

Risk-Based Assessment of Ventilation Performance in Underground Mining Workings during Fire Emergency Scenarios

Marek JAŠKO^{1*}, Marek MIHALIČ², Jozef MALENKY³, Roman GALLIK⁴ and Ivan KURIC⁵

Authors' affiliations and addresses:

¹ Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: marek.jasko@student.tuke.sk

² Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: marek.mihalic@student.tuke.sk

³ Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: jozef.malenky@student.tuke.sk

⁴ Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: roman.gallik@student.tuke.sk

⁶ University of Bielsko-Biała, 2 Willowa st., 43-309 Bielsko-Biała, Poland
e-mail: kuric.ivan@gmail.com

*Correspondence:

Marek Jaško, Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
tel.: +421 55 6023150
e-mail: marek.jasko@student.tuke.sk

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Abstract

Maintaining effective ventilation during underground fire emergencies is essential for protecting human life, ensuring operational safety, and reducing the consequences of accidents in underground mine workings. Fires in confined underground environments are characterised by rapid smoke generation, toxic combustion products, elevated temperatures, and changes in airflow patterns, all of which may significantly impair evacuation and complicate emergency response operations. Current approaches to ventilation assessment are commonly developed for specific mining operations or geological conditions, limiting their applicability to other underground environments. This study proposes a generalised methodology for evaluating the performance of underground ventilation systems during fire emergencies, independent of a particular mining site or geological setting. The proposed framework integrates the principles of mine ventilation, ventilation network analysis, fire scenario assessment, and risk evaluation into a unified methodological approach. The methodology evaluates airflow distribution, pressure losses, contaminant transport, ventilation stability, and selected safety indicators affecting evacuation and emergency response. Its applicability is demonstrated using representative fire scenarios that reflect typical underground ventilation configurations and different levels of fire severity. The proposed approach enables the systematic identification of critical sections within underground workings, improves the prediction of smoke and toxic gas propagation, and supports the optimisation of ventilation management during emergency conditions. Furthermore, the methodology provides a basis for developing quantitative indicators to objectively assess ventilation safety and operational preparedness. Owing to its generalised structure, the proposed framework can be applied to various types of underground mine workings and may serve as a practical decision-support tool for mine designers, ventilation engineers, safety specialists, and emergency response planners. It also establishes a foundation for future integration with numerical simulation techniques and digital models of underground environments.

Keywords

underground mine workings; fire safety; mine ventilation; smoke propagation; risk assessment



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Introduction

Underground mine workings represent a specific working environment in which geological, technical, technological and operational factors jointly influence worker safety and the continuity of mining activities. Compared with surface operations, underground spaces are characterised by limited escape routes, complex networks of roadways, strong reliance on technical systems, and demanding conditions for organising rescue activities. Therefore, any underground emergency represents a significant risk, with potential consequences for human life, technical equipment, and the economic continuity of mining operations (Lupo & Morrison, 2026; Han, Bao & Pasricha, 2021; Mulenga Besa & Mazimba, 2020).

Among the most serious underground emergencies are mine fires, explosions of combustible gases and coal dust, releases of hazardous substances, and failures of technological equipment accompanied by the generation of toxic combustion products. These events are characterised by rapid, dynamic development, with underground conditions potentially deteriorating within a few minutes. Increased concentrations of carbon monoxide and carbon dioxide, oxygen depletion, rising temperatures, and reduced visibility significantly hinder both personnel evacuation and the intervention of mine rescue teams. Consequently, a properly designed and reliable mine ventilation system is one of the key factors in the successful management of underground fire emergencies (Tan et al., 2025; Demirović & Marković, 2024; Fernández-Alaiz et al., 2020).

Mine ventilation performs several indispensable functions in underground mine workings. Under normal operating conditions, it provides a continuous supply of fresh air, removes hazardous gases, regulates thermal conditions, reduces airborne dust concentrations, and creates a safe and suitable working environment. During a fire emergency, its importance increases considerably, as airflow directly influences the direction of smoke propagation, the transport of toxic combustion products, fire development, and the conditions for personnel evacuation. Conversely, an inadequately designed or improperly managed ventilation system may accelerate smoke spread, reduce available evacuation time, and significantly increase the overall risk associated with underground fire emergencies (Plavčko et al., 2025; Pachet et al., 2024).

The rapid development of computational methods, numerical modelling, and simulation tools has significantly improved the analysis of mine ventilation systems under both normal operating and emergency conditions. Modern simulation software enables detailed evaluation of airflow distribution, pressure conditions, contaminant transport, and the effectiveness of proposed engineering measures before their practical implementation. Nevertheless, a considerable proportion of published studies remains focused on specific mining operations or individual engineering projects, which limits the transferability of their findings to other types of underground mine workings (Voloshyn et al., 2020; Guo et al., 2020; Sarvestani, Oreste & Gennaro, 2023).

From a safety engineering perspective, there is a clear need for a generally applicable methodological framework that is independent of the geological and operational conditions of a particular mining site. Such an approach enables the objective evaluation of ventilation system performance during fire emergencies, facilitates the identification of critical sections within ventilation networks, and allows different engineering solutions to be compared using a common set of assessment criteria. The development of universal assessment methodologies also supports more effective decision-making in the design, operation, and optimisation of underground ventilation systems (Eroglu & Duzgun, 2025; Shapalov et al., 2022; Chopde, 2023).

The aim of the presented article is to propose a general methodology for assessing the effectiveness of ventilation of underground mine workings during fire emergency scenarios. The proposed methodology is based on the basic principles of mine ventilation, airflow analysis, assessment of combustion product transport, and assessment of risks affecting the safety of persons in underground spaces. At the same time, it provides a basis for objective comparison of different ventilation system variants and serves as a useful tool for designing technical measures to increase the safety of underground mine workings during emergencies.

Analysis of the Current State of the Research

Mine Ventilation and Its Role During Emergency Situations

Mine ventilation is one of the fundamental engineering systems ensuring the safe operation of underground mine workings. Its primary function is to provide an adequate supply of fresh air to all sections of the underground mine while removing hazardous gases, airborne dust, moisture, and heat generated during mining, excavation, and other technological processes. A properly designed ventilation network also creates suitable microclimatic conditions for underground personnel and ensures the reliable operation of mining equipment and technological systems (Levin, Kuzminykh & Zhikharev, 2025; Tukkaraja, 2021; Sierra, 2020).

The importance of mine ventilation increases significantly during emergency situations, particularly in the event of fires or technological accidents involving the release of hazardous substances. Under such conditions, the ventilation system becomes the key factor controlling the direction of smoke propagation, the transport of toxic combustion products, and the thermal loading of individual sections of underground mine workings. At the same time, it provides the conditions necessary for the safe evacuation of personnel and enhances the effectiveness of mine rescue operations (Knyazev & Kormshchikov, 2023; Chen, Guo & Wang, 2016; Bi et al., 2024).

Airflow in underground mine workings is influenced by several interacting factors. The most important of these include the geometry of the underground workings, the aerodynamic resistance of individual airways, the performance of main and auxiliary ventilation fans, operating conditions, natural pressure differences, and the operational status of ventilation control devices and regulators. Any change in the configuration of the ventilation network may significantly affect airflow distribution and, consequently, safety levels during both routine mining operations and emergency situations (Su et al., 2008; Thakur, 2018; Tan et al., 2025).

From a safety engineering perspective, a mine ventilation system cannot be regarded solely as a means of providing air exchange. It represents a complex engineering system whose reliable operation directly influences the likelihood of secondary hazards, the severity of fire consequences, and the time available for the safe evacuation of underground personnel. For this reason, the design, operation, and continuous evaluation of mine ventilation systems constitute essential components of safety management in underground mine workings (Bi, Li & Shen, 2021; Liu, Liu & Zhou, 2022), as illustrated in Fig. 1.

