Synergy: International Journal of Multidisciplinary Studies
Vol. 2. **Issue** 1, 2025. Pp. 19-34
ISSN: 3048-7005

Journal homepage: https://sijmds.com/index.php/pub

Article

Advancements in Underground Mining Equipment Design: Safety, Finite Element Analysis, and Structural Innovations

Parankush Koul[1]*

1. Department of Mechanical and Aerospace Engineering, Illinois Institute of Technology, Chicago, Illinois, United States of America

*Corresponding Author: pkoul2.iit@gmail.com

Article History

Received:	10-02-2025
Revised:	28-02-2025
Accepted:	01-03-2025
Published:	07-03-2025

DOI: 10.63960/synergyint.j.multidiscip.stud..v2i1.30

Abstract:

This paper discusses improvements to the design of underground mining machines with respect to safety, finite element analysis (FEA), and structure. It illustrates the need to maximise heat and energy use in mining machinery, as shown by research on porous freon steam generators that work better than the old way. The studies also highlight computational modelling in designing structural equipment to overcome operational issues. Additionally, FEA is discussed as an essential resource for modelling complex structures and discovering where failures might occur to bring more reliability and cheaper development. The combination of automation and monitoring systems is also covered and shows how they are reducing the level of risk for humans in high-risk processes and providing safe underground environments through real-time ventilation monitoring. In all, the paper provides a detailed description of how new designs and technologies can be applied to improve the safety and performance of underground mining operations.

Keywords: Safety, Finite Element Analysis, Innovative Design, Automation, Environmental Sustainability

1. INTRODUCTION

New designs of underground mining equipment have been critical to making mining safer and more effective. The combination of these technologies not only makes operations more efficient but also seeks to reduce the inherent danger of underground mining. These advances include different methods, like FEA, which facilitates highly detailed simulations and optimisations of the devices under different load conditions, with the goal of optimising the safety profiles and performance measures [1].

Underground mining is also confronted with a lot of issues, from dangerous geology to workers' safety to the environment. As mineral resources are being demanded more and more, modern design not only to deliver the required output but to meet the required safety standards has never been more crucial. The newer equipment designs are orientated toward the use of cutting-edge materials and construction innovations that would reduce the possibility of equipment failure and accidents in the difficult subterranean environments [2].

A powerful tool here is the use of FEA, which helps engineers to simulate large structures and their dynamics during the load conditions. FEA simulates multiple conditions, which helps in pinpointing failure points and design optimisations before making actual prototypes. This will shorten development time and cost as well as increase the longevity of mining equipment [3].

And as the importance of the environment grows more prominent, innovations in mining machinery also target sustainability. It entails the development of machinery that leaves little scar to the surface and no pollution, crucial for long-term mine operations. Equipment evolution not only meets operational requirements but also more generally meets environmental and regulatory requirements [4].

In summary, the innovations in underground mining equipment design supported by safety innovations, FEA, and structure technologies help to secure the future of mining. This review article aims to dive into these developments and examine the recent innovations and how they impact underground mining safety and efficiency.

1.1. Safety innovations in Underground Mining Equipment Design

Safety innovations in underground mining machine design are key innovations for reducing hazards to personnel and increasing efficiency under harsh conditions. This report examines some innovations, why they matter, and how they influence industry safety practices.

1.2. Evolution of Braking Systems

Braking is the most important innovation of the underground mining machine design. By the mid-1970s, liquid-cooled/oil-immersed brakes from Wagner Mining and Construction Equipment were supplanting the drum and dry disc brakes. The technology greatly improved safety and maintenance through increased control and reliability under hostile underground conditions. Wagner improved on safety with the Spring Applied Hydraulic Release (SAHR) brake system, which was a fail-safe combination of liquid-cooled wheel end brakes and hydraulic release in the mid-1980s [5].

1.3. Monitoring and Ventilation Technologies

For safety reasons, monitoring technologies are needed. Systems that track ventilation data (temperature, humidity, pressure, etc.) have become vital tools for keeping underground areas clean. Real-time monitoring via the use of Internet of Things (IoT) can make operations safer. The fact that these parameters are tracked means miners are not exposed to dangerous air or harsh environmental conditions [6].

1.4. Electrical Control and Safety Features

It has been similarly remarkably easier to design electrical control boxes for subterranean mining equipment. Now they have turned to intrinsic safety designs that avert any potential electrical hazards. Electrical isolation and design safeguards are put in place to make intrinsic and non-intrinsic safety circuits operate safely without triggering dangerous conditions. These kinds of controlled conditions are very useful for eliminating electrical breakdown risks [7].

1.5. Air Quality Management Systems

It's the air in the sealed cabs of mine machines that matters to health workers. Improvements have allowed filtration and pressurisation equipment to be optimised to effectively remove respirable dust and improve the quality of air. Studies comparing MERV-16 with HEPA filters suggest that MERVs can be more efficient and less restrictive. That leads to not only cost reductions but also more comfortable working conditions for operators [8].

1.6. Support Technologies and Automation

Safety measures in underground mining are also affected by automation and robotics. Autonomous drilling systems, for example, resolve most of the older safety issues by avoiding direct human involvement in dangerous activities. When we have robotic drills and support personnel available, there is less risk of accident, which makes the results safer [9].

2. FEA IN UNDERGROUND MINING EQUIPMENT: APPLICATIONS AND IMPLEMENTATION FRAMEWORK

FEA is an efficient computational technique to calculate structures under a number of different conditions by reducing them to smaller components that can be solved easily. When applied to underground mining equipment, FEA can be used for various designs and optimisations of these devices.

2.1. Applications of FEA in Underground Mining

FEA in underground mining machinery solves a host of issues related to integrity, choice of material, and cost effectiveness. Key applications include:

- *Structural Analysis*: Through FEA, the mining structures' strength and stiffness under varying loads and environments can be measured. This also entails analysing the impact of dynamic loads like rock bursts or earthquakes [10].
- *Equipment Design*: When a heavy machine, like a conveyor belt hydraulic system, is to be designed, stress and deformation must be carefully thought out. FEA helps to tune the design parameters to improve safety and productivity, such as the design of dynamic belt clamps for heavy-duty drift belt installation [11].
- *Material Behaviour Simulation*: FEA can be used to understand materials in mining equipment, like the creep behaviour of polymers for support liners. They simulate the viscoelasticity of such materials to identify their lifetime performance [12].
- *Safety Assessments*: Since underground mining can cause hazards such as rockbursts, ground control auxiliary systems are essential. FEA helps simulate the effectiveness of these systems in preventing accidents and improving worker safety [10].

2.2. Steps to Implement FEA in Underground Mining Equipment

Implementing FEA involves several critical steps to ensure

https://doi.org/10.63960/synergyint.j.multidiscip.stud..v2i1.30

accurate modelling and analysis. The basic process is as follows:

- *Problem Definition*: A clearly defined problem is required, such as what the goal of the problem is and what the details about underground mining equipment to be investigated are. This can include setting up the operating environment, stresses, and limitations of the equipment in its lifetime [13].
- *Geometry Creation*: Create a geometric sketch of the machine, then create an orthogonal sketch of it. That often involves the CAD design of the mining machine parts to make it just right. This geometry will be important for good meshing and analysis [14].
- *Meshing*: The geometry needs to be broken down into finite elements, which can be of any shape and size depending on the analysis task. More accurate mesh, but also a bigger computational investment. Finding the right mesh density is a compromise between precision and speed [15].
- *Material Properties Specification*: Define material properties on model objects. These are Young's modulus, Poisson's ratio, yield strength, and other pertinent mechanical parameters describing how each part of the machinery responds under stress.
- *Boundary Conditions and Loading*: Create appropriate boundary conditions to simulate constraints on the device, like static support or applied loads in operation. The load app needs to elicit real-world scenarios like static and dynamic loads [16].
- *Solving and Analysis*: Once the model is set up, the simulation is performed in FEA software. It will yield outputs describing stress distribution, deformation, and other relevant parameters needed to test equipment performance [17].
- *Result Validation*: We need to check the FEA results against the experimental results or the benchmarks. This is to help make sure that the model captures the physical behaviour of the equipment [16].
- *Optimisation and Iteration*: Based on results, optimise the design with a parameter or component change. The review can be incrementally improved in order to optimise performance, save weight, or add safety [18].
- *Documentation and Reporting*: Finally, gather the information into a report of how it was conducted, the outcomes, and suggestions for equipment design or improvements. This documentation is needed by stakeholders and regulatory requirements.

