 (rank 3)	0,24	2082
Route 1 (rank 4)	0,84	2912

Table 9.
Ranked evacuation routes from the optimization process for scenario S-1 with the use of a SCSR.

or for a suggestion of additional systems that could help in the evacuation process for those affected by the fire scenario.

Table 9 shows the results from the optimization methodology for scenario S-1 in which the routes are sorted by their ranking, taking into account the use of a SCSR.

Considering the use of a SCSR, the optimal evacuation route for scenario S-1 is route 3 which has the best rating according to the present methodology.

Table 10 shows the results from the optimization methodology taking into account the possibility of malfunction of the SCSR for scenario S-1.

The optimal evacuation route for scenario S-1 in which we assumed the malfunction of the SCSR is route 4 which according to the present methodology has the best rating.

	FED	Route length [m]
Route 4 (rank 1)	0,18	3327
Route 2 (rank 2)	0,74	2082
Route 3 (rank 3)	0,69	3282
Route 1 (rank 4)	1,5	2912

Table 10.
Ranked evacuation routes from the optimization process for scenario S-1 without the use of SCSR.

	Optimal route with SCSR			Optimal route without the use of SCSR		
Scenario S-2	Route 3	FED = 0	Length = 3282 m	Route 2	FED = 0,421	Length = 2082 m
Scenario S-3	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,115	Length = 3327 m
Scenario S-4	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,112	Length = 3327 m
Scenario S-5	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,175	Length = 3327 m
Scenario S-6	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,168	Length = 3327 m
Scenario S-7	Route 3	FED = 0	Length = 3282 m	Route 2	FED = 0,439	Length = 2082 m
Scenario S-8	Route 3	FED = 0	Length = 3282 m	Route 2	FED = 0,432	Length = 2082 m
Scenario S-9	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,165	Length = 3327 m
Scenario S-10	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,161	Length = 3327 m
Scenario S-10	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,159	Length = 3327 m
Scenario S-11	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,174	Length = 3327 m
Scenario S-12	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,163	Length = 3327 m
Scenario S-13	Route 3	FED = 0	Length = 3282 m	Route 2	FED = 0,448	Length = 2082 m
Scenario S-14	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,170	Length = 3327 m
Scenario S-15	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,169	Length = 3327 m
Scenario S-16	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,162	Length = 3327 m
Scenario S-17	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,156	Length = 3327 m
Scenario S-18	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,171	Length = 3327 m
Scenario S-19	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,144	Length = 3327 m
Scenario S-19	Route 3	FED = 0	Length = 3282 m	Route 4	FED = 0,173	Length = 3327 m

Table 11.
Optimal evacuation route for every fire scenario generated by the Monte Carlo simulation model.

Table 11 Shows every optimal evacuation route for group 1 based on the fire scenarios generated by the Monte Carlo simulation model. As previously mentioned the simulation process in the VentFIRE™ module is done from the same fire location for each of the generated scenarios.

6. Conclusion and future aspects

A methodology for determining optimal evacuation routes in case of underground mine fire has been developed based on the results from simulated fire scenarios. The presented methodology can be consistent with the actual situation of the mine because the development of the fire scenarios is based on the risk analysis generated from the current production plans, and the simulation of the developed scenarios are performed on the ventilation network from the mine.

To address the stochastic nature of the fire scenarios, the methodology implements the Monte Carlo simulation technique to emphasize the fact related to the inability to accurately determine the input parameters for the fire modeling process. From the large list of stochastic input parameters that can have a noticeable effect on the fire scenarios itself, the authors decided to elaborate only on the process of obtaining fire load inputs, from which the size of the fire depends and thus the amount of generated toxic gases. The results of the proposed methodology point to the fact that by treating the stochastic input parameters presented in this chapter in the form of a fire load, the generated conditions influenced the process of determining the optimal evacuation routes.

The Monte Carlo simulation model with the above-defined parameters which follows the normal distribution is implemented on a case study from “SASA”-R.N. Macedonia mine. After the analysis with the proposed methodology, a fire scenario generated by the mechanization Scooptram ST7 is located which represents the total fire load. The stochastic model is set to generate 20 variations from the fire load that are treated as separate scenarios in the process of determining the optimal evacuation routes.

The process of modeling and simulation of the generated fire scenarios is done with the VentFIRE™ module which uses the ventilation network to calculate the movement of the smoke and toxic gases from which the evacuation process depends.

The fire parameters obtained from the simulated scenarios are used to calculate the optimal evacuation routes for each of the generated scenarios.

The proposed methodology as the main factors influencing the evacuation process treats the inhalation of CO through the evacuation route presented in the form of FED and COHb, factors in the form of tunnel slope, and smoke visibility that affect the speed of evacuation and also the SCSR.

In the analysis presented in this chapter, differences in optimal routes for evacuation were located only in the conditions of SCSR malfunction. The results presented in **Table 11** highlight the importance of this additional analysis that is possible only by creating multiple variants of one fire scenario which is actually the underlying purpose of the proposed methodology. In the conditions of using the SCSR, the proposed methodology has determined and confirmed route 3 as optimal for evacuation in all variants of the generated fire scenarios. The results obtained from the conditions of SCSR malfunction located the changes in the optimal evacuation between routes 2 and 4 depending on the variable conditions that determined all the fire scenarios. This approach of analyzing fire scenarios offers certainty in the process of confirming the optimal route as well as locating possibilities for its change depending on the variable fire conditions.

In order to further improve the methodology, we need to expand our research by introducing the other stochastic variables that may have impact on the evacuation process such as the physical status of mineworkers that is related to age, gender, exercise ability, and response ability.

This research provides a convenient methodology for improving the accuracy of determining the optimal evacuation routes which significantly can increase the safety in underground mines.

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