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Review paper

DESIGN AND OPTIMIZATION OF VENTILATION SYSTEMS FOR DEEP UNDERGROUND MINES

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Abstract: The combination of environmental factors in deep underground mines poses risks to worker safety and health while negatively affecting operational cost efficiency. As mines reach greater depths, maintaining safe and energy-efficient ventilation becomes a central engineering challenge due to elevated heat, gas accumulation, and airflow resistance. This paper aims to analyze and evaluate optimization strategies for deep underground mine ventilation systems, focusing on methods that enhance airflow performance, energy efficiency, and occupational safety. Through a comprehensive literature-based assessment, the study examines key optimization techniques, including ventilation-on-demand, dynamic fan control, computational fluid dynamics (CFD) modeling, and artificial intelligence (AI)-driven monitoring, to identify best practices for sustainable mine ventilation. Technological innovations such as automation, digital twins, and Internet of Things (IoT)-based control systems are also discussed for their role in enabling intelligent and adaptive ventilation management. The findings highlight that integrating optimization with modern technologies not only improves air quality and energy efficiency but also strengthens safety performance and environmental compliance in deep mining operations. Overall, this study provides an updated synthesis of global research and industrial practices to guide the design and optimization of ventilation systems that ensure both operational effectiveness and long-term sustainability in deep underground mines.

Keywords: Ventilation Optimization, Deep Underground Mining, Energy Efficiency, Automation, Airflow Management, Safety

1 INTRODUCTION

The global resource extraction industry relies heavily on deep underground mining to meet the growing demand for valuable minerals and metals, which must be obtained from ever deeper locations beneath the earth's surface (Liu et al., 2024). Mining operations that penetrate deeper into the earth face elevated challenges, which include managing dangerous heat levels, toxic gases, dust accumulation, and high humidity levels, all of which threaten worker safety and equipment functionality (Hardcastle and

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Kocsis, 2004). Deep mining environments with their high temperatures, limited airflow, and hazardous gas build-up require constant development of advanced ventilation systems (Shi et al., 2024).

Mine ventilation in deep underground operations performs essential duties beyond fresh air supply since it establishes the mining environment while ensuring worker safety and operational efficiency (Okechukwu et al., 2024). Ventilation systems perform the vital roles of removing toxic gases and explosive vapors while controlling airborne particles and managing heat stress to protect worker health and meet regulatory standards (Yang, Yao and Wang, 2022). The complexity of underground networks, which have been expanded through years of mining operations alongside existing infrastructure, requires urgent attention toward modernizing ventilation systems for optimization. Modern deep mining requires superior air quality and thermal management capabilities, which outdated or poorly controlled systems do not provide, thus driving the need for ongoing innovation in system design and operations (Roy et al., 2022).

Research developments, together with technological progress, have transformed deep mine ventilation practices during recent years through the combination of mine aerology evolution and digital monitoring and control systems, which enable intelligent, energy-efficient operations (Zhang et al., 2023). Current trends necessitate both resilient ventilation systems that adapt to changing underground conditions and sustainable approaches that decrease energy use alongside environmental degradation (Shriwas and Pritchard, 2020). The IoT, big data analytics, and advanced computational modeling represent emerging technologies that transform ventilation system management by facilitating real-time monitoring and automated control to optimize airflow while minimizing operational costs (Semin et al., 2020).

Despite these advances, there remains a need for a systematic synthesis of optimization strategies that directly target energy reduction, improved airflow performance, and safety assurance in deep underground mines. This paper aims to analyze and evaluate key optimization approaches for deep mine ventilation systems, emphasizing how technological innovations, including automation, digital twins, and intelligent control, support energy-efficient and safe operations.

The field of underground mine ventilation design requires balancing environmental and safety factors to maintain safe and healthy operations while maximizing efficiency. The ventilation design must manage hazardous gas and contaminant removal while regulating the mine's climate and adhering to regulatory standards to reduce environmental impacts and operational costs alongside emergency prevention and handling.

The complex challenges faced today create an essential and immediate need for a systematic examination of deep underground mine ventilation systems design and optimization. This investigation examines the basic concepts that guide mine ventilation alongside the primary goals and modern innovations propelling its development. The study will investigate essential technical and safety aspects along with environmental impacts related to ventilation system design while presenting a historical overview together with recognized best practices and modern optimization techniques based on new technology developments. The review will use comprehensive analysis to develop deeper insights into the engineering and management of modern ventilation systems that address deep underground mining challenges to enable safer and more sustainable resource extraction.

Following this introduction, a comprehensive literature review is presented to contextualize recent studies and practical developments in ventilation optimization. Subsequent sections detail optimization strategies, supporting technological innovations, industrial case studies, and future challenges shaping the evolution of deep mine ventilation systems.

2 LITERATURE REVIEW ON DESIGN AND OPTIMIZATION OF VENTILATION SYSTEMS FOR DEEP UNDERGROUND MINES

This section synthesizes recent studies from 2020–2024 relevant to the optimization and design of deep mine ventilation systems.

The number of articles covered in this review for the design and optimization of ventilation systems for deep underground mines are shown in Figure 1 from 2020 through 2024.

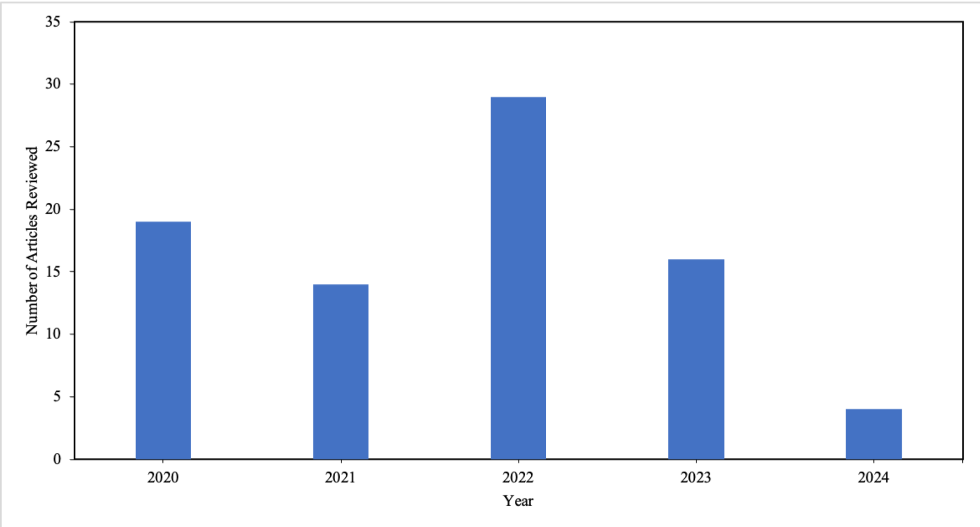

Figure 1 Articles reviewed (2020-2024) for the design and optimization of ventilation systems for deep underground mines

Table 1 below shows a quantitative distribution by publisher of the number of articles related to design and optimization of ventilation systems for deep underground mines.

Table 1 Number of articles from different publishers reviewed for design and optimization of ventilation systems for deep underground mines

Publisher	Number of Articles Reviewed
MDPI	21
Springer	16
Elsevier	9
Taylor & Francis	5
IOP Publishing	4
Wiley	3
EDP Sciences	2
Frontiers	2
IEEE	2
Polish Academy of Sciences	2
The Southern African Institute of Mining and Metallurgy	2
ACS Publications	1
Brazilian Association of Metallurgy, Materials and Mining	1
Empress Catherine II Saint Petersburg Mining University	1
Journal of Computers	1
Lembaga Penelitian dan Pengabdian Masyarakat (LPPM)	1
National Mining University of Ukraine	1
PLOS	1
Polskie Towarzystwo Przeróbki Kopalin (Polish Mineral Engineering Society)	1
Russian Mining Industry Journal	1
Sage Journals	1
Universidad Nacional de Colombia	1
University of Belgrade	1
University of Montevideo	1
University of Zielona Góra	1
Total	**82**

The Computational Energy Dynamics (CED) model created by Danko et al. (2020) simulates temperature and heat flow in mine ventilation networks through integration of heat capacity principles and variable rock conduction along with latent heat effects. The model they created that incorporated a thermal flywheel effect to manage timedependent temperature changes successfully mirrored real-world climate conditions with high precision, which helped optimize ventilation system thermal performance. Nadaraju et al. (2020) explored mine ventilation systems from an environmental and energy standpoint through simulations that optimized Ventilation Air Methane (VAM) abatement processes to decrease low-concentration methane (CH_4) emissions. The simulation results indicated that optimization techniques successfully reduced emissions while simultaneously boosting energy efficiency and cutting operational expenses, thus providing combined advantages in safety and sustainability. Sridharan and Sastry (2020) focused their study on aerodynamic aspects to reveal major discrepancies in current shock loss factor models that calculate pressure drops from mine car trains. They developed improved prediction models through CFD combined with scale model analysis, which decreased overestimations and enhanced simulation fidelity, leading to more effective airflow planning.