3. STRUCTURAL INNOVATIONS IN UNDERGROUND MINING EQUIPMENT

Exploration of underground mining equipment structural innovations that help to optimise operations, ensure safety, and minimise the risks associated with mining. These solutions solve various issues in the extreme environment of subsurface, where devices are exposed to high-temperature wear, corrosion, and stress during operation.

3.1. Key Innovations in Equipment Design

Newer mining machinery design focuses on using premium materials and design to enhance toughness. Ti-Cu coatings, for example, are shown to provide protection from biocorrosion, which is a serious problem in subsurface mining where microbes speed up metal corrosion [19]. These composite coatings don't just enhance anti-corrosion properties but also strive to improve tribological properties, critical for the long-term service of equipment that will be exposed to extremes of the mining environment.

3.2. Equipment Selection Models

For maximum productivity, choosing the right equipment for underground mining is vital. Establishing advanced models that evaluate all of these associated factors allows operators to choose the correct equipment. These models consider the compressive strength of rock, operating expenses, and machine capabilities [20]. Analysis of these parameters can help mining operators select the machinery not only for better productivity but also with low maintenance and operating costs.

3.3. Automation and Technological Integration

This is where automation comes in handy to tackle the problem of underground mining. The self-driving car and advanced control systems are all in the works to improve operational security and performance. Autonomous vehicles, for instance, have high-end communications protocols for the real-time communication of information, which enhances situational awareness and operational decision-making [21]. Furthermore, the control panels of mining equipment are being revamped to correct ergonomic problems to increase the comfort of operators and minimise the likelihood of accidents [22].

3.4. Use of Mobile Technologies

Mobilisation of technologies (such as LiDAR for structure mapping) is another innovative concept in underground mining. Convenient portable LiDAR can quickly and effectively map underground buildings in 3D to provide miners with information on possible rock mass failure modes and overall mine safety [23]. It is a technology that can do detailed structural description without the invasive effort of analysing previously and has the potential to improve productivity at the subsurface.

3.5. Environmental Considerations

Environmental stewardship has never been more of an issue in subsurface mining technology. For instance, scientists are trying to find a way to better deal with and remove mining spoils like coal gangue by way of underground backfill. This not only solves the issue of waste but also contributes to the better sturdiness of the mine's workings [24]. Designs such as these are examples of a more general effort to minimise the environmental impact of mining.

4. ADVANCING UNDERGROUND MINING EQUIPMENT DESIGN: LEVERAGING SAFETY INNOVATIONS, FEA, AND STRUCTURAL ADVANCEMENTS

4.1. Safety Innovations in Underground Mining Equipment Design

- Carroll Technologies Group is a major supplier and service provider in the mining, steel, construction, and tunnelling industries. They have a reputation for taking safety seriously and are available 24/7, providing increased availability and an emergency response [25].

- MineARC Systems is the global innovator of controlled environments and safety solutions for underground mining. Their technology focuses on providing refuge solutions and security chambers that significantly improve underground safety systems [26].

- ChromeGuard provides safety solutions to improve equipment performance and longevity. They use cylinder guards, which can save expensive equipment from breakage, prolonging the life of the machine and making it safer to mine [27].

- Point.Laz has built an automated mine shaft inspection system using 3D laser scanning. It greatly eliminates manual inspection, which in turn provides better safety for miners and operational efficiencies through predictive maintenance data [27].

- SafeGauge is developing wireless pressure testing equipment for heavy equipment, the SafeTest PT Series. With this technology, hydraulic pressures can be monitored at a distance without risk of being injured during maintenance [27].

4.2. FEA in Underground Mining Equipment Design

- Predictive Engineering has more than 20 years of FEA consulting experience. They offer comprehensive stress and dynamic analysis of various engineering problems, such as specific equipment for the mining industry [28].

- Friedman Research uses FEA to develop occupant protection from blast and ballistic forces to dramatically enhance the safety performance of mine equipment in hazardous environments [29].

- Acuren uses FEA for a variety of applications, from pressure vessels to mining machinery. They provide expertise to ensure operation and safety upgrades with in-depth structural assessments [30].

- Finfinite Engineering specialises in FEA services for the high-end requirements of mining equipment. Their solutions are essential for successful mining infrastructure design and maintenance [31].

- ProForma Engineering is an FEA and simulation solution company for a variety of sectors, such as construction and mining. Their comprehensive reviews ensure machinery and equipment are kept safe and effective [32].

4.3. Structural Innovations in Underground Mining Equipment Design

- Caterpillar Inc. is known for their high-quality underground mining machinery engineering; the company's recent Cat 3000H Load-Haul-Dump machine incorporates modern technology to enhance load capacity and production productivity [33].

- Sandvik Mining has gone through some massive design improvements in their DD321 underground drill rig, which includes improved safety and functionality designed to deliver greater productivity in challenging mining environments [33].

- Komatsu's comprehensive offering includes cutting-edge technologies and construction solutions for optimised performance and safety in underground hard rock mining [34].

- Joy Global is also known for its bespoke underground equipment that incorporates the most modern improvements in safety and efficiency. Their quadbolters feature a revolutionary design for safe and efficient mining [33].

- Atlas Copco has introduced many high-tech mining solutions, like the Scooptram ST18 loader. These tools are designed in such a way that they increase the comfort and productivity of the operator and consequently enhance the level of safety of the underground [33].

5. LITERATURE REVIEW ON SAFETY INNOVATIONS, FEA AND STRUCTURAL INNOVATIONS IN UNDERGROUND MINING EQUIPMENT DESIGN

The number of articles covered in this review on safety innovations, FEA, and structural innovations in underground mining equipment design is shown in Fig 1. from 2019 through 2024.

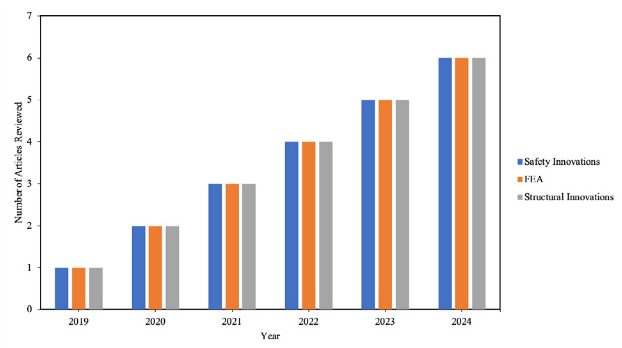

Fig. 1: *Articles reviewed (2019-2024) on the safety innovations, FEA and structural innovations in underground mining equipment design*

https://doi.org/10.63960/synergyint.j.multidiscip.stud..v2i1.30

5.1. Advancing Safety in Underground Mining: Innovations in Equipment Design to Minimize Accidents

Table 1 below shows a quantitative distribution by publisher of the number of articles related to the safety innovations in underground mining equipment design.

Table 1: *Number of articles from different publishers reviewed on the safety innovations in underground mining equipment design*

Publisher	Number of Articles Reviewed
IEEE	4
Springer	2
Yandy Scientific Press	2
AGSER	1
ASERS Publishing	1
Darcy & Roy Press	1
Elsevier	1
Hrček	1
iJRASET	1
IOS Press	1
MDPI	1
National Research Institute of Industrial Safety and Occupational Health	1
NCMMI (STU)	1
Penerbit UTeM Press	1
Scientific Technical Center of Industrial Safety Problems Research	1
SZABIST	1
Total	21

Adjiski et al. (2019) created an intelligent PPE device that has sensors integrated for workers to detect the health and environmental risks from work in real time. They had five layers, enabling interoperability, real-time risk management, and situational awareness to avoid accidents with predictive warnings [35]. In contrast, Li et al. (2020) used image processing to find equipment abnormalities, like oil leaks in mining transformers, with advanced algorithms and H-S colour histograms. They had a much better detection performance with their technique, thus allowing an early response to eliminate hazards [36]. Rudakov (2020) went the other way around, modelling environmental and occupational safety using multifunctional safety systems (MSS) and geo-mechanical process modelling. The program was geared towards minimising rockfall accidents and optimising the mine's stability through cutting-edge monitoring and control systems [37].

Alam et al. (2021) designed a smart miner helmet that sensed environmental data (toxic gases, temperature, humidity) and health indicators (heartrate) and provided instant notifications and crisis alarms in case of accident. The system used collision detection and focused on simplicity and value [38]. Sarkar et al. (2021) built a Hybrid Mine Hazard Alert System (MHAS), including video-based and SMS-based alerts, to help communicate and respond to fire, water flood, and strata failure. Their field trials in hard rock mines revealed that the system can find and warn staff about several hazards at once—a significant step up from single-target systems [39]. Meanwhile, Fayyaz et al. (2021) had suggested a smart helmet design for coal miners, which tackles environmental, chemical, and thermal hazards of mining. Its design was to minimise risk through monitoring and warning of environmental conditions in real time with the statistical documentation of mining accidents as evidence of its need [40].

