



# Monte Carlo simulation of uncertain parameters to evaluate the evacuation process in an underground mine fire emergency

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## Synopsis

In the process of designing a fire safety system for underground mines, computer fire models can be used to analyse and estimate the consequences of fire scenarios for the evacuation process and the safety of mineworkers. The models need to be fed with data, some of which is stochastic in nature. Recent literature addresses the need for a computationally effective methodology for introducing uncertainties in the input parameters of fire and evacuation models to improve safety in underground mines.

This research paper presents the results obtained from a methodology that implements Monte Carlo simulation, which follows the normal distribution of the fire load and the pre-movement time uncertainty to generate multiple scenarios that are simulated in a 3D model to show the propagation of combustion products through the mine ventilation network. These results are then used to estimate the fractional effective dose (FED) of fire combustion products in workers, and the available safe egress time (ASET) and required safe egress time (RSET), which can highlight the safety issues in the evacuation process.

To demonstrate the model, a case study of the SASA- R.N. Macedonia lead-zinc mine was used in which 50 variations of scenarios were simulated. The results from the simulations are analysed and potentially harmful fire scenarios highlighted.

In addition to being able to identify potentially dangerous fire scenarios, the model can also help in the process of conducting fire risk assessment and in improving the evacuation system in the case of an underground mine fire.

## Keywords

underground mines, Monte Carlo simulation, available safe egress time, required safe egress time, fractional effective dose.

## Introduction

Underground fire represents one of the most dangerous hazards in mining, with potential to cause large losses of human life and other challenging safety issues (Smith and Thimons, 2010; Adjiski, Despodov, and Serafimovski, 2017). For this reason, much effort has been devoted to predicting the effects of underground fires and using the results to design emergency procedures to protect people working underground.

When using fire simulation models for carrying out analyses of fire consequences and evacuation procedures, there is a degree of uncertainty concerning input variables (Kong *et al.*, 2013; Li, Hadjisophocleous, and Sun 2018; Azarkhail, Ontiveros, and Modarres, 2009). Due to the fact that some of the input parameters are stochastic in nature, the results of the simulation need to be treated carefully. Examples of such parameters that affect fire and evacuation simulation models are fire location, fire load, fire growth parameter, pre-movement time of evacuation, speed of evacuation, *etc.* (Guanquan and Jinhui, 2012; Hietaniemi, 2007; Jahn, Rein, and Torero 2008). If the uncertainties in such parameters are ignored and point estimates are selected, the output from the fire simulation could indicate either a safe or an unsafe situation, depending on the inputs selected by the user. Therefore, in order to obtain more accurate results, there is a need for more advanced techniques to quantify uncertainties. There are few techniques that can address uncertainty, but the most cost-effective and reliable technique is the Monte Carlo simulation (Kong *et al.*, 2013; Vanorio and Mera 2012; Au, Wang, and Lo, 2007).

Numerical simulations of fire scenarios where uncertainty in input variables is considered can be computationally expensive, and therefore a technique is needed that can combine the results from the fire simulation and evacuation in a computationally effective way. The work presented in this paper introduces a methodology that combines four steps, shown in Figure 1, to evaluate the evacuation process.

In the first step of this methodology, the basic fire parameters are calculated using computational fluid dynamics (CFD) analysis. These will serve to guide more precise modelling of the burning rate

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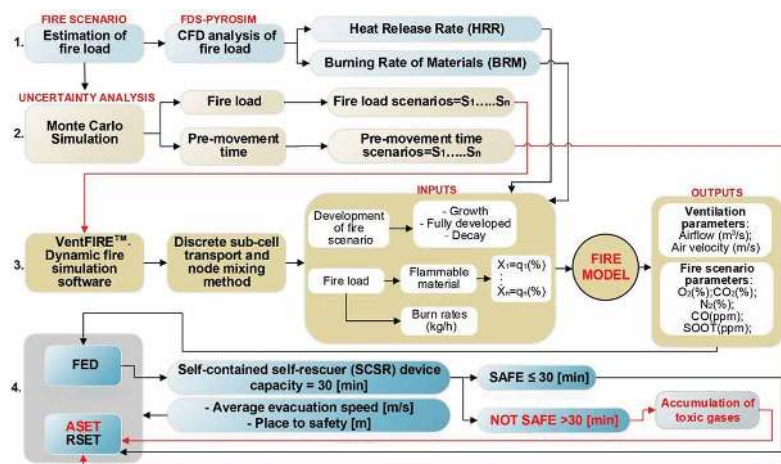


Figure 1 – Flow chart for the implementation of the methodology

(BR) of the material and also for comparison of the heat release rate (HRR) curves from the generated fire scenarios. The second step combines Monte Carlo simulation with a fire load model to address the propagation of uncertainty in the materials affected by the fire, which will generate variations of the fire scenario. In this step we will also construct a model for the propagation of uncertainty in the pre-movement time in the evacuation process. The third step uses the VentFIRE™ module in the ventilation software Ventsim, for simulation and calculation of combustion products from the scenarios previously generated with the Monte Carlo technique. The VentFIRE™ module uses dynamic simulation techniques to simultaneously model toxic gases, heat, and air flow changes from the fire scenario in an underground mine environment over a period of time. For increased accuracy in modelling the input parameters of fire scenarios in the VentFIRE™ module, we will use the data obtained from the CFD analysis, which will allow us to input the BR curve and also to compare the generated HRR curves. In the fourth step, we will calculate the FED and the ASET/RSET values when evacuating from a specific location in the mine for all of the generated fire scenarios. In the process of calculating the FED and the ASET/RSET parameters, we take into account the pre-movement time uncertainty that is modelled by the Monte Carlo simulation, variations of the average evacuation speed, and the fixed (30 minute) capacity of the self-contained self-rescuer (SCSR) device.

## Literature review

This section presents a narrow-scope literature review, serving to situate the current study within the relevant literature. Since research into fire safety and its effects in underground mines involves many disciplines, previous research efforts have been conducted in many different areas.

Salem (2016) presented results obtained from combining the Monte Carlo simulation technique with a fire model to predict the ASET in four different fire scenarios that involve typical ship layouts. His results indicated that the ASET is always affected by the input stochastic parameters.