Tutak and colleagues (2020) conducted research on the actual effects when an active longwall mining site switched from U-type to Y-type ventilation infrastructure. The Y-type system successfully decreased CH_4 concentrations but also unintentionally increased spontaneous combustion risks because it allowed more oxygen to reach the goaf. In contrast, Yi et al. (2020) tackled the problem through computational methods by using ANSYS CFX to run CFD simulations, which helped optimize blowing and exhaust duct arrangements at a mining face. Numerical experiments showed that strategic placement of ducts and adjustments to mass flow rates effectively minimized air stagnation and contamination through design-dependent airflow dynamics. Jia et al. (2020) developed an algorithm for network-level optimization that merges the independent path method with an adaptive genetic algorithm to improve and simplify the visualization of ventilation network feature graphs. The new method improved the visualization of airflow patterns while decreasing graphical complexity and enabled better management decisions for airflow adjustments and resistance control.

Wei and colleagues (2020) performed numerical simulations and laboratory experiments to study how ventilation duct height and wind velocity affect airflow structure and dust movement in underground coal mine headings. The research indicated improved dust extraction and reduced dangerous vortices when the duct was placed at 0.625 roadway height with a minimum 2 m distance from the working site. The research conducted by Cahyono (2020) examined the technical aspects of planning a ventilation system for the W Undercut development at PT Freeport Indonesia. Through engineering software analysis, he determined that the airflow requirement stood at 180 m^3/s for six working faces while calculating head loss and system resistance and proposed auxiliary fan installation to meet the ventilation standards. Shriwas and Pritchard (2020) examined modern ventilation monitoring and control systems through a technological lens, pinpointing research gaps in sensor accuracy and real-time data integration for Industrial Internet of Things (IIoT) applications while noting successful implementations in Canadian, Australian, and U.S. mining operations.

Pach et al. (2020) explored reversal ventilation as a fire hazard mitigation technique and performed numerical simulations to evaluate its ability to regulate CH_4 levels during emergency evacuations. Implementation of full operational control over ventilation fan subnetworks with reversal ventilation was proven to reduce escape route lengths and maintain CH_4 levels within safe boundaries, thus improving emergency response capabilities, according to their findings. The work of Liu et al. (2020) concentrated on mine ventilator system stability improvement through a universal ventilator model development and Adaptive Chebyshev Neural Network (ACNN) controller implementation. The ACNN method achieved high precision with a mean absolute error below 0.02 and showed adaptability to unforeseen disruptions during simulation tests verified by Lyapunov stability criteria and surpassed conventional control methods in dynamic mining conditions. The research team led by Zhu in 2020 created an advanced ventilation optimization model that combined mine classification systems with gas emission analysis and coal dust explosion risk assessment. The combination of MATLAB and Lingo software enabled them to ascertain minimum air volume needs for various mining faces and achieve optimized air supply at 1491.18 m^3/min to set safety ventilation guidelines for high-risk mining operations.

The study by Guo et al. (2020) examined U-type and Y-type ventilation systems in deep coal mines and found that although U-type systems showed lower initial airflow temperatures, the Y-type systems offered better long-term thermal management for adjacent working areas. The research highlights how rock wall roughness and ventilation duration impact heat transfer while proving that the Y-type system better preserves cool and stable mine conditions through time. Kuyuk et al. (2020) investigated the ventilation problems of ultra-deep Arctic mines while proposing a sustainable closed-loop bulk air conditioning system powered by renewable energy. Their research revealed that using geothermal gradients to achieve simultaneous heating and cooling led to substantial fossil fuel savings and improved energy efficiency while providing a sustainable approach designed for cold climates. In 2020, Zhong et al. concentrated on computational ventilation system design and developed an innovative solution method using Minimum Independent Closed Loops (MICL) to improve airflow distribution modeling. The improved circuit division method resulted in accelerated iteration convergence and increased computational stability for complex networks, which provides a strong optimization tool for ventilation infrastructure.

Szczurek and colleagues (2020) assessed underground mine mobile machinery cabins' microenvironment and found traditional ventilation systems insufficient for health and safety compliance due to ambient air pollutants entering the space. A team developed an analytical air quality model that included a hybrid solution of ventilation combined with air-conditioning and filtration systems along with personal clean air supplies to maintain safe exposure levels for operators in all external conditions. Saki and colleagues in 2020 developed optimization methods for gob ventilation boreholes (GVBs) in longwall mining to enhance CH_4 extraction capabilities while also preventing explosive gas zones

(EGZs). CFD simulations allowed them to assess the impact of borehole location, diameter, vacuum pressure, and GVB activity levels on gas extraction, which led to the understanding that careful adjustment of these variables provided optimal gas removal results and improved safety conditions. Research by Liu et al. (2020) provided insights into longwall gob material behavior by testing rock compaction experimentally to understand their compaction properties and permeability. Research showed that when gob compaction increased under stress conditions, it changed its porosity and permeability, which led to different patterns of gas transport pathways. The researchers developed a predictive framework for mine-scale ventilation planning by measuring how material deformation influences airflow and gas dispersion patterns.

The Boliden Garpenberg mine implemented a model-based control strategy using a data-driven dynamic model created from both historical operational data and step-change experiments, according to Sjöström et al. (2020). The implementation of their optimized control system led to a 40% reduction in energy consumption for main and booster fans while enhancing airflow controllability. Tu et al. (2021) undertook an analysis of heat sources combined with evaluations of ventilation strategies that incorporate free-cooling techniques in mineral mines. The study showed that both segmented cooling (SC) and heat shield-assisted centralized systems (CCHS) made temperature profiles at working faces better, while indirect evaporative cooling (IEC) increased the annual energy efficiency ratio (EERann) by up to 32% based on ambient conditions. Li et al. (2021) utilized numerical simulation to evaluate thermal performance in an excavating roadway through a fully coupled model that integrates moving mesh methods. The study determined that increasing airflow volume only provides minimal cooling benefits, while reduced duct diameter and shorter outlet-to-face distances create adverse thermal effects.

Heriyadi and Zakri (2021) examined effective air ventilation systems as a crucial factor for underground coal mining operations in Sawahlunto City. The researchers established a direct relationship between insufficient ventilation and workplace accidents like CH_4 gas explosions, which caused deaths from 2009 to 2017. The research demonstrated that managing air quality and quantity through a well-maintained ventilation system enhances workplace safety and worker productivity by increasing confidence and comfort levels. The 2021 study by Zgrzebski et al. explored the increasing aerological hazards that emerged at KGHM Polska Miedź S.A. during the expansion of mining operations to deeper levels. Their efforts concentrated on improving ventilation systems to reduce the hazards associated with toxic gases and dust particles. Research findings revealed that optimizing airflow management along with real-time monitoring systems decreased dangerous gas levels and thus enhanced miner security. The research conducted by Li et al. (2021) explored the effects of ventilation on the extent of excavation damaged zones (EDZ) within high-temperature tunnels in Enhanced Geothermal Systems. When ventilation systems were used in high-temperature settings, they induced tensile stress in surrounding rocks, which altered the size and shape of the EDZ. The research demonstrated that ventilation control is essential for managing damage zones within deep mines with high temperatures, which requires ventilation system designs to account for both thermal properties and mechanical forces.