Nikitenko et al. (2022) focused on the invention of mechanised walking supports and special dust gauges for dealing with organic aerosols and dust-methane-air combinations that were unsafe and the need to detect dust levels accurately to avoid explosions [41]. Likewise, Xu (2022) went further with an intelligent positioning system using Ultra-Wideband (UWB) and obtained accurate real-time location tracking of personnel with static and dynamic positioning errors of 0.3 m and 7.3 m, respectively, drastically improving emergency response effectiveness [42]. Meanwhile, Qian et al. (2022) surveyed all Collision Avoidance Systems (CAS) technologies and discovered advanced positioning and communication algorithms that can be centimetre-precise with nanosecond end-to-end latency, giving situational awareness and decreasing collision incidents [43].

Miao and Niu (2022) focused on neural networks and signal processing to process electrical equipment signals, predicting accidents in advance, and managing electrical safety in coal mines. They found that O-Net monitoring systems and designed algorithms reduced the risk of electrical safety accidents based on top risk factors [44]. Chaitanya et al. (2023) moved in an IoT direction with its Air QuBlynk network that provides real-time air monitoring and miner health data from sensors and phones. This network helped in disaster relief and operation safety by transmitting environmental and physiological signals continuously [45]. Cholke et al. (2023) highlighted IoT-connected helmets to track toxic gases, prevent helmet tampering, and follow miners. These helmets met physical and environmental risks and had the potential to reduce accidents and offer safety monitoring in real time [46].

He et al. (2023) dedicated to mining safety concepts and technologies—the necessity of international cooperation and new designs for deep-mine safety concerns such as rockbursts and gas explosions. They also outlined the necessity of adaptive safety systems as the deep mining landscape became more complicated [47]. Salahudeen et al. (2023) introduced a LoRaWAN-based smart PPE system with sensors to monitor conditions and workers' vitals in real time for proactive action in the event of a hazardous situation. This research covered topics such as sensor reliability and data security for improving safety control with predictive analytics [48]. Reshotka and Tkalych (2023) inspected the VDNU-4TX machine installation using HAZOP to detect and eliminate working at heights, falling objects, and fire risks. They proved that hazard analysis and planning can lead to reductions in installation accidents and increase operational effectiveness [49].

Vishwakarma et al. (2024) worked on a smart helmet with IoT integration that would monitor the environment, identify when the helmet is removed or damaged, and issue real-time warnings to increase worker safety. The findings revealed the huge opportunity for accident mitigation and data-driven hazard prevention [50]. Similarly, Dange et al. (2024) demonstrated a prototype smart helmet equipped with IoT devices and sensors for hazardous gases such as methane and carbon monoxide, which could provide emergency response to miners in need. Its study was specifically orientated to solving global mining safety issues in high-accident areas of the world and foresaw significant reductions in death [51]. In contrast, Pääkkönen et al. (2024) created and evaluated a reference architecture (RA) for digitalising underground mining with respect to situational awareness, emergency stops, and high-speed location monitoring via digital twin modelling, MQTT messaging, and 5G networks [52].

Klyuev and Gavrilova (2024) targeted electrical safety by retrofitting unsound components of the power grid with new cables and motors with better insulation. Their experimentation detected flaws in power supply infrastructure and suggested equipment upgrades and full-spectrum inspection systems to prevent electrical failure accidents [53]. Zhang (2024) investigated the use of intelligent technologies, such as BIM, IoT, and AI, to enhance safety monitoring. The research showed that intelligent mining platforms facilitated risk analysis, tracking, and response in the event of an emergency, thereby reducing accidents by optimising decision-making [54]. He et al. (2024) devoted themselves to disaster management in coal mining with a focus on developments in dust-control technologies and disaster prediction models. They concluded that chemical dust control, increased monitoring, and advanced prediction systems were key to reducing explosion risks and protecting miners [55].

5.2. Advancements in FEA: Enhancing the Design, Accuracy, and Structural Integrity of Underground Mining Equipment

Table 2 below shows a quantitative distribution by publisher of the number of articles related to FEA in underground mining equipment design.

Table 2: *Number of articles from different publishers reviewed on FEA in underground mining equipment design*

Publisher	Number of Articles Reviewed
IOP Publishing	3
MDPI	2
Taylor & Francis	2
Wiley	2
AIP Publishing	1
Australian Centre for Geomechanics (ACG)	1
DergiPark Akademik	1
Elsevier	1
Institute for research and design in industry	1
Institution of Engineering and Technology (IET)	1
JERR	1
Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu	1
Ore & Metals Publishing house	1
Polish Academy of Sciences	1
RUE Publishing House "Belaruskaya Navuka"	1
Tech Science Press	1
Total	21

Nguyen et al. (2019) evaluated the dynamic behaviour of a new rockbolt, the Superbolt, in dynamic loads, using drop tests with Abaqus to test for impact capability in rockburst-prone mining applications. They showed that the performance of the bolt varied with the epoxy resin and the hardness of the bolt material and that the Superbolt could be used for better ground support and safety in subsurface mining [56]. Garcia Rosero and Zsaki (2020), by contrast, proposed a priori local p-refinement method for finite element mesh accuracy of stress analysis in subterranean diggings. They found that this approach significantly improved mesh quality, stress prediction error, and numerical simulation convergence under complex geological conditions. This perfectionism helped create safer and more efficient tunnelling and mining designs [57]. Ibrahim et al. (2020) went even further and developed an automated p-adaptive mesh improvement algorithm for subterranean prismatic cross-sections. They developed a computerised model that yielded higher computational efficiency with extremely accurate stress analysis, especially for models of difficult material properties and loadings. The automated approach helped us save computational time and yielded better quality outputs for geotechnical engineers and researchers [58].

Wang et al. (2021) focused on numerical simulations of surface movement and deformation by underground mining in stratigraphic environments. Their work resulted in a novel MATLAB-based interface program for finite element software that can be used to controllably generate 3D surfaces based on CAD contours. The simulation paired with FLAC3D software produced simulations close to field data, showing that this method could predict subsidence and surface deformation under geologically complex conditions [59]. Dmitriev et al. (2021) have also devised a new method for modelling stress-strain states in rock layers with structural differences using 3D models and structured meshes. Their technique used a dedicated zero element to keep the mesh regular while modelling contact elements, making geomechanical modelization in mining much more precise. These conclusions gave engineers an efficient mechanism to design geomechanical models to more accurately reflect structural instability in rocks [60]. Rotkegel et al. (2021), by contrast, used FEA to investigate composite C-profiles as lining materials for arch supports in mine digs. They used pultrusion technology to make prefabricated composite materials, and simulations revealed how well and how poorly the material operated, so composites might be a suitable replacement for standard steel and concrete linings. Although they did not perform any field tests, they showed that composite materials could be used to improve the structural integrity in mining applications [61].

Berdoudi et al. (2022) evaluated the stability of underground mine structures in Algeria with a 2D FEA model based on the New Austrian Tunnelling Method (NATM) for tunnelling. Their findings showed a lot of ground motion while tunnelling, well above the limits, and advised raising tunnel cover height to limit dangers [62]. In contrast, Batsaikhan et al. (2022) focused on the pipe-jacking process for supporting underground coal mining tunnels, especially in porous rock layers. They demonstrated by 3D-FEA simulations that smaller tunnel inclination angles permitted better tunnel advance and stability, and they found that precast concrete pipes could be used for structural integrity without grouting provided that crown deformation was within safe limits [63]. Hu et al. (2022) utilised a full 3D-FEA model to investigate the structure of a subterranean cavern complex. Simulating the mining of all caves showed that displacement and stress prediction were substantially different for full versus simplified simulations and advised the entire simulations for more accurate and safe design [64].

Bernuzzi et al. (2022) explored the durability of derrick cranes—so essential to mine production—by assessing local injury in different geometrical designs. They ran FEA to run various damage conditions, detecting the critical parts and suggesting design optimisations to maintain structural integrity over the lifetime of the crane [65]. Guo et al. (2023) used transient dynamic FEA to analyse mining excavators' gear transmission systems. Their work included an accurate simulation of gear contact stress during operation at various stress distributions and failure sites. They also tested the fatigue of gear tooth surfaces, which is part of the system's overall reliability assessment [66]. Dönmez and Tunçdemir (2023), meanwhile, were interested in support pressures for underground buildings using FEA as well as convergence-confinement. They looked at the stability of the digs by comparing the rock faces with the supporting structures. Both strategies were effective but also highlighted the practical merits of the convergence-confinement strategy, especially in soft rock masses [67].