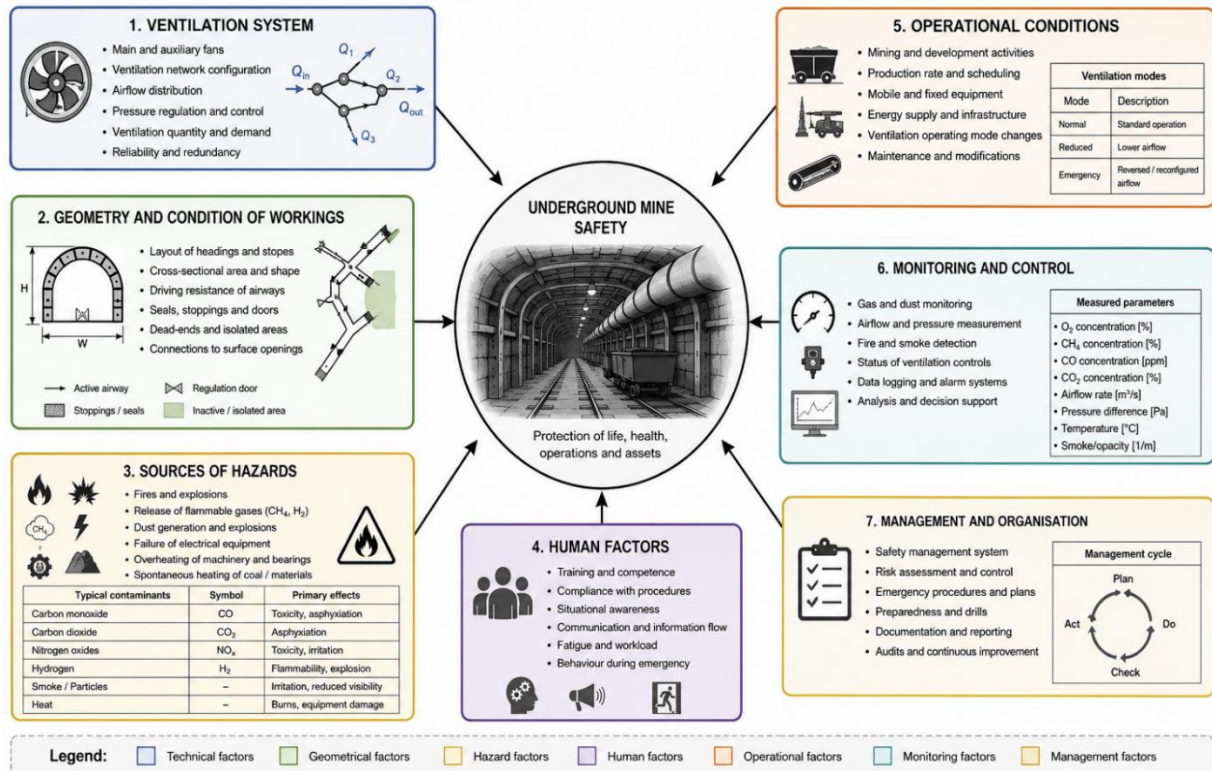


Fig. 1. Main factors affecting the safety of underground mine workings (source: authors)

Fire Hazards and Combustion Product Propagation in Underground Mine Workings

Fires in underground mine workings represent one of the most serious emergency situations because their development is strongly influenced by the confined nature of the underground environment. Unlike surface fires, underground fires are characterised by the rapid accumulation of combustion products, a progressive reduction in oxygen concentration, and the gradual deterioration of conditions for personnel movement and rescue operations. The confined geometry of underground workings accelerates smoke accumulation and the spread of toxic gases, significantly reducing the time available for safe evacuation and increasing the complexity of emergency response (Yuan, Zhou & Smith, 2016; Lu, Lu & Jiang, 2015; Szücs et al., 2025).

The most common causes of underground mine fires include failures of electrical equipment, overheating of mechanical components, fires involving mining vehicles, friction of moving machine parts, technological processes involving open flames, and, in some types of mines, the spontaneous heating of rock masses or stored combustible materials. Regardless of the ignition source, every underground fire generates large amounts of heat, smoke, and toxic gases, the propagation of which is strongly influenced by both the direction and intensity of the ventilation airflow (Danish & Onder, 2020; Banerjee, 2021; Kim & Hwang, 2020).

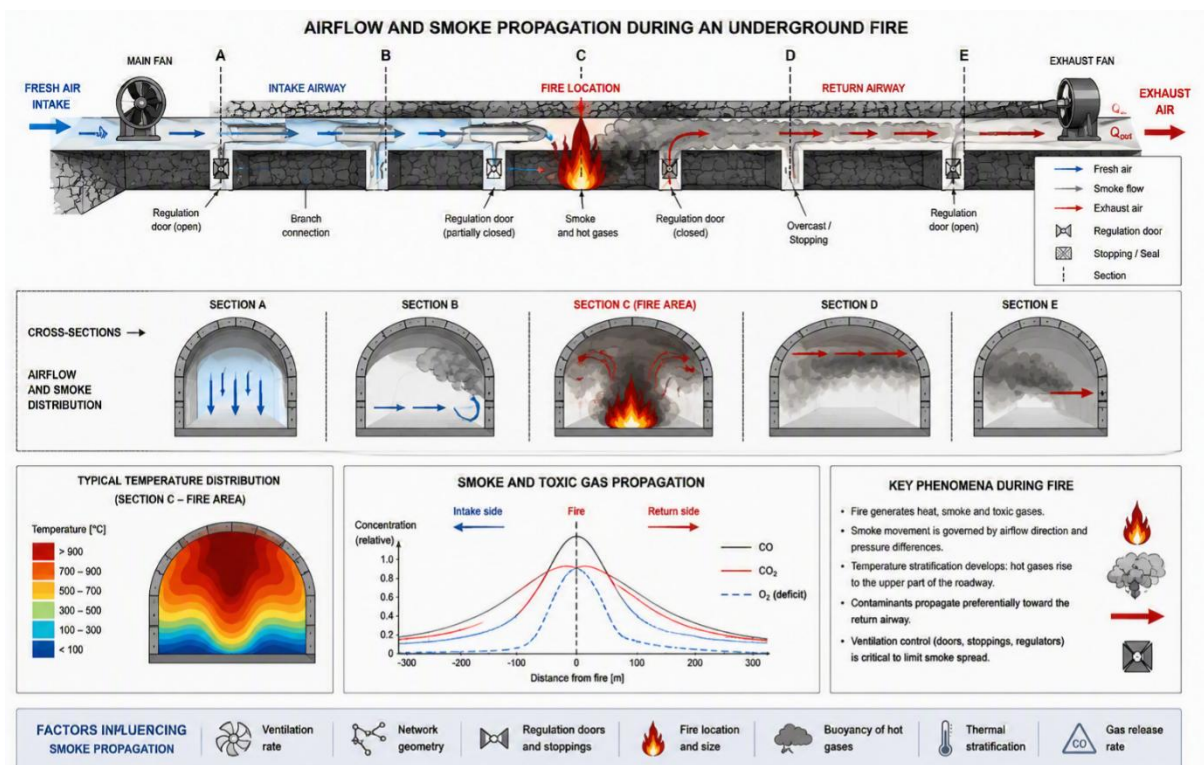
Based on an analysis of the most common causes of mine fires and their consequences, the principal categories of hazard sources affecting air quality, ventilation system performance, and the overall safety of personnel in underground mine workings can be identified. Their systematic classification is presented in Tab. 1.