Wu and his colleagues (2021) explored how dual-radial swirl shielding ventilation can be optimized to manage dust levels in fully mechanized excavation faces. The study used numerical simulations along with experimental validation to identify that a blowing and suction air volume ratio of 1.5 yielded optimal dust control, which provided essential knowledge about managing airflow in mines. The research by Hurtado et al. (2021) aimed to improve the connection between intake fans and mine ventilation shafts through optimization to minimize energy losses while enhancing airflow volume. Utilizing CFD simulations, researchers determined optimal guide vane configurations and elbow curvature ratios, which showed possibilities for saving energy and improving airflow in ventilation systems. The research extended its usefulness to multiple engineering sectors outside of mining. Xin et al. (2021) evaluated the cooling performance of the far-forcing-near-exhausting (FFNE) and near-forcing-far-exhausting (NFFE) auxiliary ventilation systems using field measurements and simulations. The NFFE configuration achieved superior performance compared to the FFNE system when the exhaust-to-forcing volume flow rate (Re/f) reached 1.5 alongside optimal duct placement. The study demonstrated that proper ventilation configuration plays a critical role in ensuring thermal comfort and safety for underground mining operations.

Through numerical simulation with FLUENT, Jiang et al. (2021) assessed different tunnel drilling ventilation systems and found that the “long pressure and short suction” ventilation layout enhanced dust control efficiency near the work area by about 60%, which played an essential role in maintaining health standards and visibility in long single-ended tunnels. Iliinov et al. (2021) explored strategic optimization of mine-wide ventilation systems to accommodate growing mechanization demands in deep underground mining operations. Through staged ore block commissioning, the team achieved localized airflow control, which resulted in a 30% reduction of air travel paths and at least a 20% pressure drop decrease while improving airflow efficiency without extra energy consumption. Gao et al. (2021) used both CFD and physical modeling to establish the best blowing-to-suction flow ratio for wall-mounted swirling ventilation systems in mechanized coal excavation faces. The optimal blowing-to-suction flow ratio of 0.8 delivered the best dust suppression performance, reducing total dust by 90.33% and respirable dust by 87.16% through improved airflow disturbances and radial containment.

Janus (2021) created an advanced numerical simulation model that includes real longwall geometries along with goafs and their porosity and permeability properties to analyze airflow within a u-ventilated longwall system. The research model provided detailed insights into turbulent airflow patterns, which became a powerful way to improve ventilation systems. Si et al. (2021) demonstrated how variable fuzzy theory can optimize sensor placement for dynamic ventilation monitoring. The investigative team identified ten optimally placed sensors that monitor air quantity across 19 ventilation branches, showing an effective solution for continuous accurate airflow management in complex networks. The research of Obracaj et al. (2021) focused on controlling CH_4 emissions by implementing an overlap auxiliary ventilation system for mechanized roadways. CFD simulations demonstrated that maintaining an overlap zone length between 5 and 10 meters reduced CH_4 accumulation while showing how return air vortices near the dust scrubber affected outcomes.

Xie and colleagues (2022) performed a COMSOL Multiphysics CFD simulation to study how carbon monoxide (CO) and sulfur dioxide gases move through small, low-pressure roadway systems inside non-metallic mines located in Hunan Province. Their study showed that tunnel design and airflow speed played crucial roles in pollutant build-up through vortex patterns, and they proposed enhancements to structural ventilation systems through auxiliary pipes. The research by Wu et al. (2022) extended the analysis of CO migration after blasting in high-altitude tunnels with an inclined shaft where CFD simulations showed that different fan modes altered vortex positions and CO distribution. The researchers introduced a dual-phase ventilation approach, which led to 18% better ventilation efficiency (VE) and a 33% decrease in energy usage. Niewiadomski and colleagues (2022) conducted research on CH_4 dispersion in longwall mining through the simulation of 32 different ventilation setups using ANSYS Fluent software. The research showed auxiliary systems generally performed well, but the exact positioning of the brattice and air duct did not affect CH_4 levels unless they were near the tailgate caving line.

The study by Nguyen et al. (2022) evaluated the Thanh Cong–Cao Thang coal mine's ventilation system in Vietnam and found structural and operational inefficiencies after the mine's consolidation, which led to recommendations for routine evaluations and system improvements alongside personnel training to enhance airflow and diminish safety risks. Wang et al. (2022) investigated the effects of natural wind pressure changes on ventilation stability within the deep Tangkou Coal Mine using field measurements and FLUENT simulations to demonstrate the potential of atmospheric pressure variations to alter airflow direction and underscored the critical need for continuous environmental monitoring to avoid gas buildup. Jacobs et al. (2022) enhanced mine ventilation design and optimization through their calibrated digital twin model for South African mines, which allowed predictive analysis of thermal, dust, and gas hazards for proactive ventilation strategy optimization over the mine's lifespan.

Wang et al. (2022) created an advanced path algorithm for controlling airflow in multi-fan mine ventilation systems, which addresses the shortcomings of current algorithms, including false paths and poor regulator placement, and their case study confirmed the algorithm’s success in airflow optimization and safety improvement. Kohmann and Silva (2022) researched airflow patterns in a Brazilian coal mine through measurements and Ventsim Lite simulations, which confirmed regulatory compliance yet revealed potential airflow distribution improvements, especially in densely populated worker areas, along with suggestions for routine monitoring and greater sampling frequency. Bosikov et al. (2022) conducted research on mathematical modeling and control mechanisms for gas-dynamic processes in mine ventilation systems and introduced an algorithm that combines static and dynamic characteristics to optimize airflow management while reducing energy consumption; their findings highlighted the importance of understanding aerodynamic parameter dependencies throughout the ventilation network.

Kumar et al. (2022) implemented VoD in Indian underground coal mines, which, through dynamic ventilation fan adjustments and constant-speed reduction using variable speed drives (VSD), achieved annual energy savings of 1,070,618 kWh and reduced greenhouse gas emissions by 37%. Guo and colleagues (2022) used Fluent software to model ventilation designs for extended mountain tunnels and found that both reducing duct-to-face distance and enlarging duct diameter increased CO extraction effectiveness, while optimal jet fan placement near contamination points improved ventilation operations by preventing airflow short-circuiting. Xin et al. (2022) demonstrated a groundbreaking use of Data Envelopment Analysis (DEA) to assess air supply efficiency in deep mine headings through Cooling Efficiency (CE) and VE metrics. Through their simulations, researchers established that the most effective thermal balance requires an air supply temperature differential of 6 °C.

Saeidi and Allen's 2022 research explored how transitioning to battery-electric mobile equipment affects ventilation systems by demonstrating reduced harmful emissions from electric fleets, which reduced air volume needs but increased focus on heat management and proper air velocity. The research by Vives et al. (2022) applied CFD to refine auxiliary ventilation layouts by evaluating four different duct placement options to measure airflow and heat dissipation effectiveness; they found through simulations backed by real mine data that duct location near the working face was critical and that the optimal duct positioning depended on specific temperature or airflow goals. Janus and Ostrogórski (2022) focused on modeling mine tunnel geometries through terrestrial laser scanning (TLS), which they proved to be the most accurate method among five tested approaches for cross-sectional area measurement essential for ventilation calculations.

The research by Boantă and Tomescu (2022) involved using the CANVENT software together with the Hardy Cross method to model airflow optimization in the Vulcan Mine's complex ventilation system of 251 nodes and 300 branches; their work resulted in better air distribution in real-time operations and increased safety through predictive responses to potential risks. The research by Chikande et al. (2022) resulted in a VoD system that operates in a Zimbabwean platinum mine with IoT technologies for air quality and worker monitoring, which achieved 23% power savings and 6% productivity growth, demonstrating digital transformation advantages in energy efficiency and operational performance. Nie et al. (2022) combined CFD with the entropy weight method to evaluate dust-laden airflow dispersion and absorption during sub-regional coal cutting operations, establishing three dust behavior zones and an optimal air-absorption volume of 575 m^3/min for efficient dust control.

The case study by Słota and Słota (2022) examined tunnel ventilation design with special attention to how fan parameters and duct configurations affect both airflow efficiency and energy usage. The study demonstrated that wider duct diameters combined with dual installations led to lower ventilation power needs, while parallel duct systems resulted in 30-50% higher energy usage, which emphasized the need for strategic duct sizing and layout choices. Gao et al. (2022) employed fractal analysis to create a new calculation model for tunnel wall roughness-induced ventilation friction resistance, which showed traditional empirical models did not adequately estimate airflow resistance. Through simulations with a mere 3% error margin, researchers produced a more dependable foundation for intelligent ventilation modeling in rough rock environments. Liu et al. (2022) developed an efficient graphical algorithm to optimize ventilation monitoring through sensor placement while introducing the "independent cut set" method, which allowed airflow reconstruction with sensors installed in less than 30% of tunnels. The algorithm tested in a large-scale mine maintained accurate air volume estimation through reduced sensor deployment, which led to better cost-efficiency and operational effectiveness.