Hostikka and Keski-Rahkonen (2003) developed a risk analysis tool for computing the distributions in the fire model output variables. The tool combines Monte Carlo simulation and a two-zone fire model (CFAST) to estimate the failure probability of redundant cables in a cable tunnel fire, and the failure and smoke filling probabilities in an electronics room during an electronics cabinet fire. A methodology for the calculation of sensitivity

of the output variables to the input in terms of the rank order correlations is also presented

Xie *et al.*, (2012) presented a methodology that combines Monte Carlo simulation with FDS plus Evac to quantify the impact of uncertain parameters on evacuation time in commercial buildings. The results indicate that the methodology can effectively quantify the uncertainty in evacuation time caused by the uncertainties associated with the input parameters. They also stated that the pre-movement time is the most significant factor among the uncertain input parameters considered.

Guanquan and Jinhua (2006) presented the effect of occupant pre-movement time and occupant density on evacuation time in two hypothetical scenarios inside a multi-compartment building. According to the results, there are different effects on evacuation time when pre-movement times are characterized by explicit values and a normal distribution. Therefore, to calculate the evacuation time more reasonably, the main conclusion stressed the use of probability distribution to depict the occupant pre-movement time. In this article, the authors use normal distribution to characterize the pre-movement time to study its effect on evacuation time.

Tosolini *et al.*, (2012) presented a sensitivity study for the ASET performance criteria. The authors make a comparison between the Fire Dynamic Simulator (FDS) results and an analytical approach for a quick estimation of the ASET in an enclosure. The results of this study show that the methodology is usable as a decision support tool for emergency evacuation design.

Li-li *et al.*, (2013) used the FDS software and the evacuation software Building-Exodus to simulate smoke movement and the egress of the occupants of an underground pedestrian street. From their simulation, they obtained results for the ASET and the RSET, and by comparing both times, they were able to conclude whether the existing underground pedestrian street meets the evacuation requirements.

Adjiski *et al.*, (2015) developed a system that uses available software to work out complete evacuation plans that include the analysis of fire scenarios and the optimal routes for evacuation. The authors also presented a methodology for the modelling and simulation of fire scenarios in underground mines.

Most of the reviewed studies focused on fire stochastic parameters of the two-zone fire models or the CFD models of buildings or small civil areas. Very few studies extended this phenomenon to underground mines or considered the effect

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it has on the evacuation process. This research will present a methodology for introducing uncertain parameters in fire and evacuation scenarios in underground mines. The main idea is to take a fire scenario and, by processing the stochastic inputs for fire and evacuation parameters with Monte Carlo simulation, to generate multiple scenarios that will help to easily identify weak links in the fire and evacuation system.

## Methods

### CFD analysis of a fire scenario

Using sophisticated CFD fire models, we can simulate the movement and concentration of gases and heat generated by a fire through an area, and estimate the response of various fire protection systems. We used the PyroSim software, which is a graphical user interface for the Fire Dynamics Simulator (FDS) (PyroSim User Manual, 2014). The FDS simulates fire scenarios using CFD optimized for low-speed, thermally driven flow. The numerical method essentially consists of a finite difference approximation of the governing equations and a procedure for updating these equations in time. The software solves numerically a large eddy simulation (LES) form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires (McGrattan *et al.*, 2013). The governing equations and the numerical method can be found in McGrattan, Baum, and Rehm (2007).

In this paper, we will model a fire scenario in which we will approximate the fire load from the Atlas Copco Scooptram ST3.5 loader and calculate the HRR and the BR in PyroSim. Moreover, for simplification purposes it can be assumed that the tyre, hydraulic fluid, and diesel fuel which are contained in the fire load are known values, regardless of the fact that the value for the diesel fuel is usually stochastic in nature, depending on fuel tank status (full, empty, or in-between).

The 3D geometry, meshing, and numerical modelling were carried out using PyroSim. The geometry of the underground mining section and the operating parameters of the ventilation system are shown in Figure 2.

In the LES simulation, the grid size is an important factor to be considered. A more detailed and smaller grid size gives more information of the turbulent flow but needs a longer computing time. According to the FDS6 user's guide for simulations involving buoyant plumes, a measure of how well the flow field is resolved is given by the non-dimensional expression  $D^*/\delta x$ , where  $D^*$  is a characteristic fire diameter and  $\delta x$  is the nominal size of a mesh cell (McGrattan *et al.*, 2013):

$$D^* = \left( \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{5}} \quad [1]$$

where  $\dot{Q}$  is the heat release rate (kW),  $\rho_\infty$  the density (kg/m<sup>3</sup>),  $c_p$  the specific heat (kJ/kg\*K),  $T_\infty$  the ambient temperature (K) and  $g$  the acceleration due to gravity (m/s<sup>2</sup>);



Figure 2—3D geometry and ventilation parameters of the model

Table 1

Approximate fire load calculation and input parameters for the fire scenario from Atlas Copco Scooptram ST3.5

	Tyre	Diesel fuel	Hydraulic fluid
Weight or volume	248*4=992 kg	250 L	170 L
Density (kg/m <sup>3</sup> )	1150	918	760
Simplified chemical hydrocarbon formula	C <sub>4</sub> H <sub>6</sub>	C <sub>12</sub> H <sub>23</sub>	C <sub>36</sub> H <sub>74</sub>
Heat of combustion (kJ/kg)	44 004	46 108	48 544
Burning rate of material kg/m <sup>2</sup> .s] (Roh <i>et al.</i> , 2007)	0.045	0.062	0.039

A reference citation in the FDS User Guide (Stroup and Lindeman, 2013) used a  $D^*/\delta x$  ratio between 4 and 16 to accurately resolve fires in various scenarios.

With consideration of the computational time and numerical accuracy, a moderate mesh size is suggested as follows:

- Characteristic fire diameter  $D^*$ : 1.488
- Nominal size of a mesh cell  $\delta x$ : 0.149
- $D^*/\delta x$  ratio: 9.98
- Actual  $\delta x$  are 0.139; 0.148; 0.15 (m)
- Distances are 30; 4; 3; (m)
- Total number of cells is 116 640.

