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Safety Challenges in Battery Swapping Operations of Electric Underground Mining Trucks

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Abstract: Recently, the global landscape of public transportation has witnessed a transformative shift towards sustainable and efficient modes of mobility, with particular emphasis on electric vehicles (EVs) and their integration into industrial applications. The mining industry, including the underground mining of the mineral resources sector is following this trend. However, underground mines are critical environments and the adoption of EVs needs to be carefully analysed. This study investigates the associated hazards and risks of adopting EVs (such as dumpers and loaders) focusing on the swapping battery operations. First, current hazards related to battery swapping are identified—21 in total, occurring in 25 instances. After, risks are assessed and associated with specific hazards. Finally, possible measures and solutions for reducing the impacts of these risks on the performance of the EVs are offered.

Keywords: underground mines; electric vehicles; safety; risk analysis

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1. Introduction

Electric vehicles (EVs) are transforming various sectors by offering more sustainable alternatives to conventional machines with internal combustion (IC) engines. In recent years, the global landscape of public transportation has witnessed a transformative shift towards sustainable and efficient modes of mobility, with particular emphasis on battery electric vehicles (BEVs) and their integration into industrial applications [1]. In particular, the underground mining industry is starting to introduce Li-ion battery-powered electric vehicles, mainly for loading and hauling [2]. These innovations are crucial for enhancing operational efficiency while reducing environmental impacts in the extraction of mineral resources [3].

Underground mining typically involves challenging conditions, including limited space and a complex network of roadways. Consequently, the choice of vehicles used in this environment is paramount [4,5]. Electric underground trucks, designed specifically for underground mines, address several significant concerns. Firstly, they mitigate the emissions of harmful gases in confined spaces, contributing to improved air quality and the health of miners. By relying on Li-ion batteries instead of IC engines, these trucks significantly decrease noise pollution, enhancing the working environment [6].

Incorporating battery-powered electric trucks in underground mining operations also aligns with global trends toward sustainability of raw materials industry and energy efficiency [7]. As mineral resources are increasingly scrutinised for their environmental impact, mining companies are under pressure to invest in cleaner technologies. Electric trucks not only reduce carbon footprints but also lower operating costs due to lesser maintenance requirements and lower energy expenses compared to traditional IC engine vehicles [6].

Furthermore, advancements in battery technology, including quicker charging times and extended range, have made battery-powered electric underground trucks more viable for day-to-day mining operations [8]. Many manufacturers are actively developing specialised trucks that can operate efficiently in the steep gradients and unique terrain conditions found underground [9].

Integrating digital solutions, such as telemetry and automated systems [10], with electric trucks amplifies their effectiveness and safety, such as improved air quality and ventilation demands [11,12]. As the industry continues to evolve, battery-powered electric underground trucks represent a promising pathway to achieving both operational excellence and environmental stewardship in the extraction of vital mineral resources [13]. Overall, the adoption of electric vehicles in underground mining represents a significant innovation that addresses environmental concerns, improves safety and efficiency, and aligns with evolving regulatory requirements in the mining industry. However, the transition to battery-powered vehicles brings some challenges that need to be carefully investigated. Research presented in this paper is related to health and safety challenges during the swapping and charging of batteries in the conditions of underground mining of mineral resources.

2. Current Battery Swapping Methods for Underground Electric-Powered Trucks

Key performance indicators in modern production industries, including underground mining machines, are productivity, efficiency, and operational costs [14]. More recently, these indicators have included low environmental impact, which is becoming more and more relevant [15]. Battery-powered machines are proving to have lower environmental impact and operational costs, due to the elimination of exhaust emissions, lower price of electricity in comparison to diesel fuel and similar. In comparison to IC machines, trade-offs are made in the areas of productivity and efficiency, but the gap is closing with the introduction of Li-ion batteries of higher energy density and shorter charging times [16–18].