Ilyasov et al. (2023) had applied the finite-discrete element method (FDEM) to the stability of tunnel openings using support structures. They also showed that FDEM was more accurate in its predictions of induced stresses and stability than finite element methods (FEMs), especially under geologically complex conditions. Using numerical simulations, they were able to tune support systems and show how FDEM could be used to develop cheaper and more efficient support for mine excavation [68]. Liang et al. (2023) focused on underground mining efficiency of roadheader cutting and FEA modelling of the cutting operation. They validated their research with experimental data to prove that FEA can properly simulate cutting dynamics and distributions, which improve stability control and cutting efficiency. They combined theoretical calculation with FEA using MATLAB to provide insight into torque waveforms and cutting forces, which led to the more efficient and stable operation of roadheaders [69]. Diulin et al. (2023) studied the stress-strain condition of mine shaft linings by FEA in the ANSYS Workbench. Their study was designed to test the lining of the shaft for structural integrity and locate leaking spots that needed repair. They illustrated with detailed stress distribution charts how the shaft's bearing capacity can be evaluated and how to monitor and maintain it for safe operation [70].

In the mining of extra-thick coal seams, Mai and Li (2024) used FDEM to simulate water-conducting fractures in faulted roof layers. The importance of constitutive models and numerical simulations to the forecasting of rock failure and water inrush accidents, one of the primary safety hazards in underground mining, was emphasised by them. These findings showed that repeated deformation and collision of single rock blocks could be easily modelled, and the durability of sand mudstone as a substrate for propagation of fractures during successive mining disruptions [71]. Downey (2024) instead aimed at infrasound resonance in underground mine tunnels using a discontinuous Galerkin FEM. The focus here was on the sensitivity of infrasound signals to tunnel geometry and boundary changes, which is critical for monitoring and structural analyses of mine tunnels. Downey's data indicated possibilities for volcanic and industrial monitoring to learn more about the tunnel's dynamic behaviour [72]. Wu et al. (2024) designed a modular and parametric model system for finite element modelling in the subsurface. They applied the method to the Shuangjiangkou Hydropower Station and integrated Python-based cloud servers to generate models very quickly under astro-geological conditions. This work confirmed the general applicability of parametric models for describing deformation and stress around excavated caverns and verified the method by comparing it with classical ANSYS models [73].

Wang et al. (2024) focused on the support effects and fracture characteristics around deep-line tunnels using a combined FDEM (CGP-FDEM), which integrated GPU parallel processing to simulate large-scale rock fractures. Their results indicated that reinforcement significantly affected the excavation damaged zone and surrounding rock deformation, with weak rock masses experiencing increased stress concentrations and instability. They proposed a uniform reinforcement principle to mitigate stress concentrations and improve roadway stability [74]. In comparison, Jialin (2024) optimised the structural design of a 60T electric mining vehicle frame, employing FEA to analyse stress and deformation under various loading conditions. The study found that increasing the thickness of the support plate and enhancing its stress area reduced stress by up to 39.2% during turning, leading to improved durability and stability despite a slight increase in weight [75]. Similarly, Sun et al. (2024) applied FEA to the design of a large vibrating screen, using an equivalent static load method and topology optimisation to reduce stress and enhance fatigue durability. The optimisation led to a 46.8% decrease in maximum stress and a 14.9% reduction in weight, contributing to improved efficiency and durability of the screen in dynamic loading conditions [76].

5.3. Advancements in Materials Science and Computational Modelling : Shaping the Future of Structural Innovations in Underground Mining Equipment Design

Table 3 below shows a quantitative distribution by publisher of the number of articles related to structural innovations in underground mining equipment design.

Table 3: *Number of articles from different publishers reviewed on the structural innovations in underground mining equipment design*

Publisher	Number of Articles Reviewed
MDPI	5
Springer	4
Elsevier	2
Scientific Electronic Library	2
AGH University of Science and Technology	1
EDP Sciences	1
Erdélyi Múzeum-Egyesület	1
IOP Publishing	1
M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine	1
Ore & Metals Publishing house	1
Scientific Council of Dnipro University of Technology	1
Taylor & Francis	1
Total	21

Xue et al. (2019) examined directional blasting fracturing for stabilising critical layers of deep coal. Their work generated structural models that lowered abutment pressures and roof fracturing mechanisms by up to 60% for mining safety. When the study's results were implemented in the Hongqinghe coal mine, the technology had been shown to be successful in stabilising the mine space and reducing stress levels [77]. Alternatively, Sokolov et al. (2020) analysed how to build new underground geotechnologies that utilised design concepts to extract more ore, increase the efficiency of labour, and reduce the cost. Their studies focused on sophisticated methods for environmental protection and the efficiency of resource extraction. This reported the significant improvement in ore extraction completeness, labour efficiency, and cost savings, as well as the use of mining waste in more sustainable processes [78]. Kaplunov et al. (2020) compared the cost of transitioning to new technologies in underground mining as work reached higher depths. Their research was on cutting-edge waste separation and backfilling equipment and emphasised the cost-benefit and operational benefits of installing equipment below ground as opposed to on the surface. According to the study, the improved technological configuration reduced costs, specifically in the area of transportation and lifting [79].

The article by Zhao et al. (2021) developed and tested hybrid roof standing supports with new materials to supersede existing pumpable supports in underground mining. The hybrid columns showed superior load capacity and stability according to the experiments and were found to improve the safety and productivity in the mining process [80]. In contrast, Zhang et al. (2021) focused on the stability control for full-mechanised longwall mining, Equipment Recovery Passage (ERP). Their work was based on FLAC3D numerical simulations that tested the effects of different longwall face speeds and roof structure optimisation on abutment stress reduction and demonstrated that speeding up the longwall face and roof structure could significantly increase ERP stability [81]. Zhao et al. (2021) studied the optimisation of NPR (Negative Poisson's Ratio) cable support in deep shaft environments with heterogeneous stress fields by implementing FLAC3D simulations to analyse the distribution of stress and modes of failure. It was shown that when the spacing and length of NPR cable supports were implemented at the highest, the plastic zones and failures were significantly decreased while also enhancing shaft stability [82].

Zhang and Zhao (2022) proposed a hybrid mine-supporting structure for underground operations that integrates fibre-reinforced polymer (FRP) with polyvinyl chloride (PVC) composites for increased load capacity and deformation resistance. According to their lab findings, the FRP-PVC tubular standing support (FPTSS) showed better mechanical attributes—for example, higher compressive strength and axial deformation capacity—than standard support systems. The results pointed to the structural integrity and economic efficiency of the FPTSS that could enhance safety and productivity in the mining industry [83]. Wojtas (2022) focused on the mechanisation of support systems with the HENNLICH-20/43-CH type crossing-powered support. The system, which was intended to eliminate handwork and improve productivity, proved the power of hydraulic operation and motorised power steering versus single props. These studies showed the business benefits, such as safety and lower physical pressures on workers [84]. On the contrary, Y. S. Oryngozhin et al. (2022) tried out a different kind of mining, bottom-up mining using self-propelled haulage vehicles. This way ore bodies could be better mined, waste rock removed more effectively, and it made the operation more economic and sustainable. Houlage ramps for exploration also facilitated mine work [85].

The paper by András et al. (2022) wrote on how mechatronics and advanced technologies of manufacturing can be integrated in the design of mining machines in order to overcome the economic, environmental, and safety problems in mining. The work stressed functional analysis and new manufacturing methods to optimise the alignment and functionality of mining machines and a long-term view of technological maturity triggering an evolution into innovation [86]. Florea, Toderas, and Itu's paper (2023), by contrast, investigated the reliability and maintenance of mining machines, in this case, the TR-7A scraper conveyer, which was regularly worn out. Operational information and failure analysis led the authors to formulate a reliability enhancement plan based on maintenance optimisation and wear considerations, including lubrication and sealing. They discovered that there is a need for better design in order to minimise operational disruption and maintenance [87]. Meanwhile, Liu et al. (2023) conceived of an energy-absorbing rockbolt (SD-bolts) protection system for active disasters such as rockbursts in deep underground mining. They performed field experiments showing that the SD-bolt reduced the effect of moderate rockburst significantly, enhancing both worker protection and equipment life [88].