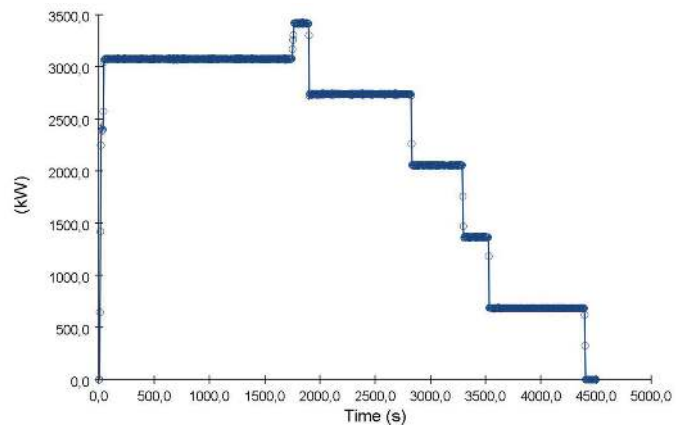


Figure 3—HRR from one tyre

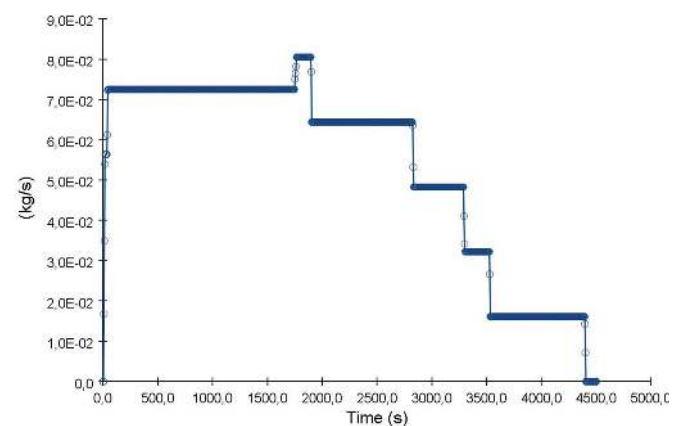


Figure 4—BRM for one tyre

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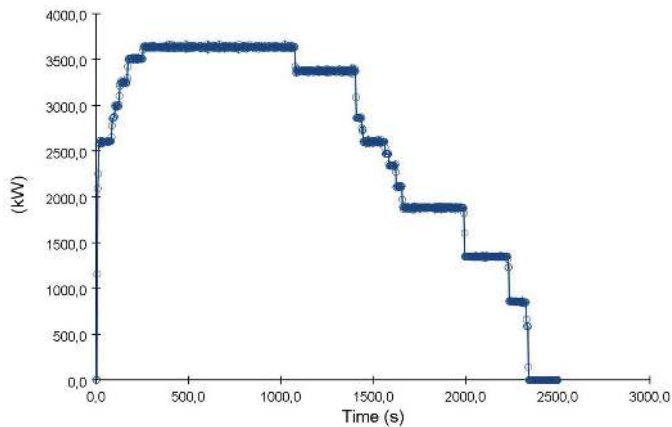


Figure 5—HRR for diesel fuel

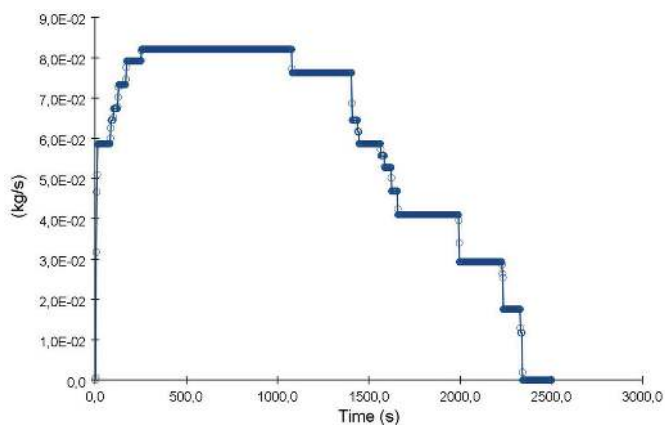


Figure 6—BRM for diesel fuel

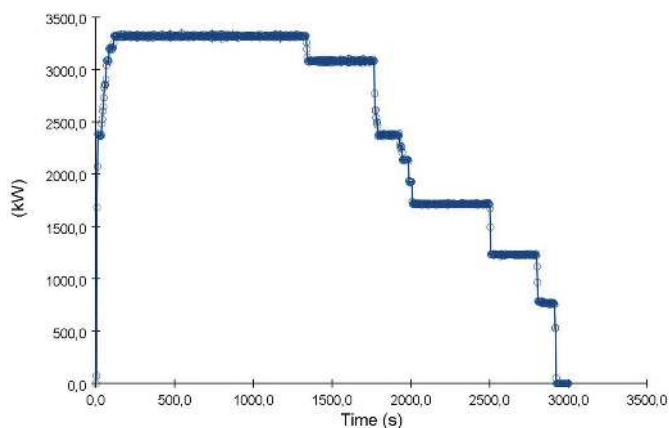


Figure 7—HRR for hydraulic fluid

From the approximate fire load calculation and the chemical and physical characteristics of the materials shown in Table I, we get the results shown in Figures 3–8 from PyroSim. These results will serve as a guide that will allow us to input the BR curve to the VentFIRE™ software module and also to compare the generated HRR curves. Figure 9 shows the simulation results from the fire load in the underground mining section calculated in PyroSim.

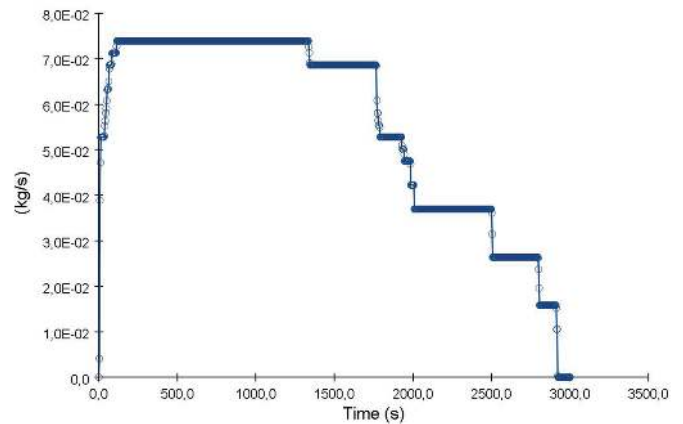


Figure 8—BRM for hydraulic fluid

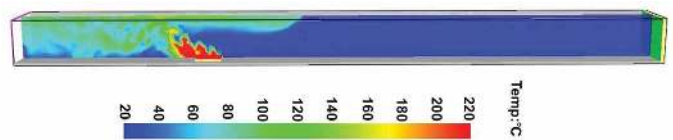


Figure 9—Simulation results from the fire load in the PyroSim software

### Monte Carlo simulation

In the process of modelling fire scenarios, some uncertainty is related to the input values to the simulation, which may be caused by lack of information on the actual conditions. In fire scenarios and evacuation procedures, any outcome, such as the concentration of toxic gases in a certain location and the time for evacuation, is a function of all possible uncertain input variables having an effect on that outcome. For example, if we define an event  $F$  as the concentration of toxic gases in a certain location being above a certain value  $y$ , the probability of  $F$  happening depends on a number of random variables, each of which has a probability distribution. These random variables can be denoted by a vector  $X = [X_1, X_2, \dots, X_n]^T$ , and the probability that  $F$  happens is then a function of  $X$  and time, as the fire scenario or evacuation procedures is a time-dependent model (Lindström and Lund, 2009):