Xia et al. (2022) designed a three-dimensional (3D) CFD model to optimize ventilation shafts in large-scale underground cavern groups for pumped-storage power plants and discovered that an 8-meter diameter shaft with 80° inclination resulted in the best airflow distribution supported by on-site validation. Chen et al. (2022) explored fire safety in underground tunnels by analyzing how water curtains interact with mechanical ventilation through CFD-based fire simulation models. Through their research they established that setting mechanical ventilation at 0.8 m/s was essential for enhancing the smoke control capabilities of the water curtain, which resulted in better tunnel visibility and lower CO levels during fire incidents. Li and their team (2022) introduced the Bare-Bones Particle Swarm Optimization algorithm (BBPSO-Para-Improved), which targets power consumption reduction and air demand maximization through dynamic penalty terms and strategic optimization to improve convergence efficiency in complex ventilation networks. Their approach received validation from practical mining operations, where it proved to excel in economic savings as well as safety improvements. Yu and Shao (2022) developed an Improved Equilibrium Optimizer (IEO) specifically for energy efficiency, which combines chaotic mapping and Gaussian disturbance techniques. The implementation of their algorithm at Wangjialing Mine resulted in a 17.83% energy savings along with substantial cost reductions, thereby demonstrating the value of energy efficiency and economic operations. The team led by Nie et al. (2022) worked on optimizing ventilation systems for tunnels by studying the effects of airflow rate and duct-wall distance on dust control from an environmental and health safety perspective. The combination of numerical simulations and field measurements revealed that press-in airflow reduction to 150 m^3/min along with duct placement 1.5 meters from tunnel side walls dramatically reduced dust spread while improving air quality near excavation areas.

Zhang and colleagues used CFD simulations in 2022 to determine the best arrangement for dedusting air ducts in mechanized excavation work and found that duct location played a critical role in controlling dust diffusion and removal effectiveness. Optimal dust suppression was achieved when the duct was placed on the roadway's opposite side and kept 4–5 meters away from the tunneling head, according to their findings. Szlązak and Korzec (2022) suggested a modular fan station design for existing mine shafts to address the inefficiencies of oversized main fans during decommissioning. Polish coal mines saw substantial energy consumption reductions after implementing this solution, which proved both scalable and cost-effective. Hao et al. (2022) introduced a multi-branch joint adjustment approach based on sensitivity analysis to improve traditional ventilation-on-demand system performance. The implementation of a sensitivity change rate matrix together with Lagrangian interpolation enabled them to build a comprehensive dispatching model that provided precise and stable regulation of air volume across multiple branches. The potential application of their method to emergency response planning expanded its operational usefulness.

The research conducted by Hu and colleagues in 2023 involved safety optimization through experimental and numerical analysis of smoke movement within downward ventilation patterns during fire situations. The team discovered that enhancing fan power led to increased fire dynamics and established a critical wind speed threshold of 1.8 m/s where fire wind pressure matched fan output to support emergency planning strategies. Yan and colleagues (2023) created a sensor layout optimization method for underground ventilation systems through DETMAX and Tabu search algorithm integration, which enhances real-time airflow measurement accuracy and reduces both error and cost. The researchers demonstrated their model's superior monitoring efficiency and system intelligence performance by validating it against traditional algorithms such as Monte Carlo and Ant Colony methods through data collected from the Wangjialing coal mine. The 2023 research by Semin and Levin included mathematical modeling of air distribution across different ventilation modes in a potash mine with a U-tube design while factoring in shock losses and airflow reversals. Shock losses played a major role in air redistribution during ventilation mode changes, according to their study, while their model showed accurate predictions within 15% relative error when validated by experimental results.

Stolbchenko et al. (2023) developed a mathematical model to minimize external air leakage at the main ventilation unit by optimizing the interaction between main and counteracting fans. The study revealed that combining a 40° blade angle for the main fan with a 33° angle for the counteracting fan significantly decreased leakage while ensuring stable underground airflow, which enhanced both safety and efficiency. Through CFD analysis, Adhikari et al. (2023) determined that forced ventilation systems achieve five times better fume dilution than exhaust systems and found that both muckpile porosity and explosive types played significant roles in determining dilution time. Chen et al. (2023) implemented ANSYS-Fluent to optimize CFD models for reducing high temperatures in coal mining areas. Through their research they established that 36.81 m^3/s of air volume and 298 K temperature were optimal for their purposes and suggested a spray cooling system, which lowered pavement temperatures by 0.5–1°C to improve summer ventilation.

Bosikov and team (2023) presented a new analysis method using mathematical statistics and probability theory to study gas-dynamic processes while improving fire safety through ventilation network modeling, which demonstrates how diagonal connections affect air distribution and CH_4 management. Field experiments at Mine 31 confirmed their work, which introduced a spherical ventilation network design to improve critical connection identification and fire hazard prevention in CH_4-rich coal beds. Swanepoel et al. (2023) examined project-level decision-making processes through multi-criteria decision-making frameworks analytic hierarchy process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to determine environmental improvement priorities for deep-level mines. Their simulation-based analysis showed surface refrigeration as the best option for thermal comfort, and their method offered a systematic approach to balance cost with implementation time and risk while considering workers' conditions. Lian and Qi (2023) developed an energy optimization solution that uses a ventilation control model that integrates operational constraints and an improved Grey Wolf optimization algorithm. The approach implemented at Tangshan A Group B Coal Mine achieved its dual aim of decreasing energy consumption and maintaining necessary airflow levels through complex branched ventilation systems.

The study by Wróblewski et al. (2023) generated precise geometric models of mining excavations from 3D laser scanning data and incorporated these models into CFD simulations to study airflow patterns. The study showed that Light Detection and Ranging (LiDAR)-based geometries improved simulation precision in complex ventilation networks, which allowed for more accurate air velocity predictions and enhanced operational safety. Agson-Gani et al. (2023) approached the issue of airflow simulation through porous regions by integrating a conjugate porous media model into existing mine ventilation network software. The research presented a new friction factor coefficient for broken rock-filled drawpoints, which validation against 3D CFD models proved achieved more than 99% reduced computation time while preserving accuracy for real-time mine environment simulations. Estrada and Manzano (2023) used Ventsim 3D software for long-term ventilation planning at Santander Mine, which produced airflow rates at 102% of the necessary capacity through precise simulation scenarios. They implemented practical solutions by analyzing real mine data, which showed Ventsim enabled detailed airflow and pressure visualizations to help future system optimization and regulatory compliance.

The researchers Szlązak et al. (2023) developed strategies for CH_4 hazard control by designing ventilation and drainage systems for coal seams 404/1 and 403/1 located in southern Poland. The team studied CH_4 emission forecasts, which identified maximum emissions of 134.34 m^3/min and proved the requirement for U-type ventilation systems that operated with 38.3–40.6% efficiency while suggesting CH_4 capture for power generation to improve system performance. Kashnikov and Kruglov (2023) created a fuzzy logic-based automatic control method to tackle ventilation control issues at the 3RU mine of OAO Belaruskali. The study based on simulations demonstrated that fuzzy logic controllers led to enhanced airflow regulation while avoiding fresh air deficits and reducing main fan power consumption through a responsive and adaptive optimization process. Shao and colleagues conducted a 2023 study that tackled thermal hazard mitigation in deep metal mines through the combination of refrigeration technologies and air cycling systems. Through experimental and simulation-driven analysis backed by artificial neural network modeling with $<5\%$ prediction error, researchers showed improved energy efficiency and cooling effectiveness while the heat transfer rate of main exchangers increased by up to 16.38% during variable fan operation.