Tab. 1. Main sources of hazards affecting air quality in underground mine workings (compiled by the authors based on Hallman, 2024)

Hazard source	Typical causes	Main consequences	Impact on the ventilation system
Technological equipment fire	Electrical failures, bearing overheating, mechanical friction	Smoke generation, high temperatures, CO production	Increased demand for combustion product removal
Mine vehicle fire	Engine failure, fuel leakage, electrical short circuits	Intensive production of toxic gases	Changes in airflow direction and smoke contamination of airways
Combustible gas explosion	Methane, hydrogen, process gases	Blast wave, secondary fires	Damage to ventilation structures and control devices
Dust explosion	Coal dust, organic dust, fine particulate matter	High thermal loading, blast wave	Disruption of the ventilation network
Diesel-powered equipment	Fuel combustion	CO, CO ₂ , NO _x , particulate matter	Increased ventilation air requirements
Development and extraction operations	Blasting, mechanical excavation	Dust generation, gas release	Local increase in the required airflow rate
Spontaneous heating of rock or stored materials	Oxidation processes, chemical reactions	Fire initiation, long-term CO generation	Requirement for continuous environmental monitoring
Ventilation system failure	Fan failure, damaged ventilation doors, power outage	Reduced airflow, air recirculation	Loss of ventilation efficiency throughout the network

The data presented in Table 1 indicate that most underground emergency situations are characterised by the generation of toxic gases, elevated temperatures, and changes in the aerodynamic conditions of underground workings. Therefore, the assessment of mine ventilation system preparedness should simultaneously consider technical, operational, and environmental factors, as their combined effects determine the development and consequences of emergency situations.

The data presented in Table 1 confirm that individual hazard sources differ not only in their mechanisms of occurrence but also in the extent of their impact on the ventilation system. A common characteristic of most underground emergency situations is the generation of toxic combustion products, increased temperatures, and changes in the aerodynamic conditions of underground workings. Therefore, the assessment of mine ventilation system preparedness should consider technical, operational, and environmental factors as an integrated system, since their interaction determines the overall effectiveness of ventilation during emergency conditions.

**Fig. 2.** Schematic illustration of combustion product propagation in an underground mine working (source: authors)

The greatest threat to personnel underground is not the flame itself but the combustion products generated during a fire. Carbon monoxide, carbon dioxide, nitrogen oxides, and other toxic gases may reach life-threatening concentrations within a relatively short period. At the same time, reduced visibility, increasing temperatures, and deteriorating orientation conditions significantly prolong evacuation time and decrease the effectiveness of mine rescue operations (Zhou et al., 2018; Yuan, Zhou & Smith, 2016).

From the perspective of safety management, fire must be considered as a dynamic process whose development depends not only on the magnitude of the fire source but also on the configuration of the ventilation network, the volume of supplied air, the position of ventilation control devices, and the current operating conditions of the underground mine. The interaction of these factors determines the propagation of combustion products, the development of thermal conditions, and the effectiveness of evacuation and emergency response measures (Fig. 2).

Current Approaches to Mine Ventilation System Assessment and Identification of the Research Gap

In recent years, significant advances have been made in the development of numerical methods for analysing the performance of mine ventilation systems during both the design stage and emergency scenario assessments. Simulation tools based on ventilation network modelling and computational fluid dynamics (CFD) have become increasingly important for evaluating airflow distribution, pressure conditions, contaminant transport, and the effectiveness of proposed engineering measures. These methods provide valuable support for predicting ventilation system behaviour under various operating conditions and contribute to improving the safety and reliability of underground mining operations (Jiang et al., 2019; Lilic, Obradovic & Stankovic, 2026; Shao et al., 2023).

Despite considerable technological advances, a substantial proportion of published research remains focused on specific mining operations or individual engineering projects. Consequently, the reported results are often closely associated with particular geological conditions, specific ventilation network configurations, or the technical characteristics of individual mines. As a result, the transferability of these findings to other underground mine workings is limited and usually requires substantial modifications of the original models before practical application (Tukkaraja, 2021; Bandopadhyay & Ganguli, 2004; Chao, 2024).

From a safety management perspective, there is still no universally accepted methodological framework for objectively assessing the preparedness of mine ventilation systems for fire emergencies, regardless of the type of underground mining operation. In particular, there is a lack of a comprehensive approach that can simultaneously account for the aerodynamic characteristics of the ventilation network, the propagation of combustion products, evacuation safety requirements, and the operational control of ventilation systems during emergency situations. The integration of these aspects into a single assessment methodology remains a major challenge in contemporary mine safety management (Jianshuang, 2024; Wang & Li, 2020).

The research gap identified above provides the basis for the present study, whose primary objective is to propose a generally applicable methodology for evaluating the effectiveness of mine ventilation systems during underground fire emergency scenarios. The proposed approach is not restricted to a specific mining site or particular geological conditions, thereby enabling its application to the design, assessment, and optimisation of ventilation systems in various types of underground mine workings.

Materials and Methods

Conceptual Framework of the Proposed Methodology

The proposed methodology is based on the assumption that the safety of underground mine workings during a fire emergency cannot be assessed using a single parameter, such as the quantity of supplied ventilation air or the capacity of the main ventilation fan. The actual development of an emergency situation results from the interaction of multiple technical, operational, and environmental factors that collectively influence the initiation, development, and consequences of a fire.

The proposed methodological framework integrates principles of mine ventilation, fluid flow mechanics, fire safety engineering, and risk assessment into a single comprehensive evaluation model. Its primary objective is to establish a universally applicable tool for the objective assessment of mine ventilation system preparedness for fire emergencies, regardless of the type of underground mine working or the specific geological conditions under which it operates.

The methodology has been designed to be applicable throughout the entire life cycle of underground mine workings. It can be employed during the design of new mining operations, the optimisation of existing ventilation systems, the preparation of emergency response plans, and the development of training scenarios for mine rescue teams. An important advantage of the proposed approach is its modular structure, which allows the methodology to be extended by incorporating additional assessment parameters according to the specific characteristics and operational requirements of individual underground mining environments.

The proposed methodology is based on the sequential assessment of the key factors affecting safety in underground mine workings. The evaluation includes the geometric characteristics of the underground mine, ventilation network parameters, operational conditions, fire scenarios, the propagation of combustion products,

and the capability to ensure the safe evacuation of underground personnel. The integrated assessment of these factors provides a comprehensive evaluation of the mine ventilation system's preparedness to manage fire emergency situations effectively.

To facilitate a better understanding of the proposed methodological framework, its basic logical structure is illustrated in Fig. 3.