$$P_x(Y \geq y) = g(X, t) \quad [2]$$

$P_x$  belongs to a random distribution and in this paper it is calculated using the Monte Carlo simulation technique, where the input variables are sampled randomly from their respective distributions to generate variations in the fire scenarios and the evacuation process. The distributions of the uncertain parameters are drawn from their probability density function (PDF), which shows the values that the parameter can be assigned and how often these values are to be expected. The PDF is defined by the type (normal, lognormal, triangular, uniform, *etc.*), the minimum, the maximum, the mean ( $\mu$ ), and the standard deviation ( $\sigma$ ). Which PDF should be chosen for each random input parameter of the fire scenario is a question that many researchers have tried to answer (Frantzich, 1998; Holborn, Nolan, and Golt, 2004; Magnusson, Frantzich, and Harada, 1995). It should be noted that many of the fire input parameters are stochastic in nature and no-one can be certain about the type and amount of material involved in a certain fire scenario. Because of this, in order to

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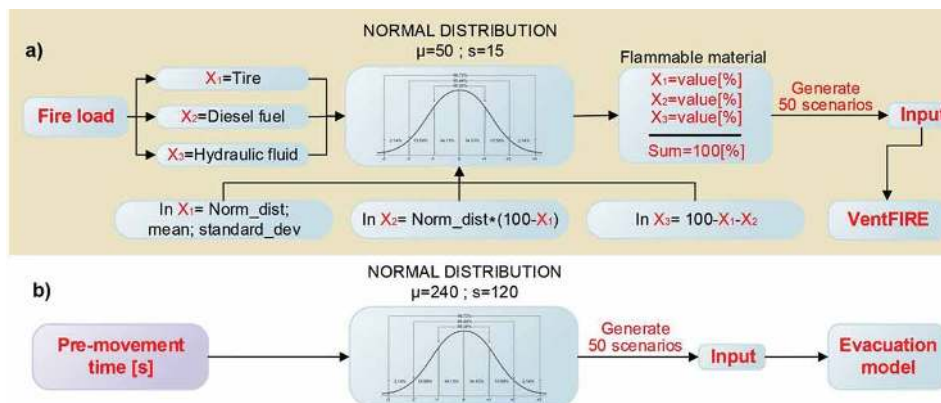


Figure 10—Monte Carlo simulation model for (a) fire load and (b) pre-movement time

reduce the complexity of this process, the authors decided that uncertain input values for the fire scenarios simulated using Monte Carlo simulation would be the fire load, on which the amount of smoke and toxic gases generated depends, and also the pre-movement time, which has an impact on the time for evacuation.

Due to the lack of data about which type of PDF to choose, which is usually impossible to decide upon in practice, the authors refer to Frantzich (1997), who pointed out that it is not that important if the random input parameters have not been assigned the exact distribution type, and also added that the most important information concerning a random parameter is the minimum and maximum values, mean, and standard deviation, which should be chosen based on a combination of statistical and experimental data and also expert judgment. He also noted that the most common type of PDF used for most of the random input parameters is the normal distribution. Because of this, the authors decided to use the normal distribution for the PDF. Figure 10 illustrates the basic idea behind the approach adopted.

In the process of introducing the uncertainty of the fire load, we took the assumed approximate calculations for the amount of flammable material in the fire scenario (Table 1), and input them into the Monte Carlo model with a normal distribution, defined by  $\mu = 50$  and  $s = 15$  (Figure 10a). The reason for the selected numbers behind  $\mu$  and  $s$  is to give a versatile distribution of fire load for each generated fire scenario, because no-one could

be certain about the type and amount of flammable material involved. The model is set to generate scenarios in which the amount of flammable material is expressed in percentages for direct input into the VentFIRE™ software module. In the pre-movement time, during which the mineworkers need to recognize and react to the fire scenario, we introduce uncertainty in the form of normal distribution-generating scenarios that will have different impacts on the evacuation time (Figure 10b). In determining the values for the mean and the standard deviation of the pre-movement time, we took the assumed time for recognition and reaction in the event of a fire and also the assumed time for putting on the SCSR. For the reaction time, we will assume that the workers will not try to extinguish the fire. These assumptions set  $\mu = 240$  seconds and  $s = 120$  seconds for the pre-movement time. The source and basis for the selected values constitutes a research investigation in itself. With the assumption that the mineworkers will not try to extinguish the fire, this leaves only the time parameters for recognition of fire scenario and for putting on the SCSR. The time to recognize a fire scenario and process this information at the same time when panic begins is very difficult to determine. The time needed to put on the SCSR is usually around 60 seconds, which leaves the assumption time to recognize a fire scenario at around 180 seconds. The standard deviation of 120 seconds is set because of the differences in perception and training for SCSR usage for each mineworker.

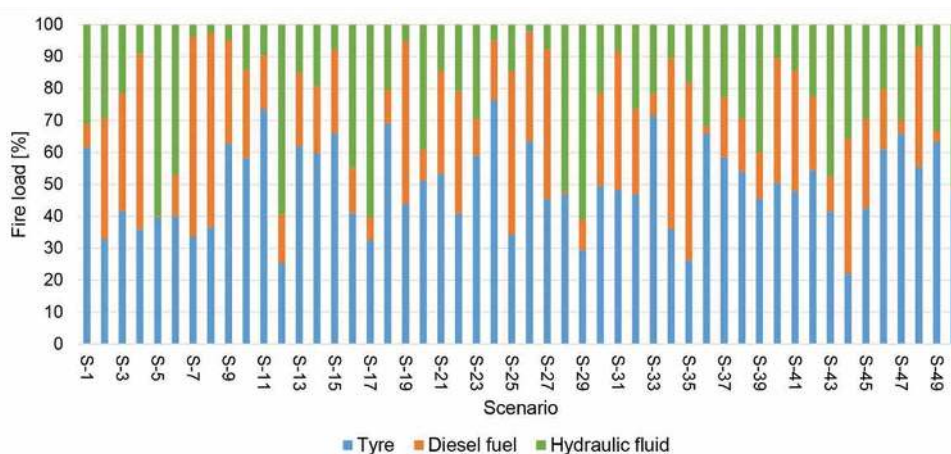


Figure 11—Generated scenarios for fire load from the Monte Carlo simulation model