Aboelezz et al. (2023) focused on the development of an intrinsically safe drone propulsion system for underground coal mining, utilising computational and experimental methods to optimise design features such as motor spinners and structural components. They found that new designs could greatly increase performance, weight reduction, and safety due to reduced heat hazards, leading to more effective operation in hazardous mining sites [89]. Mishra (2023) dealt with the introduction of Mass Production Technology (MPT) in the underground coal mines of India, with an emphasis on longwall technology. These studies exposed the problems and possibilities of growing underground coal output to reach ambitious targets and indicated that MPT would increase output and competitiveness against opencast. They used computational modelling to illustrate how the design of structural equipment could be very useful for solving operational and regulatory issues [90]. Lukisha et al. (2023) studied the thermal-hydraulic performance of porous freon steam generators in mine power plants. They computed these generators to show that, compared with smooth-wall generators, they would cut system length and differential pressure costs and thus achieve a higher energy efficiency. Using optimal thermal management, this work made computational methods the priority in the design of mining machines for optimal performance and low power consumption [91].

Wang et al. (2024) demonstrated non-explosive mechanised and intelligent mining by using automation, in-field monitoring, and intelligent control technology to combat critical issues such as rock breakage and stability in deep hard rock formations. They focused on environmental, rock, and excavation parameters as the most important factors in the optimal mine. Their results derived a proposed cyclic management model (PDCA)-based safety and efficiency for the safer and more effective alternative to conventional mining methods [92]. In contrast, Nikitenko et al. (2024) involved creating a safety module for walking robots on a roof for an underground mine. Their work used numerical modelling to evaluate the stability of roof members by plotting load distributions and stresses near the preparation face. A remote control system meant the system could be operated without collapse and without risk to people. This research went toward structural improvements to enhance mine safety in potentially dangerous settings [93]. Meanwhile, Shalomeev et al. (2024) dealt with material fatigue by adding aluminium, vanadium, calcium, and rare earth metals to medium carbon steel 40HL to make it resistant to wear in mine tools. The study found that these types of changes vastly improved the mechanical characteristics and durability of hard-wearing parts (unloading grates and ladles), which often fail. Their research made it clear that a better combination of composition and geometry was critical to optimise material composition and form to lessen the frequency of maintenance and prolong the life of mining machines [94].

Herasymenko et al. (2024) surveyed alternative transport for underground mining, with a special focus on suspended monorail systems with diesel locomotives as an alternative to cars. Their studies, based on both expert assessments and operational parameter reasons, concluded that these transport solutions considerably increase the effectiveness and versatility of coal mine preparation works in the face of swollen bottom rocks [95]. Xiao et al. (2024) focused on the optimisation of large-scale polycrystalline diamond compact (PDC) teeth, using computational tools like Abaqus simulation software to optimise their structural geometry in rotary mines. They found that by making the conical tooth arc more circumferential, the impact resistance increased, and an optimised form was capable of withstanding high impacts and thus extending the lifetime of excavating equipment [96]. Lastly, Liu et al. (2024) reviewed all the intelligent technology used in underground mining, including drilling, blasting, and ventilation. They also discussed the gains in production efficiency and safety with deep learning and big data. The ongoing problems of fully autonomous, unmanned mining, they wrote, are another concern for their research, namely technological innovation [97].

6. CONCLUSION

Underground mining equipment design has been a big step forward in terms of safety, efficiency, and sustainability. FEA is used to upgrade the occupant protection against blast and ballistic damage to drastically reduce the risk associated with mining. With FEA, not only does it accelerate development, but it also reduces costs through optimising equipment design and performance, so machinery is reliable and effective in extreme environments. The paper emphasises innovative design solutions consistent with regulations and standards. Such is the creation of machinery that reduces surface disturbance and pollution to the lowest levels necessary for the viability of mining. Especially as the industry transitions to greener initiatives, waste minimisation and environmental footprint minimisation are becoming ever more critical. For these, solutions like underground backfilling technology are being considered. Developing advanced equipment-selection models helps mining companies make better and more profitable decisions to increase productivity. These models accounted for everything from rock resistance to running costs to get the best performance. In summary, the paper underscores the critical role of advanced design techniques, particularly FEA, in shaping the future of underground mining equipment. As long as safety, efficiency, and sustainability remain top priorities, the mining sector can keep evolving and adapting to modern realities.

7. CHALLENGES AND FUTURE SCOPE IN UNDERGROUND MINING EQUIPMENT DESIGN

The underground mining industry has a few issues that must be solved in order to be safe, effective, and viable. This article points out these problems and identifies potential future directions for equipment design and technology adoption.

7.1. Challenges

- *Adverse Geological Conditions*: Unpredictability of rock formations creates equipment damage and health risks. This will require more flexible and dependable machines that can flex under different circumstances.
- *Worker Safety*: Although improvements have been made, worker safety has never been a concern. There are no design alternatives that should leave as many humans as possible involved in risky operations. Automation and robotics are a must to solve these safety challenges, but they are difficult and expensive to implement.
- *Environmental Impact*: As the environment gets more tightened, mining has to adjust to leave the least carbon footprint possible. Among those, there is the disposal of waste and pollution (which presents a real design challenge for the equipment).
- *Technological Integration*: The new technologies (automation, advanced materials, etc.) take investment and training to be incorporated. Making sure that the workforce can be trained to deal with these technologies is an issue the industry has to solve.

7.2. Future Scope

- *Innovative Materials and Designs*: The next generation of equipment designs must be focused on advanced materials that can be durable and low maintenance. Explorations in composite coatings and other safeguards could mean longer-lasting gear.
- *Sustainable Practices*: Sustainable methods will be a feature of the design of the underground mining equipment in the near future. Technologies for handling waste, like the underground backfilling, can help keep costs low and ensure the sustainability of operations.
- *Enhanced Computational Modelling*: Computational modelling and FEA will only become more accurate as the industry develops, which in turn will make it possible to predict the performance of equipment in a variety of conditions. This could lead to huge increases in efficiency and safety in design.
- *Automation and Robotics*: The future will more and more turn to automation and robotic technologies for safety and efficiency. And future research and development could remove a lot of the old-school risks of underground mining.

DECLARATIONS

Author(s) Contribution

To the best of my knowledge, the content presented herein is authentic and does not infringe upon any copyright or intellectual property rights. All sources used in this research have been duly acknowledged and cited in accordance with academic standards. Any errors or omissions remain my sole responsibility..

Uses of AI Acknowledgement

Not Applicable

Funding Information

Not Applicable

Availability of Data and Materials

All documents referenced in this study are publicly available on the respective websites. The links to these documents are provided in the reference section for further access.

Competing Interests

There is no competent of Interest.

Clinical Trial Registration (if applicable)