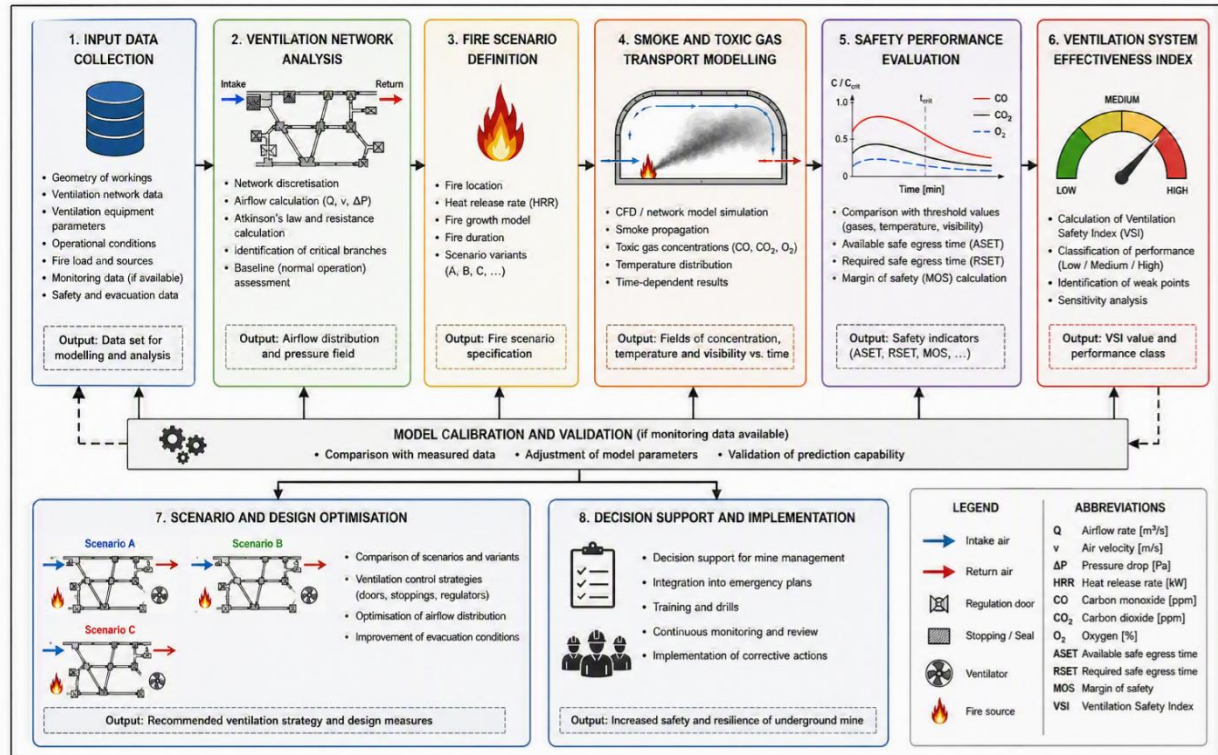


Fig. 3. Workflow of the proposed methodology for evaluating mine ventilation system performance during underground fire emergency scenarios (source: authors)

Fig. 3 illustrates the successive stages of the proposed methodology, beginning with the definition of input data, followed by ventilation network analysis, fire scenario modelling, and the assessment of combustion product propagation, and culminating in the determination of the overall safety level of the mine ventilation system. The individual stages are logically interconnected, forming a closed evaluation framework that enables the repeated assessment and comparison of different engineering solutions.

Assessment Parameters of the Proposed Methodology

The proposed methodology is based on the comprehensive assessment of technical, operational, and safety-related parameters that directly or indirectly influence the development of fire emergencies in underground mine workings. Unlike conventional approaches, which primarily focus on the aerodynamic characteristics of ventilation networks, the proposed methodology simultaneously considers additional factors affecting the propagation of combustion products, evacuation conditions, and the operational preparedness of the mine ventilation system.

Only those parameters that can be unambiguously determined from design documentation, operational measurements, or numerical simulation models were selected for inclusion in the proposed methodology. Their integrated evaluation provides a comprehensive database of input variables required for the subsequent calculation of safety assessment indicators.

Based on the analysis conducted during the development of the methodology, the principal groups of assessment parameters were identified and are summarised in Tab. 2.

Tab. 2. Basic input parameters of the proposed methodology (source: authors)

Parameter group	Symbol	Unit	Description
Airflow rate	Q	$m^3 \cdot s^{-1}$	Volume of ventilation air supplied to the evaluated section
Air velocity	v	$m \cdot s^{-1}$	Average airflow velocity
Pressure loss	ΔP	Pa	Pressure loss within the ventilation airway

Parameter group	Symbol	Unit	Description
Airway resistance	R	$\text{Ns}^2\cdot\text{m}^{-8}$	Aerodynamic resistance of the ventilation airway
Flue gas temperature	T	$^{\circ}\text{C}$	Average temperature of combustion gases during the fire
Carbon monoxide concentration	C_{CO}	ppm	Carbon monoxide concentration
Carbon dioxide concentration	C_{CO_2}	%	Carbon dioxide concentration
Oxygen concentration	CO_2	%	Residual oxygen concentration
Heat release rate	HRR	MW	Heat release rate of the fire source
Escape route length	L	M	Length of the evacuation route
Evacuation time	t_E	s	Estimated time required to evacuate the hazardous area
Smoke filling time	t_S	s	Time required to reach critical smoke conditions

Tab. 2 summarises the set of input parameters forming the basis of the proposed evaluation methodology. The selected variables were chosen to ensure applicability across different types of underground mine workings, regardless of geological conditions or the mining method employed. At the same time, they provide a consistent foundation for subsequent mathematical modelling and the safety assessment of mine ventilation systems.

The relationships among the individual input parameter groups are schematically illustrated in Fig. 4.

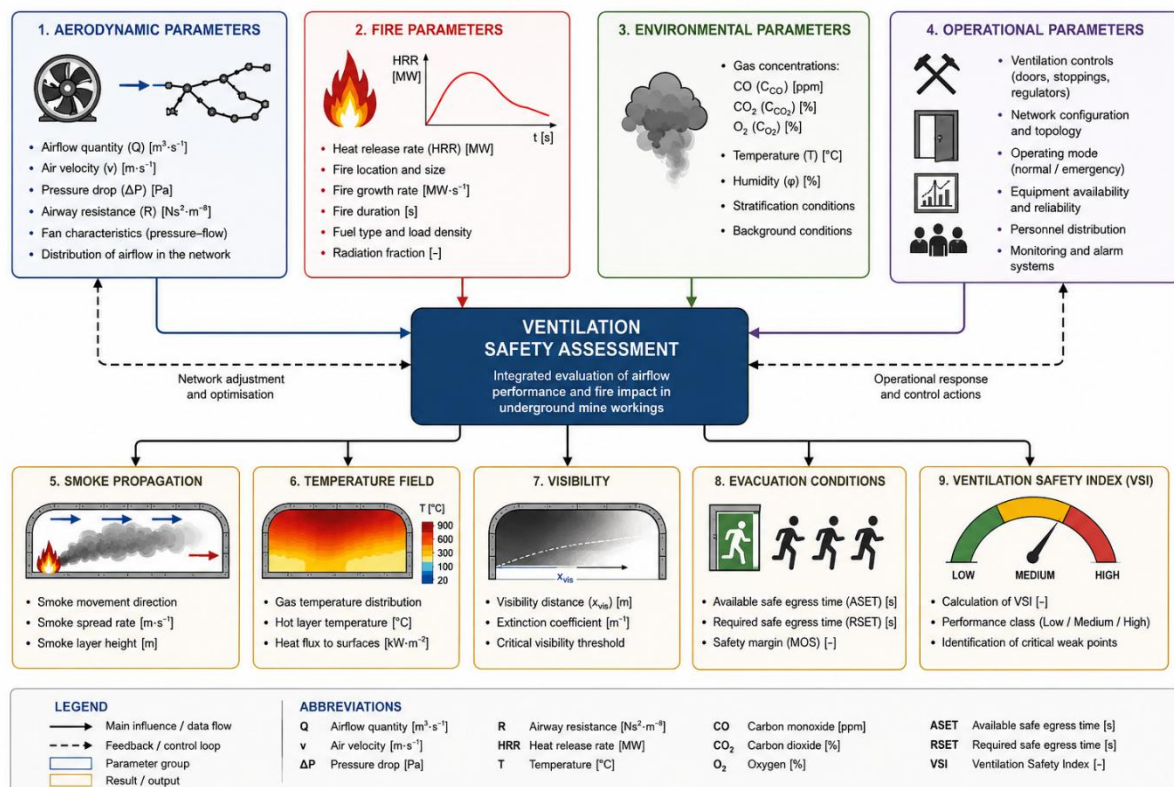


Fig. 4. Relationships among the input parameters affecting the evaluation of mine ventilation system performance during fire emergencies (source: authors)

Fig. 4 illustrates the logical relationships among the aerodynamic, fire-related, operational, and safety parameters incorporated into the proposed methodology. It also demonstrates that changes in a single parameter may significantly influence the behaviour of the entire mine ventilation system during a fire emergency, thereby justifying the need for their integrated assessment.