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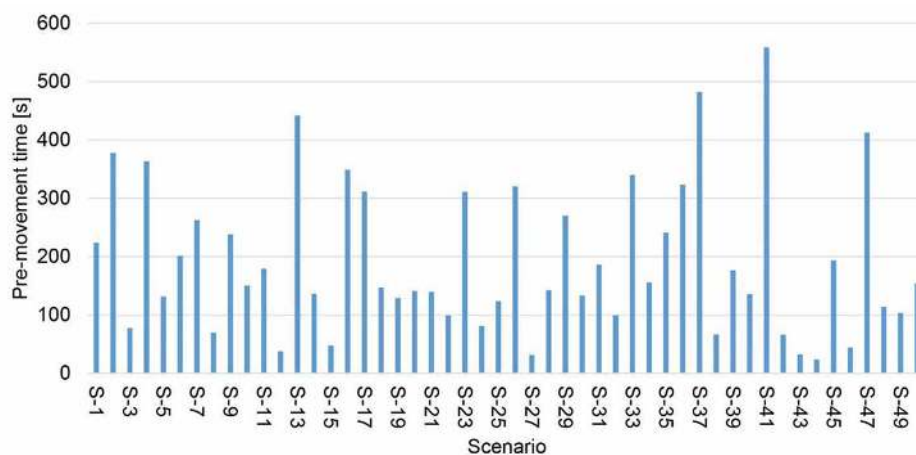


Figure 12—Generated scenarios for pre-movement time from the Monte Carlo simulation model

### VentFIRE™ software module

CFD simulations of complicated processes always involve a trade-off between the computational time required and the accuracy of the results. It should be noted that CFD analysis is usually used to represent a small section of the model, because of the large number of calculations performed in the analysis. In a situation where we have multiple complicated fire scenarios and especially in underground mines, which can have several kilometres of interconnected tunnels, a technique is needed that can generate results from different scenarios in a computationally effective way. In this paper we present a model that combines two methodologies for modelling and simulation of fire scenarios in underground mines, in order to obtain increased accuracy in generating the required results for a reasonable computing time.

The Pyrosim software is used to calculate fire parameters from a fire scenario in a small section of the underground mine ventilation network. In this CFD model, we approximate the fire load from an Atlas Copco Scooptram ST3.5 loader and calculate the HRR and the BR. The results from this step are then used as a guidance for a more precise modelling of the BR curve, and also to compare the generated HRR curves from the VentFIRE™ software module (Ventsim Visual™ User Guide 2014), which will calculate the fire combustion parameters from the fire load through the underground mine ventilation network. The VentFIRE™ software module requires as input the combustible

material composition in percentages, the time range for each time step in the BR curve, and the burn rate in kg/h. The working principle of the software allows the use of only one burn rate, and because of this the authors used the averaged value from the CFD analysis of the three material types as one burn rate.

For this purpose, a 3D model of the underground ventilation network of the SASA- R.N. Macedonia lead-zinc mine was prepared in Ventsim (Figure 13). The simulated results from this model were then used to calculate the FED and ASET/RSET for each generated scenario.

### Life safety assessment and evacuation in case of fire

In the event of fire in an underground mine the mineworkers may be subjected to untenable conditions that may lead to injury or death. Untenable conditions during fire are defined as environmental conditions in which human life is not sustainable due to exposure to heat, inhalation of toxic gases, or visual impairment due to smoke. The ultimate evaluation of performance-based fire protection design generally hinges on whether mineworkers can evacuate successfully, based on comparison of the two timelines, ASET and RSET (Purser, 2003). The basic aim of the timeline approach is to show that mineworkers are considered safe when the ASET is greater than the RSET with a sufficient safety margin (Figure 14).

This timeline approach is summarized as (Guanquan and Jinhua 2006):

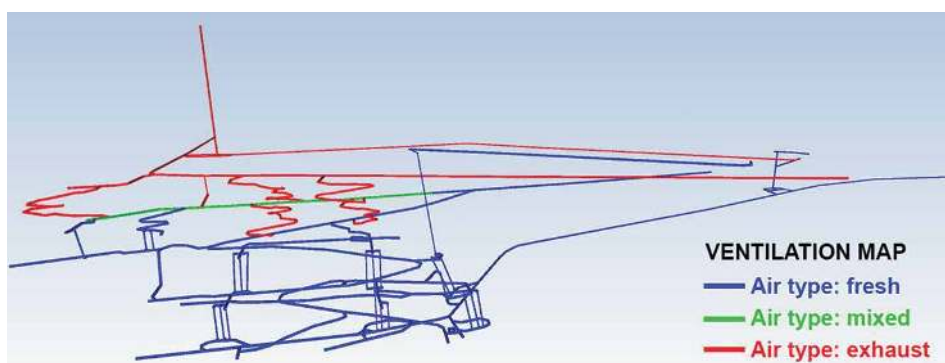


Figure 13—Ventilation network of the Sasa-R.N. Macedonia underground mine, built in the Ventsim software

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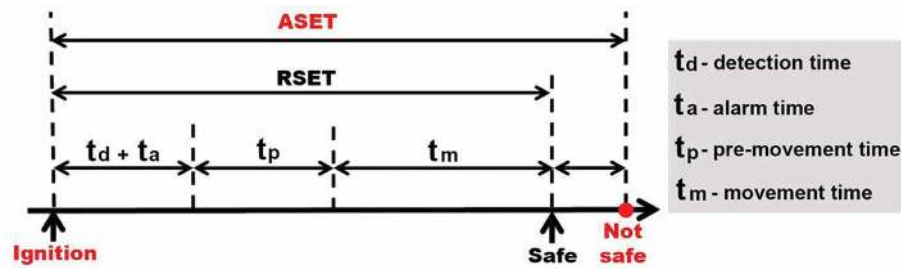


Figure 14—Timeline approach for mineworker safety evacuation

$$ASET > (RSET + \text{an appropriate safety margin}) \quad [3]$$

$$RSET = t_d + t_a + t_p + t_m \quad [4]$$

where,  $t_d$  is the time from ignition to detection,  $t_a$  the time from detection to issuing the evacuation warning,  $t_p$  the time before the mineworkers begin to move towards an exit (including the time to recognize and react to the situation), and  $t_m$  the time required for the mineworkers to travel to a place of safety.