Not Applicable

Human Ethics and Consent to Participate

Not Applicable

REFERENCES

1. Dusza-Pilarz, K., Kirej, M., & Jasiołek, J. (2024). Use of laser scanning and 3D software in mining design. *E3S Web of Conferences, 526*, 1–10. https://doi.org/10.1051/e3sconf/202452601012
2. Sheshpari, M. (2015). A review of underground mine backfilling methods with emphasis on cemented paste backfill. *The Electronic Journal of Geotechnical Engineering (EJGE), 20*(13), 5183–5208. https://www.researchgate.net/profile/Morteza-mori-Sheshpari/publication/282307412_A_review_of_underground_mine_backfilling_methods_with_emphasis_on_cemented_paste_backfill/links/5b07c59ba6fdcc8c252cb162/A-review-of-underground-mine-backfilling-methods-with-emphasis-on-cemented-paste-backfill.pdf
3. Cheban, A. Y., Sekisov, A. G., Khrunina, N. P., & Vasyanovich, Y. A. (2022). Combined ore extraction technologies in the development of crystal raw material deposits. *Mining Information and Analytical Bulletin (Scientific and Technical Journal), 7*, 55–67. https://doi.org/10.25018/0236_1493_2022_7_0_55
4. Stratton, C. (2015). Benefits of fiber optics for underground mine communications. *AFL*, 1–5. https://learn.aflglobal.com/white-papers/fiber-optics-for-underground-mine-communications#main-content
5. Meade, A. (1994). Wagner SAHR braking system. In *Northern Engineering Conference 1994: Engineering Delivers Innovation; Transactions*. Institution of Engineers, Australia. https://search.informit.org/doi/10.3316/informit.324016979413850
6. De Cassia Pedrosa Santos, R., Da Silva, J. M., Junior, W. A., Pinto, C. L., Oliveira, M. M., & Mazzinghy, D. B. (2022). Development of a low-cost device for monitoring ventilation parameters (temperature, humidity, and pressure) in underground environments to increase operational safety using IoT. *Mining, 2*(4), 746–756. https://doi.org/10.3390/mining2040041
7. Shou-Xi, H. U. (2012). Intrinsic safety design of explosion-proof and intrinsic safety type electrical control box for underground mining equipment. *Journal of Mine Automation, 38*(5), 83–86. http://www.gkzdh.cn/en/article/id/8375
8. Cecala, A. B., Organiscak, J. A., Noll, J. D., & Zimmer, J. A. (2016). Comparison of MERV 16 and HEPA filters for cab filtration of underground mining equipment. *Mining Engineering, 68*(8), 50–56. https://doi.org/10.19150/me.6712
9. Jun, Z., Jiguo, W., Qianyi, Z., Ning, W., Chaofan, W., & Lei, W. (2022). Design and workspace analysis of drilling arm of mining anchor drilling robot. *Journal of Physics: Conference Series, 2202*, 1–10. https://doi.org/10.1088/1742-6596/2202/1/012057
10. Nguyen, B. V., Cai, M., & Challagulla, K. (2019). Finite element analysis of the Superbolt under dynamic loading. In *Ground Support 2019: Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, 375–386. https://doi.org/10.36487/acg_rep/1925_25_nguyen
11. Wheatley, G. (2020). Design of a hydraulically controlled conveyor belt clamp for heavy-duty drift belt installation in underground applications: A case study. *Journal of Structural Integrity and Maintenance, 5*(3), 171–182. https://doi.org/10.1080/24705314.2020.1765267
12. D, G., & H, O. (2019). Finite element simulation on tensile creep behaviour of underground support liner. *Machines. Technologies. Materials, 13*(10), 417–420. https://stumejournals.com/journals/mtm/2019/10/417
13. Xu, W., Wan, L., Gao, K., Bu, Y., Xu, M., Ma, S., & Jiang, K. (2023). Analysis of the influence of surrounding rock state on working performance of cutting head in metal mining. *Applied Sciences, 14*(1), 1–17. https://doi.org/10.3390/app14010340
14. Hazegh, M., & Zsaki, A. M. (2012). A framework for automatic modeling of underground excavations and optimizing three- dimensional boundary and finite element meshes derived from them—framework. *International Journal for Numerical and Analytical Methods in Geomechanics, 37*(6), 641–660. https://doi.org/10.1002/nag.1130
15. Zsáki, A. M., & Curran, J. H. (2005). A continuum mechanics-based framework for optimizing boundary and finite element meshes associated with underground excavations—accuracy, efficiency, and applications. *International Journal for Numerical and Analytical Methods in Geomechanics, 29*(13), 1299–1315. https://doi.org/10.1002/nag.460
16. Zhuravkov, M. A., Nikolaitchik, M. A., & Klimkovich, M. M. (2022). Modelling of geomechanical state of the rock mass during the large scale mining of underground space. *Mechanics of Machines, Mechanisms and Materials, 4*(61), 97–104. https://doi.org/10.46864/1995-0470-2022-4-61-97-104
17. Mališ, T., Hrženjak, P., Lazarević, A. J., & Mikulec, M. (2023). Application of the SAP2000 computer programme in the modelling of an underground quarry of dimension stone. *Rudarsko-geološko-naftni Zbornik, 38*(4), 19–25. https://doi.org/10.17794/rgn.2023.4.2
18. Nigam, A., & Jain, S. (2014). Design and analysis of housing foot of a planetary gearbox using

finite element analysis. *International Journal of Research in Manufacturing Technology & Management, 2*(2), 1–5. https://iaeme.com/MasterAdmin/Journal_uploads/IJRMTM/VOLUME_2_ISSUE_2/IJRMTM_02_02_001.pdf

19. Sirota, V. V., Zaitsev, S. V., Churikov, A. S., & Egorkin, V. S. (2024). Protection of mining equipment parts operating in underground mining conditions from biocorrosion. *Sustainable Development of Mountain Territories, 16*(2), 545–557. https://doi.org/10.21177/1998-4502-2024-16-2-545-557
20. Samanta, B. K. (2017). Underground mining project equipment selection model. *International Journal of Computer Trends and Technology, 44*(1), 50–57. https://doi.org/10.14445/22312803/ijctt-v44p110
21. Chehri, A., & Fortier, P. (2020). Autonomous vehicles in underground mines, where we are, where we are going? In *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 1–5. https://doi.org/10.1109/vtc2020-spring48590.2020.9128585
22. Desire, E., Nadeau, S., & Boudreau-Trudel, B. (2015). Design of control panels for underground mining equipment: Why open innovation should be promoted as a sustainable approach to development. *Espace ÉTS*. https://espace2.etsmtl.ca/id/eprint/10473/
23. Grenon, M., Caron, A., Karampinos, E., & Dorion, J. F. (2023). Towards an efficient iPad-based LiDAR structural mapping methodology for underground mines. *All Days*. https://doi.org/10.56952/arma-2023-0741
24. Song, W., Zhang, J., Li, M., Yan, H., Zhou, N., Yao, Y., & Guo, Y. (2022). Underground disposal of coal gangue backfill in China. *Applied Sciences, 12*(23), 1–18. https://doi.org/10.3390/app122312060
25. Carroll Technologies Group. (2021). We make North American industry safer. *Carroll Technologies*. Retrieved November 29, 2024, from https://www.carrolltechnologiesgroup.com/?srsltid=AfmBOorterhMVl21uB1CC6HPJZQQk-SNfVdBEMDlyBsbfUlChAq7HdLPs
26. MineARC Systems. (2020). Advanced chamber tech, safe refuge solutions. Retrieved November 29, 2024, from https://minearc.com/
27. Roan, A. J. (2024). 10 new mining safety technologies emerge. *Metal Tech News*. Retrieved November 29, 2024, from https://www.metaltechnews.com/story/2024/07/17/mining-tech/10-new-mining-safety-technologies-emerge/1847.html
28. Predictive Engineering. (n.d.). FEA consulting services. Retrieved November 29, 2024, from https://www.predictiveengineering.com/consulting/fea-consulting-services
29. Friedman Research Corporation. (n.d.). Friedman Research are experts in finite element analysis, virtual testing, and more. Retrieved November 29, 2024, from https://www.friedmanresearch.com/
30. Acuren. (2023). Finite element analysis and computational mechanics. Retrieved November 29, 2024, from https://www.acuren.com/engineering/materials-engineering/finite-element-analysis-and-computational-mechanics/
31. Finite Engineering Associates 3D, LLC. (2024). Mining equipment design engineers in Kansas City, MO. Retrieved November 29, 2024, from https://www.fea3d.com/industries/mining
32. ProForma Engineering. (2021). Finite element analysis (simulation). Retrieved November 29, 2024, from https://www.proformaengineering.com/finite-element-analysis-simulation/
33. Admin. (2020). The latest innovations in underground mining equipment. *Mining Digital*. Retrieved November 29, 2024, from https://miningdigital.com/digital-mining/latest-innovations-underground-mining-equipment
34. Komatsu. (2021). Underground hard rock mining. Retrieved November 29, 2024, from https://www.komatsu.com/en/industries/underground-hard-rock-mining/
35. Adjiski, V., Despodov, Z., Mirakovski, D., & Serafimovski, D. (2019). System architecture to bring smart personal protective equipment wearables and sensors to transform safety at work in the underground mining industry. *Rudarsko-geološko-naftni Zbornik, 34*(1), 37–44. https://doi.org/10.17794/rgn.2019.1.4
36. Li, C., Gao, Z., Sheng, Z., Wu, W., Xu, D., & Ming, Z. (2020). Key technology simulation of equipment anomaly detection based on image processing in underground mining. In *2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC)*, 145–148. https://doi.org/10.1109/ITOEC49072.2020.9141714
37. Rudakov, M. L., Kolvakh, K. A., & Derkach, I. V. (2020). Assessment of environmental and occupational safety in mining industry during underground coal mining. *Journal of Environmental Management and Tourism (JEMT), 11*(3(43)), 579–588. https://doi.org/10.14505/JEMT.V11.3(43).10
38. Alam, S. M. M., Barua, A., Raihan, A., Alam, M. J., Chakma, R., Mahtab, S. S., & Biswas, C. (2021). Design and implementation of a smart helmet system for underground miner's safety. In *Lecture Notes in Electrical Engineering (Vol. 733, pp. 301–311)*. https://doi.org/10.1007/978-981-33-4909-4_22
39. Sarkar, F., Adhikari, P. K., & Mangal, A. (2021). Development of a hybrid type mine hazard alert system (MHAS) for inhibiting the disastrous incidences due to fire hazards, water inrush and strata failure in underground mines: An

experimental trial. *Journal of the Institution of Engineers (India): Series D, 102*, 39–46. https://doi.org/10.1007/s40033-021-00260-7