Development of the Mathematical Model for Mine Ventilation System Performance Assessment

Following the identification of the fundamental input parameters, a mathematical model was developed to enable their integrated evaluation under underground fire emergency conditions. The proposed model is based on the fundamental principles of mine ventilation and incorporates the physical laws governing airflow in

underground mine workings. At the same time, its modular structure allows the inclusion of additional parameters describing fire severity, combustion product propagation, and evacuation conditions, thereby providing a comprehensive framework for the quantitative assessment of mine ventilation system performance during fire emergencies.

The mathematical model was developed on the assumption that the performance of a mine ventilation system cannot be adequately characterised by a single parameter. Instead, it is governed by the interactions among aerodynamic conditions, fire intensity, air quality, and operational factors, which collectively determine the ventilation system's behaviour during fire emergencies. Consequently, the proposed mathematical model was formulated as a multi-parameter framework composed of a series of interconnected analytical relationships that provide the basis for the subsequent quantitative assessment of mine ventilation system safety. This approach is consistent with the principles of fire dynamics and ventilation modelling described by Ingason, Li, and Lönnemark (2015).

The first step of the proposed methodology is the determination of the airflow rate, which is one of the fundamental parameters used to assess a mine ventilation network. The airflow rate can be expressed by the following relationship (Eq. 1):

$$Q = A \cdot v \quad (1)$$

where:

Q – airflow rate ($\text{m}^3 \cdot \text{s}^{-1}$);

A – cross-sectional area of the mine airway (m^2);

v – average airflow velocity ($\text{m} \cdot \text{s}^{-1}$).

It also serves as the starting point for the subsequent mathematical evaluation of ventilation efficiency proposed in this study.

The next step involves the calculation of pressure loss in individual mine airways using Atkinson's equation, which enables the assessment of the energy required to maintain airflow and the identification of critical sections within the ventilation network. The pressure loss is expressed by the following relationship (Eq. 2):

$$\Delta P = R \cdot Q^2 \quad (2)$$

where:

ΔP – pressure loss (Pa);

R – aerodynamic resistance of the mine airway ($\text{N} \cdot \text{s}^2 \cdot \text{m}^{-8}$);

Q – airflow rate ($\text{m}^3 \cdot \text{s}^{-1}$).

Equation (2) describes the quadratic relationship between pressure loss and the volumetric airflow rate. An increase in airflow results in a significant increase in pressure loss, directly affecting the energy required to operate the mine ventilation system. Consequently, the calculated pressure loss values constitute an essential input for the subsequent assessment of ventilation system performance under underground fire emergency conditions.

To facilitate a better understanding of the relationships among the principal calculation parameters, the logical structure of the proposed mathematical model is illustrated in Fig. 5.

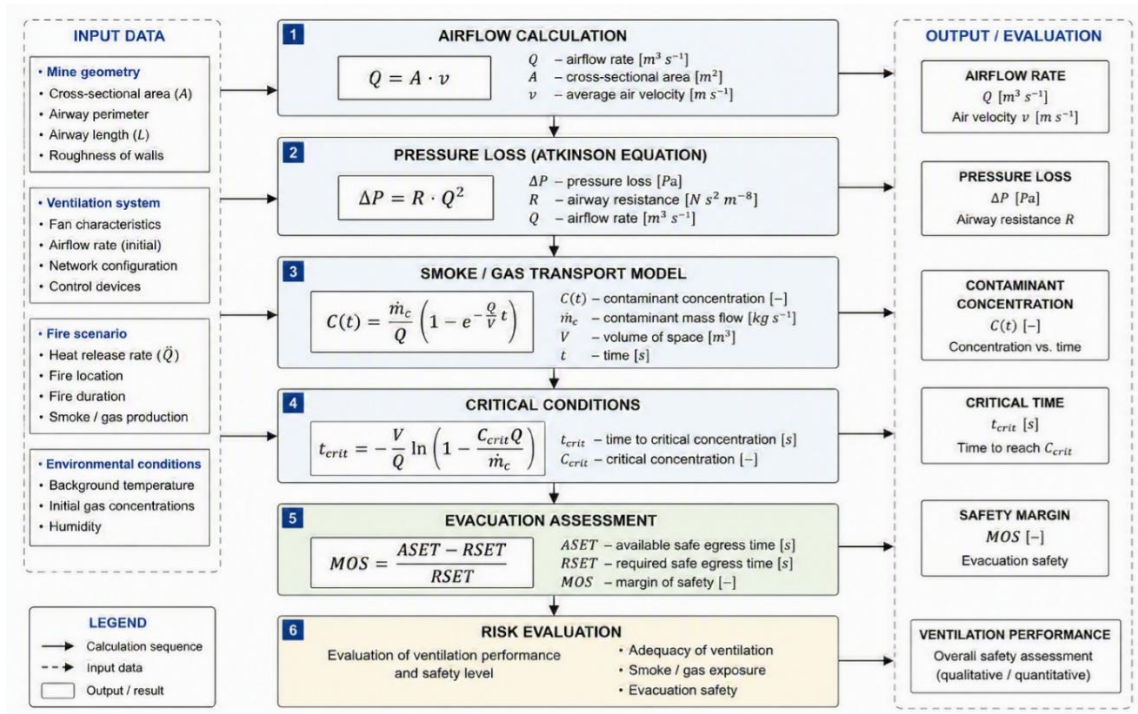


Fig. 5. Mathematical workflow of ventilation performance assessment (source: authors)

Fig. 5 illustrates the sequence of the individual calculation steps, beginning with the determination of the volumetric airflow rate, followed by the calculation of pressure losses, and culminating in the assessment of combustion product transport and the overall safety performance of the mine ventilation system during a fire emergency.

An essential component of the proposed mathematical model is the evaluation of combustion product transport. For this purpose, the model considers the time-dependent variation in contaminant concentration as a function of fire intensity, the volumetric airflow rate, and the volume of the underground space under evaluation. This relationship is expressed by Eq. 3:

$$C(t) = \frac{\dot{m}_c}{Q} \left(1 - e^{-\left(\frac{Q}{V}\right)t} \right) \quad (3)$$

where:

$C(t)$ – contaminant concentration at time t ($\text{kg} \cdot \text{m}^{-3}$);

$\dot{m}_c$ – contaminant emission rate ($\text{kg} \cdot \text{s}^{-1}$);

Q – volumetric airflow rate (ventilation capacity) ($\text{m}^3 \cdot \text{s}^{-1}$);

V – volume of the evaluated underground space (m^3);

t – time (s);

e – Euler's number ($\approx 2,71828$).

Equation (3) describes the temporal evolution of contaminant concentration during a fire emergency. Higher volumetric airflow rates promote more effective removal of combustion products, whereas lower airflow rates result in a substantially faster accumulation of toxic contaminants within the underground space.