A 2023 study by Li et al. examined how damper systems react to gas explosion impacts using numerical simulations to test damper performance with different ventilation-regulating window configurations. Research findings demonstrate that damper displacement and stress depend significantly on the presence and size of ventilation windows, which informs safer design approaches for underground ventilation systems. Ihsan and colleagues (2024) researched VoD systems using adaptive neuro-fuzzy inference systems (ANFIS) to simultaneously enhance fan power efficiency and reduce hazardous gas concentrations. Laboratory-scale experiments showed that fan energy consumption decreased by 43% while ensuring safe ventilation conditions through AI-based systems. The 2024 study by Wan analyzed intelligent ventilation systems design through automation techniques and sensor deployment to enhance air quality control and disaster response capabilities. He developed optimization strategies incorporating remote control systems and intelligent air distribution to help mitigate disaster risks. Through the use of Back Propagation Neural Networks (BPNN) and CFD simulations, Zhang et al. (2024) created models that predicted toxic fume migration while identifying wind velocity as a key factor for determining migration time. The developed models demonstrated exceptional accuracy ($R^2 = 0.9945$), which provided essential knowledge to advance ventilation systems for toxic fume control. Finally, the authors Ilić and Petrović (2024) applied IIoT techniques to improve ventilation management in Serbian coal mines through real-time monitoring and automation strategies to boost safety and efficiency. Their study showed how IIoT technologies could both prevent hazardous events and boost mine ventilation system management.

The reviewed studies highlight optimization as a central theme, motivating the analysis of specific strategies and technologies in the following sections.

3 KEY OPTIMISATION STRATEGIES IN DEEP MINE VENTILATION SYSTEMS AND THEIR UNDERLYING PRINCIPLES

Building upon insights from recent literature, this section outlines the primary optimization methods currently used in deep underground mine ventilation. Ventilation systems in deep underground mines encounter a complex set of problems due to intricate underground networks that grow with depth and increased rock temperatures along with higher humidity levels (Hardcastle and Kocsis, 2004; Hancock, 2019). The environmental conditions present in deep mines pose risks to mine worker safety and health while simultaneously reducing mining operations' efficiency and cost-effectiveness (Roy et al., 2022; Kamyar et al., 2016). Mine management must prioritize ventilation system optimization to deliver fresh air effectively while diluting hazardous gases and removing heat and decreasing energy consumption (Mapeta, 2020; Parra et al., 2006). The process utilizes several strategies that combine technology with planning and monitoring techniques together with decision-making approaches to respond to the changing demands of deep underground mining environments (Kamyar et al., 2016; Sjöström et al., 2020).

3.1 Ventilation on Demand (VoD)

VoD dynamically adjusts airflow patterns according to immediate mining operations, equipment status, and worker positions (Saleem, 2025). VoD systems optimize energy use and operational performance by directing ventilated air to active mining areas while minimizing airflow in inactive zones without sacrificing safety standards (Saleem, 2025; Sjöström et al., 2020). Advanced VoD systems that integrate IoT controls with AI automation will boost both responsiveness and sustainability within ventilation networks (Saleem, 2025). The primary technical benefit of this system is its significant decrease in excess airflow that typically occurs with traditional fixed-flow setups (Sjöström et al., 2020).

3.2 Integrated Planning and Dynamic System Design

Mine development demands that ventilation systems undergo corresponding evolution for efficient system optimization (Swanepoel et al., 2023). Integrated planning utilizes surveys and baseline data along with predictive models to create adaptable airflow routes while positioning ventilation raises and fans optimally to support future expansions of the mine (Kamyar et al., 2016). Dynamic design maintains essential airflow during worst-case conditions when mine geometry and production stages shift, thus upholding worker safety and regulatory standards.

3.3 Computational Modelling and Simulation

3D mine ventilation modeling relies on the sophisticated capabilities of network simulators and CFD tools according to modern optimization practices (Du Plessis et al., 2013; Nie et al., 2018). The predictive modeling capabilities of these systems enable engineers to examine airflow patterns, heat transfer rates, and gas dispersion to optimize fan placement and assess the performance of changes across different operational scenarios (Maleki, Sotoudeh and Sereshki, 2018). The use of simulation-based research enables the effective integration of cooling systems, which become essential in deep mines with high temperatures (Nie et al., 2018).

3.4 Advanced Fan and Refrigeration Controls

Proper management of primary and auxiliary fans together with refrigeration plants stands as another vital approach for optimization (Parra et al., 2006; Webber-Youngman, 2005). The techniques used for ventilation control involve dynamic fan speed adjustment through variable frequency drives together with automated switching that responds to demand cycles and intelligent cooling system management during periods of low demand like night shifts and holidays (Webber-Youngman, 2005). These actions ensure ventilation supply meets mine requirements while reducing electrical power usage (Dello Sbarba, 2012.

3.5 Continuous Monitoring and Adaptive Controls

Real-time tracking of essential ventilation parameters, including airflow, temperature, humidity, and gas concentrations, forms the basis of successful optimization strategies (Liu et al., 2024; Shriwas and Pritchard, 2020). Mine ventilation control systems process data collected by advanced sensor networks and perform automated or semi-automated adjustments to maintain optimal indoor air quality while mitigating hazards immediately (Liu et al., 2024). This monitoring system enables preventive maintenance and fast fault detection, which minimizes operational interruptions and strengthens system resilience (Saleem, 2025).

3.6 Multi-Criteria Decision-Making and Project Prioritisation

Optimization methods for ventilation investment evaluation and project prioritization frequently employ multi-criteria decision-making frameworks to balance safety requirements with cost constraints and energy efficiency goals (Swanepoel, 2023). These methodologies help mine managers allocate resources effectively by assessing practical considerations including regulatory compliance, hazard mitigation, lifecycle cost, and technical feasibility (Swanepoel, 2023).

3.7 Energy Efficiency and Demand Management

Deep underground mines typically face high operating energy expenses, which leads to the implementation of various demand-side management techniques (Kamyar et al., 2016; Webber-Youngman, 2005). The operational schedule for non-essential fans, together with peak energy demand management through equipment switching during high grid demand periods and the implementation of energy-efficient motors and drives, makes up these measures (Webber-Youngman, 2005). Mining operations achieve lower operational expenses and carbon emissions through these measures (Dello Sbarba, 2012).

3.8 Integration with CH_4 Recovery and Environmental Innovations

The optimization of mining operations includes the recovery of CH_4 from ventilation air as well as its utilization, which helps reduce explosion hazards and lowers greenhouse gas emissions in coal mines (Acuña and Lowndes, 2014). Ventilation systems now merge heat recovery technologies with environmental controls, which leads to beneficial outcomes in terms of energy conservation and safety while meeting environmental standards (Dello Sbarba, 2012).

3.9 Technical Impact and Documented Outcomes

Case studies show that optimization strategies deliver real improvements in deep mine VE along with safety and cost management (Saleem, 2025; Parra et al., 2006; Oosthuizen, 2020). The deployment of VoD systems combined with adaptive controls has achieved significant energy savings without compromising health and safety standards in mining operations (Saleem, 2025; Sjöström et al., 2020). Site-specific ventilation inefficiencies were resolved through simulation-driven design improvements that led to better environmental conditions throughout the mine (Maleki, Sotoudeh and Sereshki, 2018; Oosthuizen, 2020). Ventilation upgrades prioritized and managed through data-driven frameworks achieve optimal results while staying within both budgetary limits and regulatory requirements (Swanepoel, 2023). Advanced systems integrate real-time data with automation technology to deliver predictive maintenance features and minimize downtime while strengthening resilience against ventilation system failures (Liu et al., 2024; Saleem, 2025).

Table 2 Major Optimisation Strategies and Their Benefits

Strategy	Principle	Key Benefits
VoD	Dynamic airflow allocation	Large energy savings, targeted hazard control
Integrated Planning & Dynamic Design	Adaptive system evolution	Sustained compliance, effective future-proofing
Computational Modelling & Simulation	Data-driven optimisation	Bottleneck identification, efficient design changes
Advanced Fan & Refrigeration Controls	Automated demand response	Minimized energy, controlled climate
Monitoring & Adaptive Controls	Real-time data integration	Prompt hazard mitigation, improved maintenance
Multi-Criteria Decision-Making	Balanced project ranking	Optimized resource use, prioritized improvements
Energy Efficiency & Demand Management	Cost-effective operation	Reduced energy costs, lower environmental impact
Environmental Integration & CH_4 Recovery	Safety & sustainability	Enhanced air quality, reduced greenhouse gases

4 TECHNOLOGICAL INNOVATIONS IN DEEP MINE VENTILATION SYSTEMS

While optimization defines the goal, emerging technologies provide the means to achieve it. The following innovations enable smarter, more energy-efficient ventilation systems. Challenging conditions of deep underground mining operations have led to major technological developments in ventilation systems during recent years (Ranjith et al., 2017). The progression of these systems demonstrates persistent efforts to boost safety and energy efficiency while improving operational reliability and protecting the environment in complex underground networks (Onifade, Said and Shivute, 2023).