40. Fayyaz, B., Shah, U. A., & Zubair, M. (2021). Smart safety helmet for safe coal mining. *Journal of Independent Studies and Research Computing, 19*(1), 12–15. https://doi.org/10.31645/jisrc.21.19.1.8
41. Nikitenko, S. I., Kubrin, S. S., & Malakhov, Y. L. (2022). Safety ensuring in the implementation of new technologies for tunneling and production faces. *Sustainable Development of Mountain Territories, 14*(4), 615–622. https://doi.org/10.21177/1998-4502-2022-14-4-615-622
42. Xu, Q. (2022). Design of accurate intelligent positioning system through UWB technology. In *2022 IEEE 4th International Conference on Civil Aviation Safety and Information Technology (ICCASIT)*, 43, 300–304. https://doi.org/10.1109/iccasit55263.2022.9986850
43. Qian, M., Zhao, K., Li, B., Gong, H., & Seneviratne, A. (2022). Survey of collision avoidance systems for underground mines: Sensing protocols. *Sensors, 22*(19), 1–33. https://doi.org/10.3390/s22197400
44. Miao, L., & Niu, Y. (2022). Coal mine electrical safety management and accident prevention based on neural network and signal processing. *Journal of Computational Methods in Sciences and Engineering, 22*(6), 2257–2266. https://doi.org/10.3233/jcm-226370
45. Chaitanya, A., Rahul, P., Siddhartha, A., & Dholvan, M. (2023). IoT-based mining safety and air QuBlynk system. *Journal of Telecommunication Electronic and Computer Engineering (JTEC), 15*(4), 1–6. https://doi.org/10.54554/jtec.2023.15.04.001
46. Cholke, P., Kulkarni, M., Gangurde, J., Thakare, K., Waware, R., More, S., & Ghuge, A. (2023). IoT empowered helmets: Pioneering safety in the mining sector. *International Journal on Recent and Innovation Trends in Computing and Communication, 11*(10), 1102–1107. https://doi.org/10.17762/ijritcc.v11i10.8630
47. He, S., He, X., Mitri, H., Meng, S., Wu, Q., Ren, T., & Liu, S. (2023). Advances in mining safety theory, technology, and equipment. *Advances in Geo-Energy Research, 10*(2), 71–76. https://doi.org/10.46690/ager.2023.11.01
48. S, M. S., Rahul, K., Kurian, N. S., V, H. V., & M, A. (2023). Smart PPE using LoRaWAN technology. In *2022 International Conference on Inventive Computation Technologies (ICICT)*, 1272–1279. https://doi.org/10.1109/icict57646.2023.10134134
49. Reshotka, V., & Tkalych, I. (2023). Safety and work organization during the assembly of vibrating delivery and loading equipment in the mining industry. *Labour Protection Problems in Ukraine, 39*(3–4), 55–58. https://doi.org/10.36804/nndipbop.39-3-4.2023.55-58
50. Vishwakarma, A., Yash, A., Singh, A., Awasthi, D., & Yadav, R. (2024). IoT mining tracking & worker safety helmet. *International Journal for Research in Applied Science and Engineering Technology (IJRASET), 12*(5), 5310–5321. https://doi.org/10.22214/ijraset.2024.62778
51. Dange, V., Bari, R., Bambal, S., Barde, K., & Bapat, A. (2024). An approach to design a smart mining helmet. In *2024 International Conference on Intelligent Systems for Cybersecurity (ISCS)*, 1–6. https://doi.org/10.1109/iscs61804.2024.10581270
52. Pääkkönen, P., Horsmanheimo, S., Pakkala, D., Tuomimäki, L., & Backman, J. (2024). Reference architecture design and evaluation for digitalization of underground mining. *Internet of Things, 26*, 1–28. https://doi.org/10.1016/j.iot.2024.101238
53. Klyuev, R. V., & Gavrilova, A. A. (2024). Ensuring occupational safety of miners by improving power grids for underground ore mining. *Occupational Safety in Industry, 6*, 72–78. https://doi.org/10.24000/0409-2961-2024-6-72-78
54. Zhang, W. (2024). Research on the application of intelligent technology in mining safety monitoring. *Highlights in Science, Engineering and Technology, 106*, 565–569. https://doi.org/10.54097/ct50qe50
55. He, S., Zhao, D., Gao, N., Nie, W., Tong, L., & Wang, C. (2024). Progress and prospects of mining disaster prevention techniques and equipment. *Advances in Geo-Energy Research, 13*(3), 166–168. https://doi.org/10.46690/ager.2024.09.02
56. Nguyen, B., Cai, M., & Challagulla, K. (2019). Finite element analysis of the Superbolt under dynamic loading. In *Ground Support 2019: Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, 375–386. https://doi.org/10.36487/acg_rep/1925_25_nguyen
57. Rosero, D. G., & Zsaki, A. M. (2020). Finite element mesh improvement using an a priori local p-refinement for stress analysis of underground excavations. *Cogent Engineering, 7*(1), 1–24. https://doi.org/10.1080/23311916.2020.1769287
58. Ibrahim, R., Mirhosseini, F., & Zsáki, A. M. (2020). An automated a priori knowledge-based p-adaptive three-dimensional finite element mesh improvement method for stress analysis of underground excavations with prismatic cross-sections. *Geomechanics and Geoengineering, 17*(1), 141–154. https://doi.org/10.1080/17486025.2020.1716081
59. Wang, L., He, C., Cui, S., & Wang, F. (2021). Numerical simulation of surface movement and deformation caused by underground mining

with complex stratigraphic boundary. *Advances in Civil Engineering, 2021*, 1–14. https://doi.org/10.1155/2021/9967071