During the evacuation process in underground mines, there are many uncertain factors associated with the mineworkers and the process itself. Therefore, in order to achieve a reasonable level of accuracy in modelling the evacuation, the effect of uncertain parameters on evacuation time should be examined. Fire detection and alarm time are influenced mainly by fire detection and alarm systems, and in terms of the overall evacuation time are close to being a constant and do not need to be considered in any further detail in this research. Hence, the mineworker evacuation time  $t_e$  is defined as the sum of the pre-movement time and the movement time:

$$t_e = t_p + t_m \quad [5]$$

Due to the randomness of human behaviour in each evacuation fire scenario, the pre-movement time is different for each mineworker and can be considered as a stochastic value following some probability distribution.

When mineworkers are widely distributed, which is generally the case in underground mines, there is likely to be a wide variation in the pre-movement time, but when a group of mineworkers is together in a single area, the range of the pre-movement time tends to be narrower.

Existing knowledge in this area does not provide the pre-movement time probability distributions for different mineworkers, and only suggests that it has been widely accepted that the pre-movement time follows some kind of a probability

density distribution (Xie *et al.*, 2012). In this research, the Monte Carlo technique with normal distribution is presented to depict the pre-movement time (Figure 10b). To simplify the research, evacuation speed uncertainty is taken as four different average speeds, which will have an impact on the overall evacuation times for all of the generated fire scenarios. Results from the Monte Carlo simulation model of the pre-movement time are shown in Figure 12.

Untenable conditions during a fire can be examined by approaches that determine the cumulative effect of exposure to fire products over time, presented in terms of FED (fractional effective dose). The fundamental concept of the FED approach is the summation of the proportional fractions of doses of toxicants at every time increment, and when the accumulated sum reaches a specified threshold safety value, this represents the time available for escape. A FED value of 1.0 is associated with the sub-lethal effects that can make mineworkers incapable of completing their own evacuation. Purser (2002) suggests a model to assess the exposure to toxic fire products by determining the FED for each asphyxiant at each discrete time interval  $\Delta t$  as follows:

$$FED_{Toxicity} = FED_{CO} * V_{CO_2} + FED_{O_2} \quad [6]$$

$$FED_{CO} = \sum_{t_1}^{t_2} \frac{K * [CO]^{1.036}}{D} \Delta t \quad [7]$$

$$V_{CO_2} = \frac{\exp(0.1903 * \%CO_2 + 2.0004)}{7.1} \quad [8]$$

$$FED_{O_2} = \sum_{t_1}^{t_2} \frac{1}{\exp(8.13 - 0.54(20.9\% - \%O_2))} \Delta t \quad [9]$$

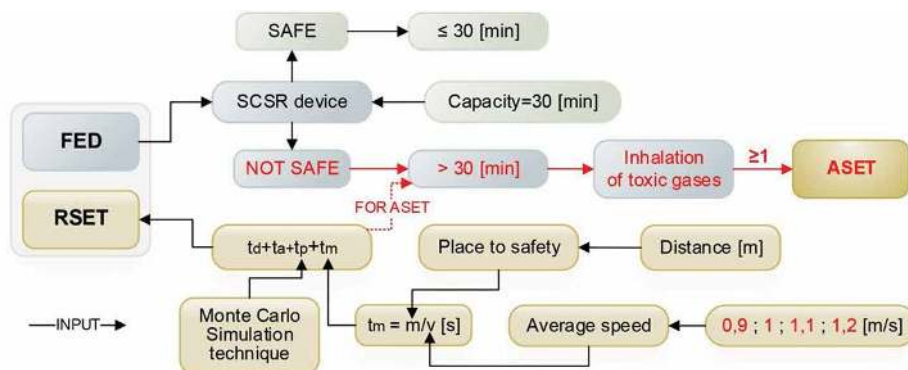


Figure 15—FED, RSET, and ASET calculation model

## Monte Carlo simulation of uncertain parameters to evaluate the evacuation process

*Table II*

**Values of constants K and D for different activity levels**

Activity	K	D
At rest	$2.81945 \times 10^{-4}$	40
Light work	$8.2925 \times 10^{-4}$	30
Heavy work	$1.6585 \times 10^{-4}$	20

where [CO] is the average concentration of carbon monoxide (ppm) over the time increment  $\Delta t$  in minutes; K and D are constants depending on the activity of the person (see Table II for values for different levels of activities); %CO<sub>2</sub> is the concentration of carbon dioxide (which although not toxic at concentrations of up to 5%, stimulates breathing and can increase the rate at which toxic fire products are inhaled; and  $(20.9 - \%O_2)$  is the oxygen percentage vitiation over the time increment  $\Delta t$ .

Accordingly, from the previous statements the ASET timeline may be taken as the interval between fire ignition and the exposure time required for  $FED_{Toxicity}$  to reach a value of 1.0. In this paper, the parameters for FED, RSET, and ASET are calculated according to the model shown in Figure 15.

From the model, it can be seen that the FED and ASET parameters are connected in terms such that the model determines the FED parameter at each discrete time interval  $\Delta t$  (Equations [6]–[9]). This process of determining the FED parameter to reach the value of 1.0 at  $\Delta t$ , after the capacity of the SCSR is exhausted and inhalation of toxic gases has started, can give the corresponding ASET timeline.

In order to calculate the RSET parameter, the model in Figure

15 requires input data for the average speed of evacuation (m/s), the distance to the place of safety (m), as well as the input data of the pre-movement time from the Monte Carlo simulation model.

### Results and discussion

In order to simplify the model presented in this paper, we will make two simplifications, in which we will not carry out a fire risk assessment to determine the locations of most likely fire scenarios, and calculate the evacuation process for only one group of workers. With these simplifications, we determine the hypothetical locations of the fire scenarios and the group of workers, which are shown in Figure 16.

The results from the CFD model for the calculation of HRR and BR for the approximate fire load from the Atlas Copco Scooptram ST3.5 loader are used to increase the accuracy in modelling the input parameters in the VentFIRE™ software module. The previously mentioned inputs for the fire load to VentFIRE™ will generate the HRR curve and a comparison with the HRR curves from the CFD analysis will serve to check the output data from the fire scenario.