4.1 Integration of Intelligent Monitoring and Fault Diagnosis

Deployment of intelligent technologies for ventilation fault diagnosis stands out as one of the major foundational innovations (Liu et al., 2024). Current ventilation systems integrate numerous sensors and sophisticated data processing capabilities, which support ongoing assessment and examination of essential mine parameters throughout the entire mine (Liu et al., 2024). The implemented technology detects faults at an early stage and provides actionable data for proactive maintenance, which leads to reduced downtime and enhanced safety for workers (Liu et al., 2024).

4.2 Adoption of Automated Ventilation Control Systems

The broad adoption of mine-specific automated control systems represents a significant development in ventilation technology (Levin and Semin, 2017). Sophisticated algorithms along with adaptive logic enable these systems to modify airflow in real-time according to operational demands, environmental shifts, and occupancy trends (Shriwas and Pritchard, 2020). Wireless communication technologies like ZigBee wireless sensor networks enable closed-loop control systems that automate secondary ventilation regulation under dynamic deep mine conditions (Di Nardo and Yu, 2021). Automation serves to improve safety levels while significantly cutting down electricity usage, thereby creating cost-effective and sustainable operations (Levin and Semin, 2017).

4.3 Application of IoT and Smart Digital Technologies

Mine ventilation network operations and monitoring have been transformed through IoT technology platforms (Zhang et al., 2023). IoT technologies connect sensors, actuators, and control units to enable complete real-time data collection and analysis for better decision support (Zhang et al., 2023). Operators who use smart digital systems can visualize ventilation performance and make predictions to optimize air delivery through extensive and complex networks at deep levels (Leonida, 2019). Such systems create safer work conditions and promote sustainable resource management (Leonida, 2019).

4.4 Energy-Efficient Ventilation Strategies

The deep mining sector recognizes the substantial energy requirements of traditional ventilation systems and actively focuses on creating and utilizing energy-efficient alternatives (Saleem, 2025). Prominent strategies include:

- VSD adjust fan operation to match actual ventilation requirements and achieve energy consumption cuts that can exceed 68% (Gonen, 2021; De Vilhena Costa and Da Silva, 2020).
- Advanced control frameworks enable ventilation-on-demand systems that direct airflow specifically to active work areas instead of continuously ventilating the whole mine (Zhang et al., 2023; De Vilhena Costa and Da Silva, 2020). The implementation of predictive optimization models based on mathematical and machine learning principles leads to improved energy savings and higher operational efficiency (Saleem, 2025).
- Distributed cooling solutions through modular cooling units target specific underground areas of high heat load to enhance both efficacy and cost-efficiency in air cooling systems.

The methods outlined here help to lower electricity usage while also making deep mining operations much more environmentally friendly through carbon footprint reduction (Saleem, 2025).

4.5 Enhanced Environmental Quality Monitoring

Next-generation ventilation systems rely heavily on innovative monitoring tools, which include rugged portable air quality monitors as well as comprehensive environmental sensor networks (De Cassia Pedrosa Santos et al., 2022). The monitoring devices perform ongoing assessments of temperature as well as humidity levels while measuring atmospheric pressure and gas concentrations and then send this data to central systems for adaptive control (De Cassia Pedrosa Santos et al., 2022). ZigBee-based wireless sensor networks stand out for their durability, minimal power usage, and expandability, which enables dependable environmental monitoring in mining operations (Di Nardo and Yu, 2021).

4.6 Advanced Simulation, Planning, and Decision-Support

Ventilation systems planning and optimization depend more and more on digital modeling and simulation tools. Today's CFD models and digital twin technologies give engineers the ability to model airflow patterns as well as heat distribution and contaminant movement across different operational conditions. The simulations deliver data-based knowledge necessary for selecting appropriate technologies as well as evaluating risks and making strategic investments in ventilation infrastructure. Multi-criteria decision-making frameworks help prioritize environmental improvement projects by optimizing safety outcomes and cost-effectiveness through coordinated efforts (Swanepoel et al., 2023).

4.7 Integration of Geospatial Information Systems (GIS)

Ventilation system management now utilizes GIS to achieve real-time mapping and visualization of airflow patterns and pressure levels along with ventilation device statuses in intricate mine layouts (Leonida, 2019). Mining operations depend on GIS platforms to maintain situational awareness while troubleshooting bottlenecks and planning network expansions or adjustments in ventilation systems (Leonida, 2019).

4.8 Eco-Friendly and Sustainable Ventilation Practices

Ventilation innovations focus on both environmental protection and sustainable development (Yang, Yao and Wang, 2022). Demand-driven ventilation systems and energy-efficient fan operations represent new control technologies that minimize energy costs and meet international environmental standards and legislative obligations (Yang, Yao and Wang, 2022). The intelligent systems maintain deep mining industry sustainability by integrating occupational health management with resource efficiency and environmental impact control (Yang, Yao and Wang, 2022).

4.9 Environmental and Safety Considerations in Underground Mine Ventilation

Efficient underground ventilation ensures air quality, thermal comfort, and environmental compliance while safeguarding worker health and mine sustainability. Key environmental priorities include managing hazardous gases such as CH_4, CO, and hydrogen sulfide (H_2S), controlling dust emissions, heat, and humidity, and treating exhaust air to prevent surface pollution (Vardhan, 2014; Srikanth, Supriya and Khader, 2023; Hartman et al., 1997; Gonen, 2018; Acuña and Allen, 2017). Ventilation systems mitigate explosion and toxicity risks by continuously diluting gases, removing particulates, and maintaining airflow adequacy (Srikanth, Supriya and Khader, 2023; Wang et al., 2024; Åstrand, 2016; Zhen, 2013). Safety designs integrate intelligent sensors, redundancy, and emergency reversal systems supported by CFD and disaster modeling for rapid response (Wan, 2024; Gillies, Wala and Wu, 2004; Ray et al., 2002). Compliance with international air quality and monitoring standards ensures ventilation reliability (Rhoton, 1980; Minin, Tauger and Minin, 2022). Best practices emphasize adaptive, data-driven systems like ventilation-on-demand and variable frequency drives, combined with predictive analytics, CFD optimization, and integrated dedusting to minimize energy consumption and enhance both safety and environmental performance (Wan, 2024; Farjow, Daoud and Fernando, 2011; Åstrand, Saarinen and Sander-Tavallaey, 2017; Aminossadati and Hooman, 2008; Sethi, 2015; Zhou et al., 2025).

5 COMPANIES EMPLOYING ROBOTICS IN UNDERGROUND COAL MINING

The following case studies from global mining companies demonstrate real-world implementation of the optimization and technological principles discussed earlier. The extreme heat and humidity in deep underground mines, along with dust accumulation and gas build-up, require complex airflow management, which means advanced ventilation systems are essential to protect miners and maintain operational productivity (Jacobs, Van Laar and Schutte, 2022). Substantial investments from major mining companies have led to the development of advanced ventilation systems that combine traditional large-scale fans with innovative technologies, including sensor-based monitoring and VoD systems, along with digital twins and battery-electric vehicles to tackle underground heat and emission challenges (Jacobs, Van Laar and Schutte, 2022; Trapani, 2019; Maestro Digital Mine, 2017; BioAge Group, LLC, 2022).