60. Dmitriev, S., Semenova, I., & Shestov, A. (2021). The numerical modeling of heterogeneities by the finite element method in 3D setting. *IOP Conference Series: Earth and Environmental Science, 833*, 1–8. https://doi.org/10.1088/1755-1315/833/1/012094
61. Rotkegel, M., Korol, J., & Sobczak, D. (2021). Analysis of the possibilities of using composite structural C-channels as lining for an arch support in mining excavation. *Archives of Mining Sciences, 66*(3), 437–455. https://doi.org/10.24425/ams.2021.138599
62. Berdoudi, S., Morsli, M. A. R., Mekti, Z., & Benselhoub, A. (2022). Numerical study on deformation around underground mining structures (Algeria). *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6*, 47–51. https://doi.org/10.33271/nvngu/2022-6/047
63. Batsaikhan, U., Hashikawa, H., Shimada, H., Sasaoka, T., & Hamanaka, A. (2022). Numerical study on the applicability of the pipe-jacking method for the main gate of an underground coal mining in weak rock mass. *Applied Sciences, 12*(3), 1–13. https://doi.org/10.3390/app12031719
64. Hu, S., Su, C., Zhang, H., Cao, E., Yuan, R., & Xu, Y. (2022). Analysis of structural characteristics of underground cavern group by simulating all cavern excavation. *Advances in Civil Engineering, 2022*, 1–16. https://doi.org/10.1155/2022/4610557
65. Bernuzzi, C., Bertinotti, E., Frau, M., & Simoncelli, M. (2022). Derrick crane robustness scenarios. *Istrazivanja i Projektovanja Za Privredu, 20*(2), 523–536. https://doi.org/10.5937/jaes0-34255
66. Guo, Y., Qian, Z.-K., & Huang, H.-Z. (2023). Transient dynamic finite element analysis and reliability assessment of mining excavators gear transmission system. *IET Conference Proceedings, 2023*(9), 747–751. https://doi.org/10.1049/icp.2023.1724
67. Dönmez, H. O., & Tunçdemir, H. (2023). Estimating support pressure with finite element and convergence-confinement method for different rock masses. *Bilimsel Madencilik Dergisi, 62*(3), 99–108. https://doi.org/10.30797/madencilik.1356042
68. Ilyasov, B. T., Kulsaitov, R. V., Neugomonov, S. S., & Soluyanov, N. O. (2023). Stability estimation in underground opening with support system using finite–discrete element method-based modeling. *Gornyi Zhurnal, 1*, 118–123. https://doi.org/10.17580/gzh.2023.01.20
69. Liang, J., Tian, M., & Huo, P. (2023). Finite element simulation study on cutting coal and rock by cutting head of roadheader. *Journal of Physics: Conference Series, 2591*, 1–9. https://doi.org/10.1088/1742-6596/2591/1/012016
70. Diulin, D. A., Prushak, V. Y., & Gegedesh, M. G. (2023). Analysis of the stress-strain state of problematic sections of the shaft of the mine using computer simulation. *Doklady of the National Academy of Sciences of Belarus, 67*(4), 322–330. https://doi.org/10.29235/1561-8323-2023-67-4-322-330
71. Mai, L., & Li, H. (2024). Finite–discrete element method simulation study on development of water-conducting fractures in fault-bearing roof under repeated mining of extra-thick coal seams. *Sustainability, 16*(12), 1–24. https://doi.org/10.3390/su16125177
72. Downey, N. (2024). Finite element modeling of infrasound resonance in an underground tunnel structure. *The Journal of the Acoustical Society of America, 155*(3_Supplement), A71. https://doi.org/10.1121/10.0026841
73. Wu, J., Zhuo, L., Pei, J., Li, Y., Xie, H., Wu, J., & Liu, H. (2024). Modularized and parametric modeling technology for finite element simulations of underground engineering under complicated geological conditions. *Computer Modeling in Engineering & Sciences, 140*(1), 621–645. https://doi.org/10.32604/cmes.2024.046398
74. Wang, W., Gao, X., Ding, Z., Ma, H., Ren, J., & Liu, Z. (2024). Fracture characteristic and support effect around deep lined tunnels using CGP-FDEM simulation and field investigation analysis. *Engineering Analysis with Boundary Elements, 161*, 29–47. https://doi.org/10.1016/j.enganabound.2024.01.012
75. Jialin, F. (2024). Structural optimization of 60T electric mining vehicle frame: Finite element simulation model and analysis. *Journal of Engineering Research and Reports, 26*(5), 262–272. https://doi.org/10.9734/jerr/2024/v26i51152
76. Sun, X., Sui, Y., Zheng, Y., Wang, L., & Zhu, H. (2024). Finite element analysis and optimization design of large vibrating screen based on equivalent static load method. *Engineering Research Express, 6*, 1–16. https://doi.org/10.1088/2631-8695/ad3520
77. Xue, H., Gao, Y., Zhang, X., Tian, X., Wang, H., & Yuan, D. (2019). Directional blasting fracturing technology for the stability control of key strata in deep thick coal mining. *Energies, 12*(24), 1–19. https://doi.org/10.3390/en12244665
78. Sokolov, I. V., Antipin, Y. G., Gobov, N. V., & Nikitin, I. V. (2020). Experience in the development of innovative underground geotechnologies for mining of ore deposits. *Mining Informational and Analytical Bulletin, 3–1*, 338–350. https://doi.org/10.25018/0236-1493-2020-31-0-338-350
79. Kaplunov, D. R., Radchenko, D., Fedotenko, V. S., & Lavenkov, V. S. (2020). Assessment of efficiency of transition to a new wave of technological innovation in underground mining during

its continuous progression to deeper levels. *Mining Informational and Analytical Bulletin, 12*, 5–15. https://doi.org/10.25018/0236-1493-2020-12-0-5-15

80. Zhao, H., Ren, T., & Remennikov, A. (2021). Hybrid roof standing supports in underground mining: Concept and behaviour. *Geomechanics and Geoengineering, 17*(6), 1707–1721. https://doi.org/10.1080/17486025.2021.1961025
81. Zhang, Z., Chen, H., Li, D., & Zhang, Z. (2021). Stability control of the equipment recovery passage in a fully mechanized longwall mining: Case study. *Geotechnical and Geological Engineering, 39*(2), 799–813. https://doi.org/10.1007/s10706-020-01522-z
82. Zhao, C., Sun, X., Zhang, Y., Zhang, S., & Zhang, J. (2021). Optimization analysis of NPR cable support considering bearing structure in the NSF condition of deep shaft based on Daqiang coal mine. *Arabian Journal of Geosciences, 14*, 1942. https://doi.org/10.1007/s12517-021-08274-x
83. Zhang, B., & Zhao, H. (2022). An innovative tubular standing support incorporating PVC and FRP composites: Laboratory tests. *Geotechnical and Geological Engineering, 40*, 249–258. https://doi.org/10.1007/s10706-021-01895-9
84. Wojtas, M., Kazubiński, D., & Pilarz, K. (2022). An innovative crossing powered support of the HENNLICH-20/43-CH type. *Mining - Informatics, Automation and Electrical Engineering, 2*(550), 7–11. https://doi.org/10.7494/miag.2022.2.550.7
85. Oryngozhin, Y. S., Bitimbaev, M. Z., Milėtenko, N. A., & Alisheva, Z. N. (2022). An innovative way of underground mining. *Eurasian Mining, 1*, 38–40. https://doi.org/10.17580/em.2022.01.07
86. András, J., Kovács, J., & András, E. (2022). New trends in mining equipment design. *Műszaki Tudományos Közlemények, 16*, 10–14. https://doi.org/10.33894/mtk-2022.16.03
87. Florea, V. A., Toderaş, M., & Itu, R.-B. (2023). Assessment possibilities of the quality of mining equipment and of the parts subjected to intense wear. *Applied Sciences, 13*(6), 1–22. https://doi.org/10.3390/app13063740
88. Liu, Y., Zhao, Y., Wang, K., Li, G., & Ge, Z. (2023). Protection technique of support system for dynamic disaster in deep underground engineering: A case study. *Sustainability, 15*(9), 1–13. https://doi.org/10.3390/su15097165
89. Aboelezz, A., Wetz, D., Lehr, J., Roghanchi, P., & Hassanalian, M. (2023). Intrinsically safe drone propulsion system for underground coal mining applications: Computational and experimental studies. *Drones, 7*(1), 1–23. https://doi.org/10.3390/drones7010044
90. Mishra, A. K. (2023). Mass production technologies for underground coal mining in India: Status, challenges, and prospects. In *Springer proceedings in earth and environmental sciences* (pp. 53–72). https://doi.org/10.1007/978-3-031-46966-4_5
91. L. A., P., L. M., A., & K. M. V. (2023). Improvement of thermal-hydraulic efficiency of mining power equipment through the application of porous freon steam generators with high heat conductivity. *Geo-Technical Mechanics, 164*, 45–52. https://doi.org/10.15407/geotm2023.164.045
92. Wang, S.-F., Wu, Y.-M., & Shi, X.-L. (2024). Non-explosive mechanized and intelligent mining/heading in underground mine. *Transactions of Nonferrous Metals Society of China, 34*(1), 265–282. https://doi.org/10.1016/s1003-6326(23)66397-6
93. Nikitenko, S., Nikitenko, M., Kizilov, S., & Khudonogov, D. (2024). Robotic walking module as underground mining safety device. *E3S Web of Conferences, 498*, 1–8. https://doi.org/10.1051/e3sconf/202449803014
94. Shalomeev, V., Brykov, M., Sheiko, S., Matiukhin, A., Yepishkin, O., Kulabnieva, O., & Tytov, O. (2024). The durability increasing of high-wear cast parts of mining and processing equipment. *IOP Conference Series: Earth and Environmental Science, 1348*, 1–13. https://doi.org/10.1088/1755-1315/1348/1/012054
95. Herasymenko, A., Shyrin, A., Inyutkin, I., & Dyachkov, P. (2024). Justification of the area of efficient use of mining transportation equipment for quick conduct of preparatory works. *Collection of Research Papers of the National Mining University, 76*, 20–32. https://doi.org/10.33271/crpnmu/76.020
96. Xiao, Z., Zhang, Y., Hu, S., Zhang, F., Jiang, J., Wang, H., & Li, J. (2024). Structural design and analysis of large-diameter D30 conical polycrystal diamond compact (PDC) teeth under engineering rotary mining conditions. *Materials, 17*(2), 1–14. https://doi.org/10.3390/ma17020477
97. Liu, X., Zhang, X., Wang, L., Qu, F., Shao, A., Zhao, L., Wang, H., Yue, X., Li, Y., Yan, W., & He, J. (2024). Research progress and prospects of intelligent technology in underground mining of hard rock mines. *Green and Smart Mining Engineering, 1*(1), 12–26. https://doi.org/10.1016/j.gsme.2024.03.007

not endorse any products, methods, or claims described in the content.

Author Bio:

1. Parankush Koul is a researcher in the Department of Mechanical and Aerospace Engineering at the Illinois Institute of Technology in Chicago, Illinois. Committed to advancing the fields of aerospace and mechanical engineering, they contribute to academic research and innovation within the institution. Their work focuses on developing technical solutions to complex engineering challenges while collaborating with peers in the scientific community.