To determine the time required for the contaminant concentration to reach a critical level that may endanger personnel safety, the following relationship can be applied (Eq. 4):

$$t_{crit} = -\frac{V}{Q} \ln \left(1 - \frac{C_{crit} Q}{\dot{m}_c} \right) \quad (4)$$

where:

t_{crit} – time required to reach the critical contaminant concentration (s);

C_{crit} – critical contaminant concentration ($\text{kg} \cdot \text{m}^{-3}$);

V – volume of the evaluated underground space (m^3);

Q – volumetric airflow rate ($\text{m}^3 \cdot \text{s}^{-1}$);

$\dot{m}_c$ – contaminant mass emission rate ($\text{kg} \cdot \text{s}^{-1}$);

$\ln$ – natural logarithm.

The determination of the critical time enables a direct comparison between the time required for personnel evacuation and the period during which environmental conditions within the underground workings remain acceptable for protecting human life and health. This comparison provides an objective basis for evaluating the effectiveness of the mine ventilation system under fire emergency conditions.

To assess evacuation safety, the safety margin indicator is introduced and defined by the following relationship (Eq. 5):

$$MOS = (ASET - RSET)/RSET \quad (5)$$

where:

MOS - margin of safety (s);

$ASET$ – available safe egress time (s);

$RSET$ – required safe egress time (s).

A positive value of the indicator indicates that a sufficient time margin is available for the safe evacuation of personnel from the hazardous underground area. Conversely, a negative value indicates that critical environmental conditions will occur before the evacuation process has been completed.

The mathematical relationships presented above provide the basis for the comprehensive assessment of mine ventilation system performance. They also establish the foundation for the development of the integrated safety index proposed in this study, which is introduced in the following section.

Proposed Framework for the Safety Assessment of Mine Ventilation Systems

Following the development of the mathematical model, it is necessary to establish a consistent framework for interpreting the calculated parameters. The determination of the volumetric airflow rate, pressure losses, or contaminant concentrations alone does not provide sufficient information to evaluate the overall safety performance of a mine ventilation system. For this reason, a methodological framework was developed to enable a comprehensive assessment of the operational condition of the ventilation network during underground fire emergency situations.

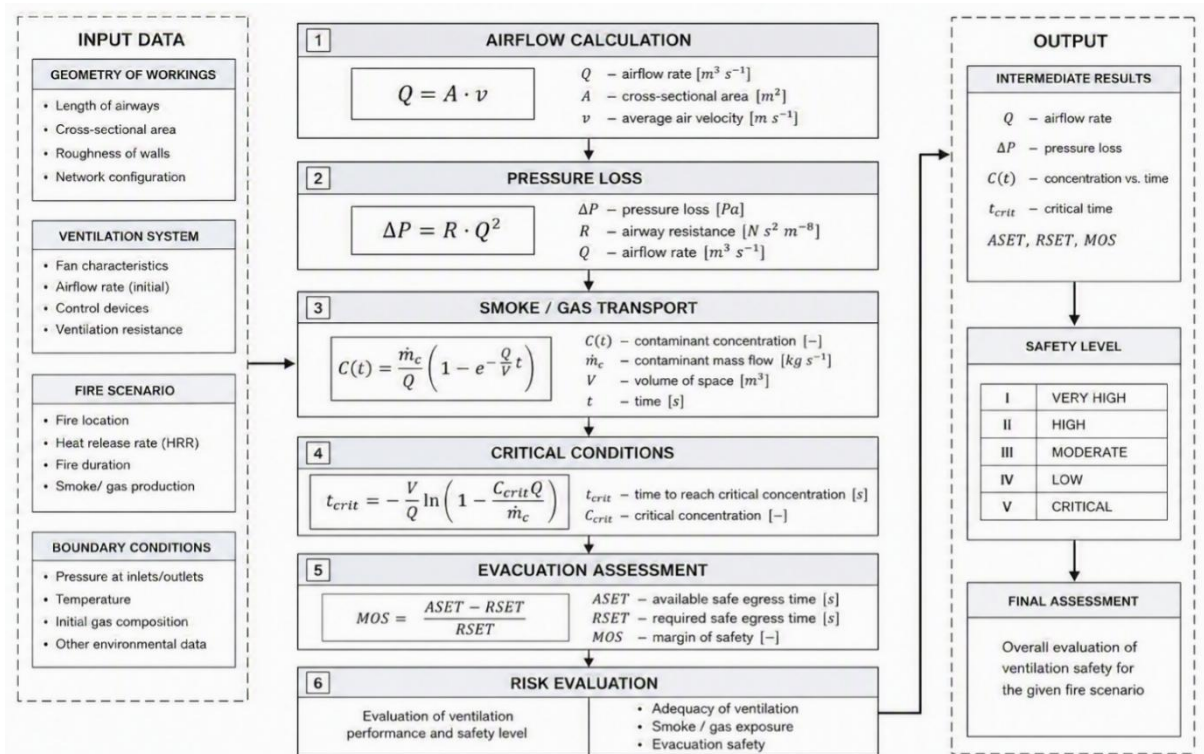


Fig. 6. Proposed framework for ventilation safety assessment during underground fire scenarios (source: authors)

The proposed framework is based on the principle of sequential evaluation of the individual groups of assessment parameters. In the first stage, the input data describing the underground mine workings, the ventilation network, and the defined fire scenario are processed. Subsequently, the mathematical relationships presented in the previous section are applied to determine the fundamental aerodynamic characteristics, the transport of combustion products, and the time-related evacuation parameters. The final stage of the methodology consists of integrating the calculated results and assigning the ventilation system to the corresponding safety level.

To facilitate a better understanding of the proposed evaluation procedure, the logical structure of the methodological framework is presented in Fig. 6.

Figure 6 illustrates the individual stages of the proposed methodology, beginning with the definition of the input data and concluding with the final assessment of the safety level of the mine ventilation system. The diagram also highlights the logical relationships among the individual calculation steps and demonstrates their role in evaluating the preparedness of underground mine workings for fire emergency situations.

Assessment Criteria of the Proposed Methodology

To ensure an objective and systematic evaluation, the assessed parameters were classified into four principal groups representing the technical, fire-related, environmental, and operational characteristics of the mine ventilation system. The classification of the assessment criteria is presented in Table 3.

Tab. 3. Assessment criteria of the proposed methodology (source: authors)

Assessment category	Assessment parameter	Označenie	Spôsob určenia
Aerodynamic parameters	Volumetric airflow rate	Q	Calculation
	Pressure loss	ΔP	Calculation
	Aerodynamic resistance of the mine airway	R	Calculation
Fire-related parameters	Heat release rate	HRR	Defined fire scenario
	Contaminant mass emission rate	$\dot{m}_c$	Calculation or numerical simulation
Environmental parameters	Contaminant concentration	C(t)	Mathematical model
	Critical time		Calculation
Operational parameters	Available safe egress time	ASET	Calculation or numerical simulation
	Required safe egress time	RSET	Calculation
	Margin of Safety	MOS	Calculation

Tab. 3 summarises the principal assessment criteria incorporated into the proposed methodology. The parameters are grouped by their functional role in the evaluation process and, collectively, provide the basis for a comprehensive assessment of mine ventilation system performance under fire emergency conditions.

Classification of the Assessment Results

To ensure a consistent interpretation of the calculated results, a five-level classification system for assessing the safety of mine ventilation systems was developed. The classification is based on a comprehensive evaluation of the calculated parameters, accounting for their mutual interactions during a fire emergency.