5.1 Glencore

Glencore leads the mining industry with its advanced ventilation systems used at the Kidd Mine, which operates as the deepest base metal mine around the globe, located nearly 3 kilometers beneath the Canadian surface (Maestro Digital Mine, 2017; Sithole, 2025). The Kidd Mine operates among the largest global vent fan systems, which work in conjunction with auxiliary fans and airflow monitoring stations to provide on-demand ventilation (Zadeh, 2025; Glencore Canada, 2023). The Maestro's Vigilante AQS™ Air Quality Stations and mine regulators measure airflow rate, direction, gas concentrations, and temperature to ensure miners operate within safe tolerances (Maestro Digital Mine, 2017). The implementation of these technologies delivers considerable energy savings that amount to 25,000 megawatt-hours each year, which equates to roughly $2 million USD annually (Maestro Digital Mine, 2017). Kidd Mine's ventilation system maintains airflow of over 1.2 million cubic feet every minute while incorporating digital twins to enhance operational efficiency (Zadeh, 2025).

Glencore's Onaping Depth Project features a fully battery-electric mining fleet that could decrease ventilation energy usage by 44% and cooling costs by 30% compared to diesel-based equipment, demonstrating how technological advancements can lessen ventilation requirements in deep mines (BioAge Group, LLC, 2022). Heavy equipment powered by batteries significantly lowers both emissions and heat production and cuts ventilation and air conditioning operating costs (BioAge Group, LLC, 2022).

5.2 AngloGold Ashanti and Harmony Gold

The deep mines operated by AngloGold Ashanti and Harmony Gold in South Africa include Mponeng, Savuka, TauTona, and Kusasalethu, which range in depth from about 3.7 kilometers to 4 kilometers (Sithole, 2025; Zadeh, 2025). The ventilation of these ultradeep mines presents unique challenges because rock temperatures reach extreme highs of up to 66°C at Mponeng's deepest points (Zadeh, 2025). The mining companies have installed systems that combine ventilation with refrigeration functions, and they also use VoD in relevant cases to manage these issues (Bruce, 2014). Obuasi Mine, operated by AngloGold Ashanti in Ghana, has developed a VoD system to replace traditional fans, which will facilitate area-specific ventilation control based on current demand and will reduce energy usage while extending equipment longevity (Bruce, 2014).

The Mponeng and TauTona mines maintain functional underground conditions through combined use of ice-slurry cooling technology alongside their ventilation systems (Zadeh, 2025). The implementation of these systems demonstrates both their ability to influence operational expenses and environmental sustainability while proving the critical need to align ventilation methods with changing mine designs (Jacobs, Van Laar and Schutte, 2022; Zadeh, 2025).

5.3 Codelco

El Teniente Mine, which functions as the world's biggest underground copper mine by volume, sits under the management of Codelco as Chile's state-owned copper producer and produces global copper output (Sithole, 2025; Zadeh, 2025). The underground network spanning more than 3,000 kilometers demands significant ventilation infrastructure with multiple large fans and ventilation raises plus scalable advanced control systems as the mine grows (Zadeh, 2025). The adoption of automation and digital monitoring at El Teniente has reinforced ventilation management efficiency with safe airflow and reduced energy consumption (Zadeh, 2025). The company receives recognition for its implementation of VoD systems, which utilize live sensor information to improve air distribution as a fundamental feature of modern deep mine ventilation design (Nyqvist and Serres, 2020).

5.4 BHP

The Australian Olympic Dam mine operated by BHP stands as one of the largest poly-metallic underground mines in the world while dealing with substantial heat and ventilation problems (Sithole, 2025; Zadeh, 2025). A highly engineered ventilation system integrates primary and auxiliary fans through performance-driven controls to support the mine's sublevel open stoping and block caving methods (Minetek Pty Ltd, n.d.). BHP stands out for its fleet transition to battery-electric vehicles, which results in decreased ventilation and cooling requirements because of lower heat production and reduced diesel emissions (Minetek Pty Ltd, n.d.). Minetek's ventilation systems, used by companies such as BHP, deploy performance-on-demand technologies to enhance airflow efficiency while reducing power consumption (Minetek Pty Ltd, n.d.).

5.5 Vale

Vale manages some of Brazil's deepest subterranean mines, which demand extensive ventilation together with refrigeration systems to handle problems that arise from depth, such as elevated rock temperatures and gas management (Johnston, 2024). The availability of explicit proprietary case studies about Vale mines is limited, but Brazilian deep-level mine ventilation now includes global best practices with VoD systems and cooling plants as well as calibrated digital twins reflecting international peer approaches (Jacobs, Van Laar and Schutte, 2022; Minetek Pty Ltd, 2024).

5.6 Rio Tinto

Rio Tinto operates major deep underground mines, including Oyu Tolgoi in Mongolia, along with large-scale operations at Bingham Canyon in the United States (Ashcroft, 2024). Large-scale mining operations maintain strong primary and secondary ventilation systems through the use of multiple shafts and high-capacity, energy-efficient fans (Minetek Pty Ltd, n.d.). Minetek's solution endorsements state that Rio Tinto adopts cutting-edge airflow management systems that enable dynamic ventilation adjustments to match operational requirements and maintain safety standards (Minetek Pty Ltd, n.d.).

5.7 Agnico Eagle Mines

The Canadian LaRonde Mine, operated by Agnico Eagle Mines, uses sophisticated ventilation systems along with automated ore handling technology at depths surpassing 3 kilometers (Zadeh, 2025). Rail-Veyor technology deployment lowers underground diesel emissions and thereby reduces ventilation system strain (Zadeh, 2025). The company benefits from Minetek's custom fan system solutions that ensure steady airflow and improved energy efficiency (Minetek Pty Ltd, n.d.).

5.8 Additional Companies and Global Practices

Barrick Gold, Newmont, Sibanye-Stillwater, and Freeport-McMoRan have implemented top-tier ventilation systems in their deep mining operations through partnerships with renowned ventilation equipment suppliers (Minetek Pty Ltd, n.d.). The mining industry worldwide is adopting digital twins to enable operators to simulate and optimize ventilation networks before implementation, which reduces risks and operating costs, as demonstrated in gold mines located in South Africa (Jacobs, Van Laar and Schutte, 2022.

Table 3 Companies and Ventilation Implementation

Company	Representative Mine(s)	Key Ventilation Features	Technological Innovations
Glencore	Kidd Mine, Onaping Depth	Large vent fans, auxiliary fans, VoD, air quality sensors	Digital twins, battery-electric fleet
AngloGold Ashanti	Mponeng, Savuka, TauTona	VoD, refrigeration, ice-slurry systems	Sensor-based monitoring, advanced cooling
Harmony Gold	Kusasalethu, Mponeng (since 2020)	VoD, conventional and digital integration	Area-based ventilation control
Codelco	El Teniente	Large fans, ventilation raises, automation, VoD	Real-time sensor networks
BHP	Olympic Dam, Escondida	Engineered duct and fan systems, VoD	Battery-electric fleet integration
Rio Tinto	Oyu Tolgoi, Bingham Canyon	Multiple ventilation shafts, dynamic controls	Endorsed third-party airflow management
Vale	Various, Brazil	Large-scale fans, refrigeration, simulation tools	VoD, digital planning
Agnico Eagle Mines	LaRonde	Automated ore handling, optimized fan systems	Rail-Veyor, Minetek fan technologies
Others (Barrick, Newmont, etc.)	Multiple deep mines	International best practice adoption	Sensor networks, modular fans, digital twins

6 CHALLENGES AND FUTURE SCOPE IN IN VENTILATION SYSTEMS FOR DEEP UNDERGROUND MINES

The optimization and innovation trends discussed above highlight both the progress achieved and the emerging challenges faced by the deep mining industry. The basic function of ventilation systems in deep underground mining operations is to ensure a safe and productive environment, but these systems face growing difficulties as mining depths extend (Bojilov, Hadjiev and Shoushoulov, 1999). Effective ventilation removes harmful gases and controls dust while reducing heat and delivering safe, breathable air, which protects miners and maintains operational efficiency (Gonen, 2018). Deep mines create unique environmental conditions that require specialized solutions, which result in ventilation planning becoming a continuously developing field through innovative techniques and technological designs.

6.1 Challenged

• Heat and Humidity Management: The primary challenge that emerges as mining operations extend into deeper levels involves controlling temperature and humidity because of increased geothermal gradients and heat generated by equipment. When mines reach specific critical depths, natural ventilation systems fail to provide sufficient cooling, which necessitates the installation of additional cooling systems, such as centralized or spot cooling, to maintain safe temperatures for miners and support their productivity (Kamyar et al., 2016). The requirement to address both air auto-compression and heat generation from geological layers increases the necessity for energy-demanding refrigeration systems (Thibodeau and Jodouin, 2014).