During the previous 7-8 years, the original equipment manufacturers (OEMs) started to supply the battery-powered machines to the underground mines at numerous locations. Recent research on battery-powered machines (BPMs) operating or on trial in underground mines, as published by Hooli and Halim [19], indicates that underground BPMs are present on every continent and are supplied by several companies. The most common machines used in underground mining are load–haul–dump machines (LHDs) for loading and trucks for transport, which are almost exclusively supplied by Company 1 and Company 2. For this reason, these two OEMs are most frequently mentioned among the underground BPM fleet. Surprisingly, there are only two instances referring to Caterpillar, and both are for trial purposes.

However, LHDs and trucks are still limited by the battery capacity, i.e., with the battery's stored energy available to do the work. This means that BPMs are required to recharge the battery once or several times during a single shift. Recharging the battery is a time-consuming process, measured in hours. Having this in mind, it is not reasonable to pull the truck or LHD out of operation for the period of battery charging. Two major OEMs

(Company 1 and Company 2 accepted the solution of replacing discharged batteries with charged ones—so-called "battery swapping". With this approach, BPM is immediately available for operation once the charged battery is installed on the machine. Also, this means that neither the BPM nor the discharged battery requires transport to the surface. On the other hand, it should be noted that this approach implies two or more batteries dedicated to one BPM (one installed on the machine—discharging, and one or more in charging stations).

It should be mentioned that the concept of battery swapping was originally introduced for electric vehicles in public transport. Such a concept was somewhat successful for passenger cars, particularly small EVs, where some solutions were developed for manually swapping individual modules of the car's battery (EV's battery consists of several modules, which are built out of cells), meaning that the predominant solution for these vehicles is point charging.

On the other hand, successful technical solutions for battery swapping are available for the trucks in public transport. This is documented in a study on battery swapping for heavy-duty vehicles, developed by the Swedish National Road and Transport Research Institute (VTI) in 2024 [20]. This study indicates that the advanced solutions are available from Chinese manufacturers, who are currently supplying the third generation of electric trucks with a battery swapping option. Several OEMs have developed a solution in which swapping stations function as pass-through facilities, constructed on the surface area sufficient for unrestricted access and egress and with an unhindered line of sight.

Regarding Occupational Health and Safety (OH&S), this study provides a list of applied Chinese laws and regulations and concludes that European countries lag in this technology, both in terms of technical capabilities and administration (legislation and standardisation). One of the outtakes is that battery swapping for heavy-duty vehicles in public transport is considered an innovative business model for logistics companies. However, this study does not provide any insight into battery swapping for industrial and off-road heavy-duty electric vehicles.

Nevertheless, this technology is developing rapidly, with around 400 battery swapping stations operated by several companies across China as of late 2023. No OH&S data on incidents are available in this study.

With this in mind and underground mining conditions, Company 1 and Company 2 developed a solution for battery swapping in a dedicated single-entry charging chamber. The number and locations of the charging chambers in the mine are determined during the design stage. The size of the chamber will be sufficient to accommodate charging equipment and a specific number of batteries. However, Company 1 and Company 2 have different methods for removing the discharged battery from the BPM and installing the charged one.

Company 1's charging station comprises charging equipment installed in the previously mentioned chamber, as well as an overhead crane which is used for battery handling. The crane supports are four steel beams forming the crane's operating area in a rectangular shape. Incorporating the crane into the charging station is a reasonable approach, since the mass of the battery pack for the underground trucks is over 5 tons. This OEM offers two options to arrange the charging stations. In the first option, BPM is parked in the roadway next to the chamber with the battery within the operating area of the overhead crane. The second option implies parking the BPM inside the chamber, also within the operating area of the crane, thus avoiding traffic blockage in front of the chamber. The described options are shown in Figures 1 and 2.