The process of introducing uncertainty in the fire load is done in the Monte Carlo model with a normal distribution in which we entered the assumed approximate calculations for the amount of flammable material in the fire scenario (Table I). The results of this fire load uncertainty model, which is set to generate 50 scenarios for direct input into the VentFIRE™ software module, are shown in Figure 11.

The results obtained in the first two steps of the methodology shown in Figure 1 are then used in the VentFIRE™ software

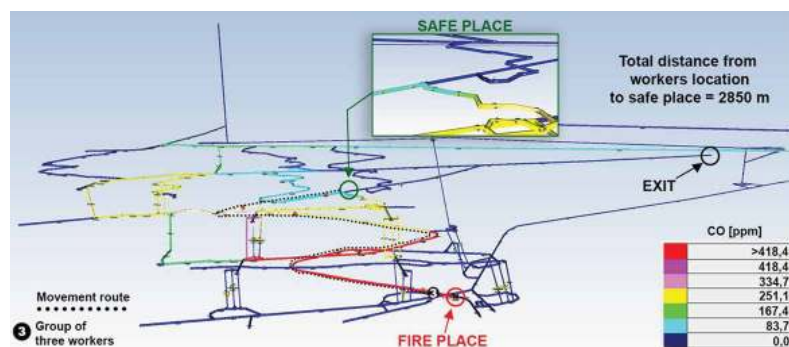


Figure 16—Set-up of fire scenarios. Screenshot from the simulation of fire combustion parameters at 30 minutes from fire ignition (scenario 1)

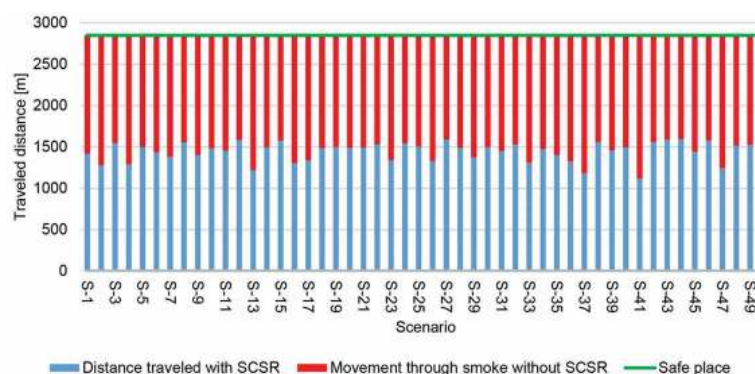


Figure 17—Distance travelled with and without SCSR for average evacuation speed of 0.9 m/s



## Monte Carlo simulation of uncertain parameters to evaluate the evacuation process

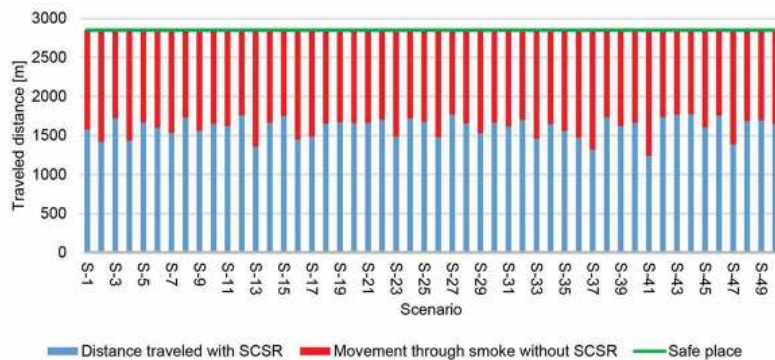


Figure 18—Distance travelled with and without SCSR for average evacuation speed of 1 m/s

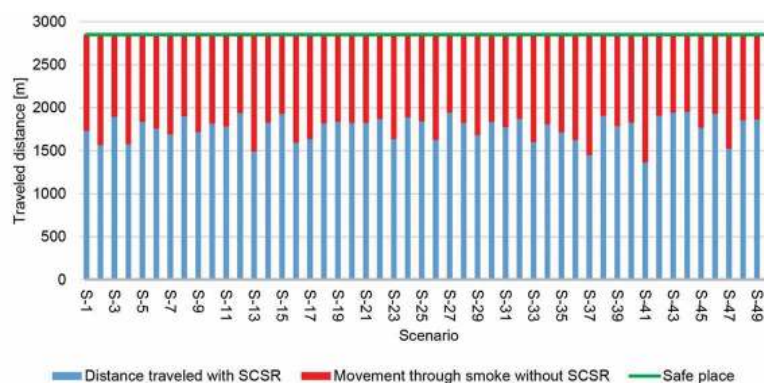


Figure 19—Distance travelled with and without SCSR for average evacuation speed of 1.1 m/s

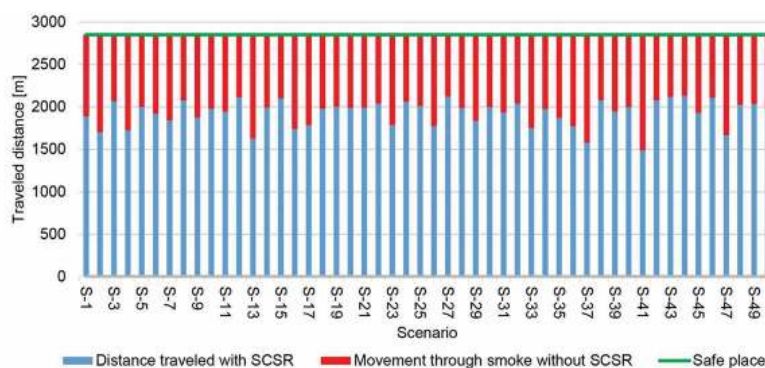


Figure 20—Distance travelled with and without SCSR for average evacuation speed of 1.2 m/s

module, from which the movement of combustion products through the mine ventilation network is calculated. The fire combustion parameters for all of the 50 generated scenarios are simulated and calculated in the VentFIRE™ software module. Due to the set-up of the ventilation system, the combustion products cannot move towards the mine exit, and therefore the safe place is considered to be the first area toward the exit where there is clean ventilation air (Figure 16).

The results obtained from the 50 scenarios are then used for the calculation of FED, RSET, and ASET, in which we used four different average evacuation speeds for each scenario, which yields 200 scenarios for analysis. The distance travelled with the SCSR device and the distance travelled after the capacity of the

device was reached for different average evacuation speeds are shown in Figures 17–20.

Figure 21 shows the results for FED accumulation of combustion products in mineworkers after the capacity of the SCSR was reached in each scenario for different average evacuation speeds.