• Control of Harmful Gas Emissions: CH_4 release from diesel equipment creates ongoing threats of toxic exposure and explosions when ventilation fails to sufficiently remove or dilute these gases (Imgrund, Bischoff and Spürk, 2019). Mining operations at greater depths present operational complexities through expanded working faces and larger equipment inventories, which boost emission volume and challenge air supply delivery to essential mine locations (Gonen, 2018; Grishin, Zaitsev and Kuzminykh, 2020). When airflow distribution fails or airflow levels remain insufficient, it results in gas stratification involving CH_4 along with the accumulation of exhaust elements such as CO and nitrogen oxides (NOx), which create severe risks to workers (Grishin, Zaitsev and Kuzminykh, 2020).

• Aerodynamic Resistance and Network Complexity: As mine depth increases, ventilation routes extend and become more complex, which leads to higher aerodynamic resistance and energy usage as well as diminished effectiveness in the ventilation system (Bojilov, Hadjiev and Shoushoulov, 1999). Mine layouts aimed at maintaining geomechanical stability tend to have smaller cross-sectional areas, which lead to increased resistance and restricted airflow, thereby complicating the process of full mine ventilation (Thibodeau and Jodouin, 2014). Notably, balancing ventilation requirements with geomechanical constraints presents an ongoing struggle: Large conduits improve airflow but jeopardize rock stability, while small openings ensure geotechnical safety despite their limitation on airflow (Thibodeau and Jodouin, 2014).

• Stability and Environmental Fluctuations: In deep mines, airflow direction and volume become unpredictable when natural wind pressure and barometric conditions change (Wang et al., 2022). When ventilation systems fail to monitor or respond effectively to airflow fluctuations, they can result in dangerous gas overruns and poor air quality, which highlights the critical need for adaptive and strong ventilation controls (Wang et al., 2022).

• High Energy Consumption and Cost: Ventilation ranks as one of the top energy-consuming operations in underground mining because it typically uses 30–50% of the mine's total electrical power (Pandey, Mischo and Drebenstedt, 2015; De Souza, 2018).

Substantial power requirements for large main and auxiliary fans that push air through complex high-resistance networks result in increased operational costs and carbon emissions (Papar et al., 1999). The financial strain becomes more severe when mines extend deeper and ventilation demands increase (Gonen, 2018).

• Maintenance and System Efficiency: Frequent problems such as leakage through stoppings and doors and inefficient fan operation in addition to outdated infrastructure without variable controls generate poor volumetric efficiency, which results in only a small portion of ventilated air being effectively used (Hairfield and Stinnette, 2009). System performance metrics demonstrate that numerous systems operate at efficiencies lower than 65%, which presents major potential for enhancements and waste minimization (De Souza, 2018).

• Safety, Health, and Emergency Preparedness: Deep mines experience heightened safety concerns because poor ventilation systems can trigger hazardous events like fires and explosions and result in gas poisoning and heat-related illnesses (Grishin, Zaitsev and Kuzminykh, 2020; Stewart, 2021). Real-time monitoring and fast system responses are essential during emergencies, yet many current models lack the ability for immediate hazard prediction or mitigation (Stewart, 2021).

6.2 Future Scope

• Advanced Monitoring and Integrated Control: The development of IoT-based monitoring systems that provide real-time evaluation of environmental factors such as gas levels, temperature, humidity, and airflow represents a key area of progress (Zhang et al., 2023). The implementation of wireless sensor networks with ZigBee technology enables ventilation control systems to dynamically adjust airflow in response to real-time underground conditions (Di Nardo and Yu, 2021).

• VoD and Automation: VoD systems stand out as a groundbreaking innovation through their automatic modulation of fans and additional systems to provide necessary airflow exactly where and when required (Pandey, Mischo and Drebenstedt, 2015). The strategy achieves energy reduction by saving up to 50% and improves carbon management through reduced ventilation during inactive periods and in vacant areas (Gonen, 2021; Farjow, Daoud and Fernando, 2011). Remote diagnostic and control systems that operate fans benefit from VoD support through the use of advanced communications infrastructure (Farjow, Daoud and Fernando, 2011).

• Energy Efficiency Optimization: Advanced mathematical models such as the Hardy Cross method combined with machine learning algorithms like gradient boosting enable optimal fan positioning and pressure management to minimize power consumption and enhance airflow distribution (Saleem, 2025). VSD installed on auxiliary fans provide uninterrupted airflow management in accordance with demand levels while boosting system efficiency (Gonen, 2021). System-wide energy audits and equipment upgrades generate non-energy advantages such as extended equipment lifespan and decreased maintenance costs (Papar et al., 1999).

• Enhanced Simulation and Predictive Modeling: The field of modern ventilation design depends more than ever on advanced simulation tools, including CFD-based software and transient analysis models, to achieve accurate predictions of airflow behavior along with thermal loading and contaminant movement (Fair et al., 2021). Mine engineers use these tools to predict how changing environmental conditions or emergency situations like fires or gas leaks will impact operations while enabling safer mine design and proactive responses (Imgrund, Bischoff and Spürk, 2019; Stewart, 2021).

• Cooling Technologies and Renewable Integration: The next generation systems will merge ventilation with sophisticated cooling technologies that surpass conventional refrigeration by including targeted cooling methods and renewable energy solutions like organic Rankine cycle systems or liquid air energy storage (Cluff, Kennedy and Foster, 2014). The integration system delivers two essential advantages by managing temperature and reducing energy costs in deep and ultra-deep mining operations (Cluff, Kennedy and Foster, 2014).

• Addressing Environmental and Geomechanical Synergism: New methods are being developed to solve the conflicting demands between proper ventilation and maintaining geomechanical stability (Thibodeau and Jodouin, 2014). Optimized mine layouts, along with strategic infrastructure planning and coordinated planning processes that address both air delivery and long-term rock support, make up essential components.

• Expansion of Real-Time Response and Emergency Management: Real-time or near-real-time simulation capabilities in dynamic ventilation modeling enable proactive responses to hazardous events through improved prediction capabilities (Stewart, 2021). The addition of these modeling functions to operational processes ensures better protection in standard operations as well as emergency situations.

• Toward Smart, Sustainable Mining: Intelligent and adaptive ventilation systems of the future will operate based on extensive data analysis while ensuring full integration with mine-wide environmental and safety management systems (Zhang et al., 2023). The development of next-generation ventilation control systems in mines will be based on system interoperability along with advanced analytics and self-powered or low-maintenance sensors together with cyber-physical security to achieve increased sustainability and safety as well as improved resilience (Di Nardo and Yu, 2021).

7 CONCLUSION

This paper, based on an extensive literature review, synthesizes current approaches to optimizing ventilation systems for deep underground mines. The paper on the design and optimization of ventilation systems for deep underground mines highlights several critical aspects that are essential for improving safety, efficiency, and sustainability in mining operations. Ventilation system optimization remains essential to achieve proper airflow while diluting dangerous gases and reducing energy use. Mining operations face greater challenges to environmental conditions when they extend deeper underground. Utilizing advanced technologies, including GIS, significantly improves ventilation management techniques. Real-time mapping and monitoring systems enable essential troubleshooting and planning of adjustments for complex mine layouts. Modern ventilation strategies aim to achieve operational efficiency while also putting sustainability at the forefront of their objectives. Demand-driven ventilation systems and energy-efficient fan operations help minimize energy expenses while meeting international environmental standards. Multiple real-world examples show that optimization strategies deliver measurable results through significant energy savings and better adherence to health and safety standards. Practical applications demonstrate how adaptive controls, along with simulation-based design improvements, successfully resolve specific ventilation problems at mining sites. The reviewed studies collectively demonstrate that ongoing research and technological development are necessary to meet evolving ventilation demands in deep mining operations. The literature establishes that effective management of ventilation systems is a vital component of safe and efficient mine operation, influencing safety standards, productivity, and environmental outcomes. The ongoing development of airflow planning techniques coupled with the addition of predictive maintenance capabilities will boost the durability and performance of ventilation systems. The paper concludes that deep mining industries need to adopt new technologies and strategies to ensure their long-term sustainability.

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