Tab. 4. Classification of mine ventilation system safety levels

Level	Classification	Interpretation
I	Very High	The mine ventilation system fully satisfies the required safety conditions.
II	High	The ventilation system meets the required safety criteria; however, optimisation of selected parameters is recommended.
III	Moderate	The ventilation system remains operational but requires technical or organisational improvements to enhance safety.
IV	Low	Increased risk of combustion product propagation and deterioration of evacuation conditions.
V	Critical	The ventilation system does not satisfy the safety requirements for the analysed fire scenario.

The proposed classification provides a consistent framework for interpreting the calculated results and establishes a common basis for comparing different mine ventilation system configurations. Its principal advantage lies in its universal applicability, as the individual safety levels are not restricted to a particular type of underground mine working but are derived from the comprehensive evaluation of all assessed parameters.

Application of the proposed methodology to representative fire scenarios

Definition of Representative Fire Scenarios

To verify the applicability of the proposed methodology, three representative fire scenarios were developed to reflect the most common emergency situations encountered in underground mine workings. The scenarios were

designed to cover a broad range of operating conditions, ranging from localised fires with relatively low heat release rates to fully developed fires involving mining equipment and characterised by the intensive generation of combustion products. The selection of representative fire scenarios was based on generally accepted principles of fire dynamics, heat release rate development, and smoke propagation in confined underground environments (Ingason, Li & Lönnemark, 2014; Sweida, Huzzain & Khalil, 2016; Kang et al., 2019).

Unlike case studies focusing on a specific mining site, the proposed approach is based on generally defined input parameters. This concept enables the methodology to be applied to different types of underground mine workings without requiring substantial modifications. The definition of each representative scenario considered the fire intensity, the characteristics of the combustible material, the expected production of toxic combustion products, and their anticipated impact on the mine ventilation system.

The principal characteristics of the proposed fire scenarios are summarised in Tab. 5.

Tab. 5. Representative fire scenarios used for validation of the proposed methodology (source: authors)

Scenario	Fire scenario description	Heat Release Rate (HRR)	Expected combustion product generation	Risk level
S1	Localised electrical equipment fire	2 MW	Low	Low
S2	Diesel-powered mining equipment fire	8 MW	Moderate	stre Moderate
S3	Fully developed fire involving a mining vehicle or major technological equipment	20 MW	High	High

Tab. 5 presents the representative fire scenarios developed for the validation of the proposed methodology. The scenarios were selected to represent typical underground fire events with different levels of fire severity, thereby enabling a systematic comparison of mine ventilation system performance under progressively increasing fire loads.

To further illustrate the proposed evaluation procedure, three representative fire scenarios were defined to reflect different fire intensities and their corresponding impact on the operation of the mine ventilation system. The scenarios differ in terms of heat release rate, combustion product generation, expected smoke propagation, and their anticipated influence on evacuation conditions. A comparative overview of the representative fire scenarios is presented in Fig. 7.

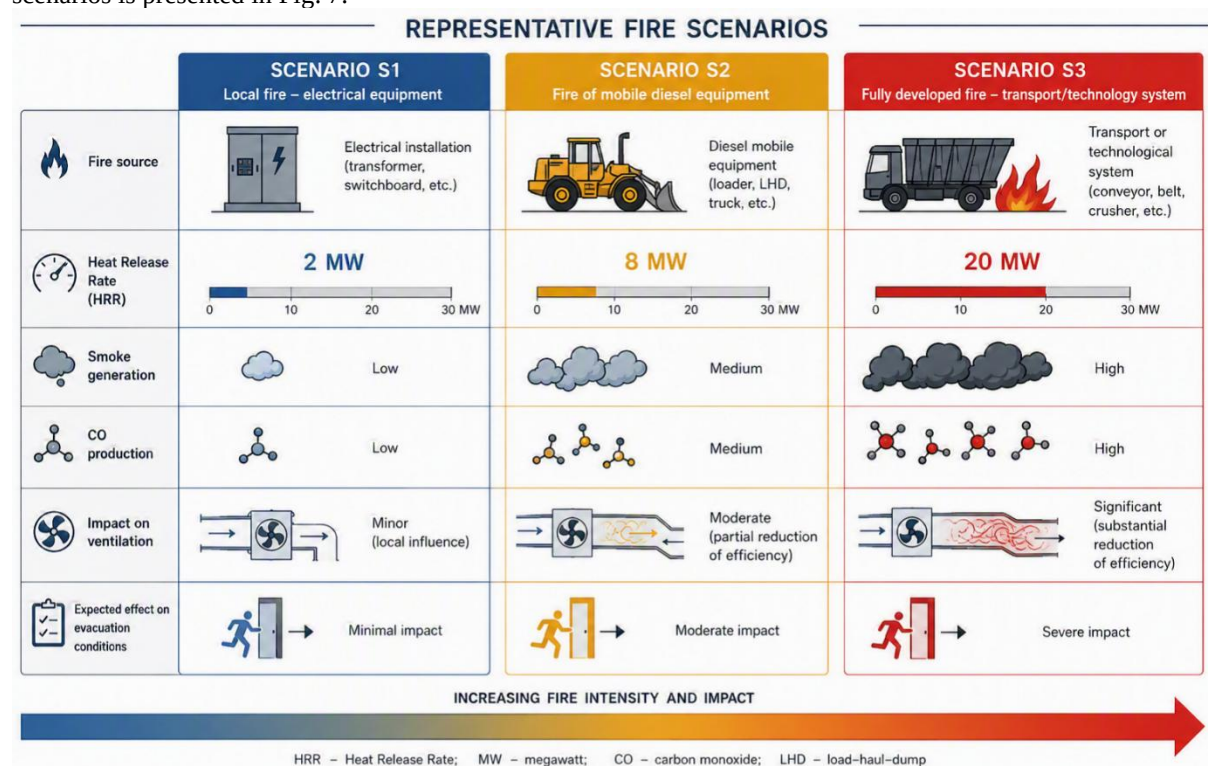


Fig. 7. Overview of representative fire scenarios used for the application of the proposed methodology (source: authors)

Results of the Application of the Proposed Methodology

The proposed methodology was applied to the three representative fire scenarios defined in the previous section. The objective of the application was not to analyse a specific underground mining operation but to verify

the functionality of the proposed approach under different levels of fire severity and to evaluate its applicability for assessing the performance of mine ventilation systems in underground mine workings.

For each scenario, the fundamental aerodynamic parameters, combustion product transport, time required to reach critical environmental conditions, and the evacuation margin of safety were evaluated sequentially. The obtained results were subsequently compared with the proposed classification of mine ventilation system safety levels presented in the previous section.

A summary of the application results is presented in Tab. 6.

Tab. 6. Results of the application of the proposed methodology for the representative fire scenarios (source: authors)

Assessment parameter	S1	S2	S3
Volumetric airflow rate	Acceptable	Acceptable	Partially acceptable
Pressure loss	Low	Moderate	High
Combustion product generation	Low	Moderate	High
Critical time (tcrit)	Long	Moderate	Short
Margin of Safety (MOS)	Positive	Marginal	Negative
Overall assessment	Level I	Level III	Level V

Tab. 6 demonstrates the variation of the evaluated parameters with increasing fire severity. Under Scenario S1, all assessed indicators remained within acceptable safety limits, and the mine ventilation system provided adequate conditions for both combustion product removal and the safe evacuation of personnel. In Scenario S2, an increase in pressure loss and a reduction in the margin of safety were observed, indicating the need for enhanced operational control of the ventilation system during emergency response. The most significant changes occurred in Scenario S3, where the high fire intensity led to substantial deterioration of airflow conditions and a considerable reduction in the time available for safe evacuation.