The results from the FED analysis can also be used to evaluate and analyse each fire scenario along with the evacuation process. The model determines the FED parameter at each discrete time interval  $\Delta t$ , and thus it also provides a timeline, and if connected with the average evacuation speed can indicate the most unsafe places generated from the mine fire scenario. This type of analysis can significantly improve the evacuation

## Monte Carlo simulation of uncertain parameters to evaluate the evacuation process

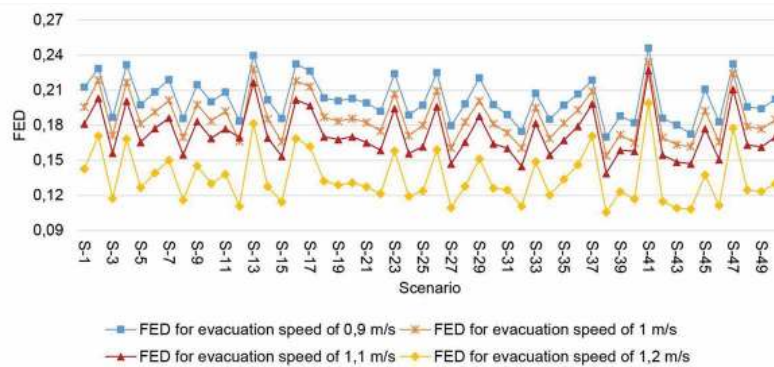


Figure 21—FED accumulation for different average evacuation speeds

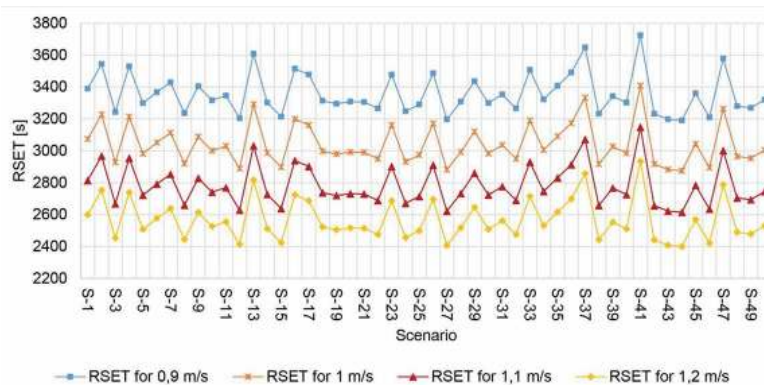


Figure 22—RSET timelines for different average evacuation speeds

and safety system in the event of a fire by introducing additional procedures in the selected areas, and also facilitate determining the optimal locations for refuge chambers.

Figure 22 shows RSET timelines, which include the sum of the pre-movement and the movement time for different average evacuation speeds.

The RSET results from this analysis show a very important element in the process of performance-based fire protection design in underground mines because they can demonstrate that the proposed evacuation procedure meets defined objectives.

Due to the use of SCSRs with a capacity of 30 minutes, none of the presented scenarios reached the critical time of the ASET in which the FED value is greater than or equal to the specified threshold safety value of 1.0.

The ASET is very important parameter in the process of evaluating each fire evacuation scenario, because of its timeline connection with the FED parameter and the possibility of identifying evacuation and fire safety design solutions that would increase the safety of the mineworkers.

Although the selected fire location in this research does not generate scenarios that reached the critical time of the ASET, the importance of the introduction and inclusion of this parameter in the research speaks for itself, and also sets the foundation for further expansion of the research.

### Conclusion

This paper highlighted the importance of introducing uncertainties in the stochastic input parameters of fire and evacuation models for predicting the FED and, ASET/RSET timeline used to analyse the consequences of a given fire scenario in underground mines.

Because of the large number of uncertainties in fire and evacuation models, and also in order to present the results within a reasonable time, the authors decided to highlight and select those uncertainties upon which the amount and concentration of combustion products through the underground mine ventilation network depend, and also the pre-movement time, which affects the time for evacuation of each mineworker. In order to simplify the research, the evacuation speed uncertainty was taken as four different average speeds.

A methodology was proposed and used that includes CFD analysis of the fire load, Monte Carlo simulation for fire load and pre-movement time to generate variations of scenarios, dynamic simulation of the movement of combustion products through the mine ventilation network for all of the generated scenarios, and calculation of the FED and ASET/RSET for each scenario.

A case study of the SASA- R.N. lead-zinc mine in Macedonia was successfully used to demonstrate the methodology, in which 50 scenarios were simulated and the results used to calculate the FED and ASET/RSET with four different average evacuation speeds for each of the 50 scenarios. The results of the analysis have proven the output sensitivity to uncertainties in the input parameters in fire and evacuation models.

With this proposed model, we can identify the fire scenarios that failed to satisfy the safety requirements and recommend improvements to the system for evacuation. Moreover, in the process of conducting the fire risk assessment, this model provides a computationally effective way to combine the results from the fire simulation and evacuation to find the safe routes for evacuation, based on the FED and ASET/RSET results.

Future work will include extension of the research to deal with the identified limitations of the proposed methodology. One

## Monte Carlo simulation of uncertain parameters to evaluate the evacuation process

of these is the safety margin for the RSET calculation, which as stated in this paper is a FED value of <1. The question is; how much less? This intrigued our team, and will be the subject of another study. The idea is to include system based on Arduino, sensor board (CO and other sensors), and a smartphone with a specially developed app for prediction of carboxyhemoglobin (COHb) levels in human blood, which can be used as approximate correlation between blood COHb level and clinical symptoms. The proposed system is for real-time monitoring of the mine environment and can be worn by every mineworker. The relationship between the methodology presented in this paper and this proposal for further research is that the smartphone app for prediction of COHb levels can use the CO concentration curve as input from the simulated fire scenario, and based on this give a timeline with prediction of COHb with the corresponding clinical symptoms and set the limit on the RSET timeline.

Opportunities for further research also involve extending the parameters with a stochastic nature, such as the fuel tank status, evacuation speed, and the remaining parameters that have a significant impact on the fire scenario or the evacuation process.

Future extension of this work will also include modifications to the methodology that will connect the process of fire risk assessment to determine the locations of fire scenarios that can reach the critical time of ASET, and to find and offer solutions based on these results.

This research outlines a methodology that will hopefully contribute to the process of identifying potential harmful fire scenarios and testing the evacuation process, which significantly increases safety in the event of fire in underground mines.

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