To facilitate a comprehensive interpretation of the results, a comparative analysis of the principal assessment parameters was conducted across all representative fire scenarios. The graphical comparison illustrates the variation in mine ventilation system performance, combustion product propagation, evacuation margin of safety, and the overall safety level under different fire emergency conditions.

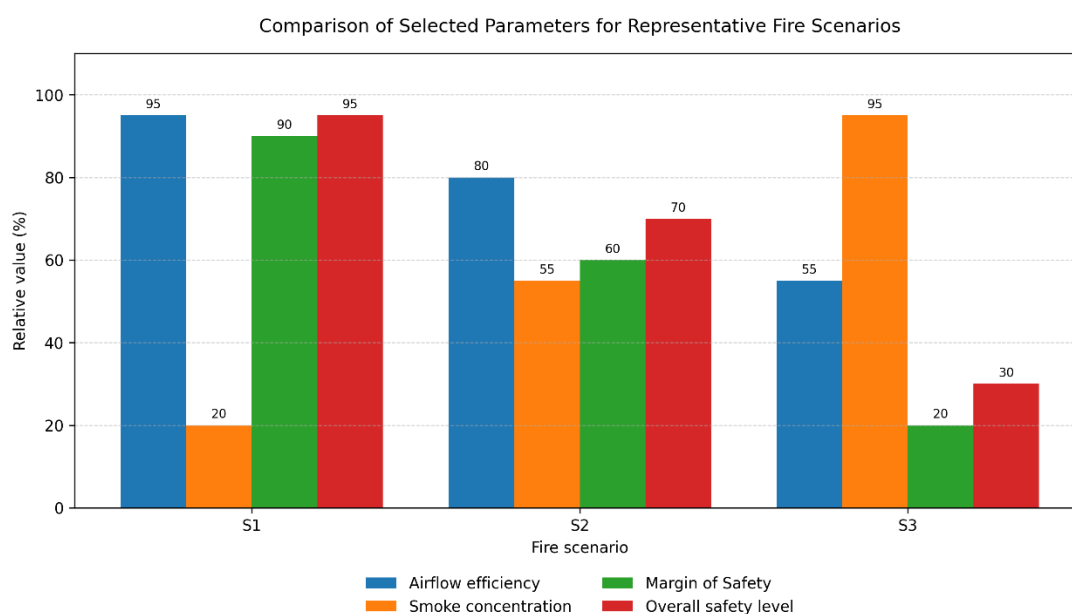


Fig. 8. Comparison of selected parameters for representative fire scenarios. (source: authors)

Fig. 8 demonstrates a clear deterioration in mine ventilation system performance with increasing fire severity. Under Scenario S1, the ventilation system remains capable of providing an adequate supply of fresh air while effectively removing combustion products, thereby maintaining favourable conditions for personnel safety. In Scenario S2, a noticeable reduction in the margin of safety is observed, accompanied by increased combustion product concentrations and a higher ventilation system load. The most critical conditions occur under Scenario S3,

where the high heat release rate results in a substantial reduction in ventilation efficiency, rapid accumulation of contaminants, and a significant deterioration of conditions for the safe evacuation of personnel.

Discussion

The application of the proposed methodology confirmed that the comprehensive assessment of mine ventilation system performance cannot be based solely on the evaluation of individual aerodynamic parameters. Although the volumetric airflow rate represents one of the fundamental characteristics of ventilation network performance, fire safety assessment also requires the simultaneous consideration of pressure losses, combustion product transport, the time required to reach critical environmental conditions, and the available time for safe evacuation. This finding is consistent with previous studies emphasising the importance of integrating fire dynamics and ventilation performance into a unified assessment framework (Ingason, Li & Lönnemark, 2014; Sweida, Huzzain & Khalil, 2016).

The comparison of the representative fire scenarios demonstrated that increasing fire severity progressively degrades environmental conditions within underground mine workings. Higher heat release rates result in increased combustion product generation, a shorter time to reach critical contaminant concentrations, and a reduced evacuation margin of safety. These findings highlight the need to adopt an integrated approach to mine ventilation assessment that considers interactions among aerodynamic, fire-related, environmental, and operational parameters.

One of the principal advantages of the proposed methodology is its universal applicability. Unlike approaches developed for specific underground mines, the proposed framework is based on general input parameters and can therefore be applied to various types of underground mine workings without requiring fundamental modifications. Consequently, the methodology may be used during the design of new ventilation systems, the assessment of existing mining operations, and the preparation of emergency response plans for underground fire scenarios.

An additional contribution of the proposed methodology lies in the integration of ventilation network characteristics with fire development and evacuation parameters into a single evaluation framework. This integrated approach enables a more comprehensive assessment of mine ventilation system preparedness and provides decision support for implementing technical and organisational measures to improve underground fire safety.

Despite these advantages, several limitations should be acknowledged. The proposed methodology is based on representative fire scenarios and therefore cannot replace detailed numerical simulations or experimental investigations performed under the specific conditions of a particular underground mine. In practical applications, the methodology should be adapted to the geological, technical, and operational characteristics of the evaluated mine.

Future research should focus on integrating the proposed methodology with computational fluid dynamics (CFD) models for airflow and combustion product transport, as well as with real-time air quality monitoring systems. Such integration has the potential to improve the accuracy of safety assessments and to support the development of intelligent mine ventilation management systems.

Conclusions

The safety of underground mine workings depends to a considerable extent on the reliable performance of the mine ventilation system. During underground fire emergencies, the ventilation system is responsible not only for supplying fresh air but also for controlling the propagation of combustion products, maintaining acceptable conditions for personnel evacuation, and providing a safe operational environment for mine rescue teams. Consequently, the assessment of mine ventilation system performance is a fundamental component of underground mine safety management.

This study presents a generally applicable methodological framework for the comprehensive assessment of mine ventilation system performance during underground fire emergencies. Unlike approaches developed for specific mining operations or particular geological conditions, the proposed methodology has been designed as a universal framework applicable to various types of underground mine workings. The methodology integrates the aerodynamic characteristics of the ventilation network with the assessment of combustion product transport, evacuation-related time parameters, and the overall evaluation of ventilation system safety.

The proposed framework incorporates a mathematical model based on fundamental mine ventilation relationships, supplemented by evaluations of contaminant concentrations, the time required to reach critical environmental conditions, and the margin of safety for personnel evacuation. This integrated approach enables consistent interpretation of calculated results and facilitates comparison of different fire scenarios, independent of the specific configuration of the underground mine.

The application of the proposed methodology to representative fire scenarios demonstrated its capability to identify changes in the principal safety parameters associated with increasing fire severity. The results confirmed

the strong interrelationship between ventilation network characteristics, combustion product generation, and evacuation conditions. Furthermore, the methodology provides a systematic basis for comparing alternative ventilation system configurations and supports the selection of appropriate technical and organisational measures to improve underground fire safety.

The principal scientific contribution of this study lies in the development of a comprehensive assessment framework that integrates aerodynamic, fire-related, environmental, and evacuation parameters into a unified methodology for evaluating mine ventilation system performance during fire emergencies. The proposed approach provides an objective tool for assessing ventilation system safety during the design, modernisation, and operational phases of underground mine workings.

Future research will focus on the experimental validation of the proposed methodology under real operating conditions, its integration with computational fluid dynamics (CFD) models for airflow and combustion product transport, and the incorporation of data obtained from continuous underground environmental monitoring. Particular attention will also be devoted to implementing digital twin technologies and intelligent decision-support systems to enhance the real-time management of mine ventilation systems during emergency situations.

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