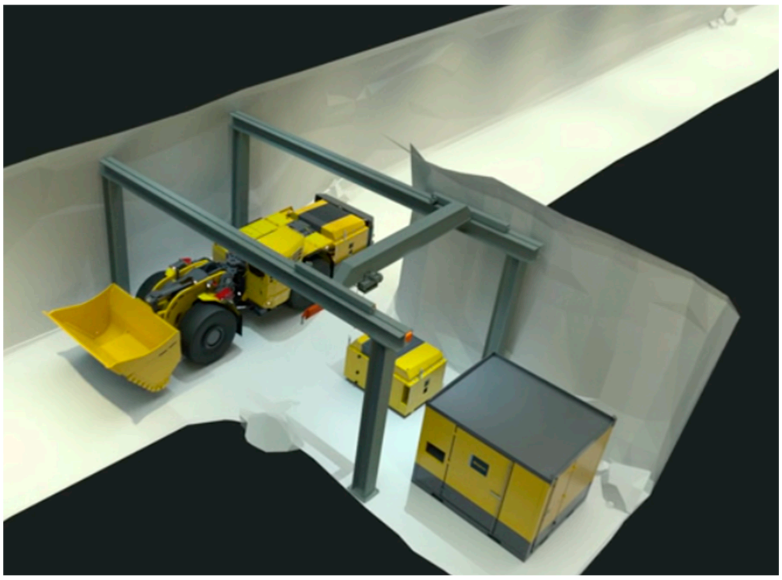

Figure 1. Battery swapping in front of the charging station (Company 1).

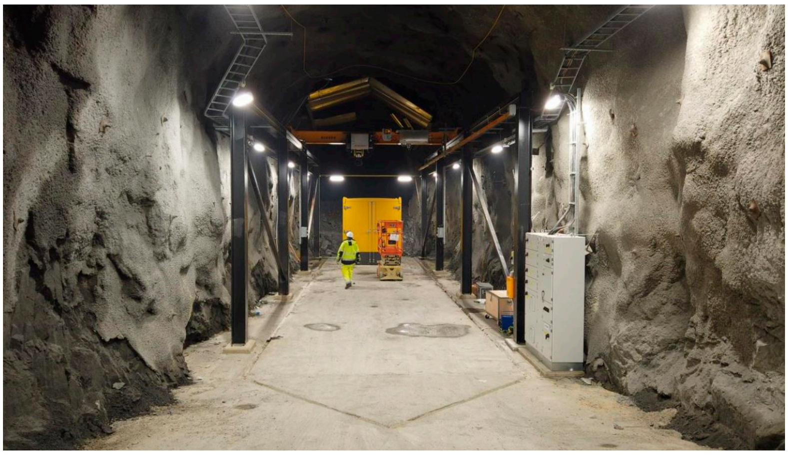

Figure 2. Battery swapping inside the charging station (Company 1).

Regardless of the option, the procedure comprises of following steps:

- Parking the machine;
- Disconnecting the charged battery from the charger;
- Disconnecting the battery on the machine;
- Removing the discharged battery from the machine with the crane and laying it down in the chamber;
- Lifting the charged battery and placing it on the machine;
- Connecting the charged battery on the machine;
- Connecting the discharged battery to the charger;
- Driving the machine from the charging station.

As can be seen, this procedure is straightforward and it does not require physical effort from the operator. Information provided by OEM is not clear on the required personnel for such a procedure, meaning that it is feasible for the truck operator to perform battery swapping without help, including operating the crane.

Major OEM, Company 2, also uses a dedicated area for swapping and charging the batteries (charging station). It also took a different approach to battery swapping by equipping the machine with a mechanism for lowering discharged and lifting the charged battery (Figure 3), thus eliminating the additional external infrastructure (such as the crane).

Also, this mechanism eliminates manual battery connecting and disconnecting on the machine. Specific for this approach is that once the battery is lowered, the BPM loses its main power supply, and it can operate for a limited time and on very short distances on an auxiliary battery. The purpose of the auxiliary battery is to enable manoeuvering the machine from the lowered discharged battery to the charged one and to lift it onto the machine, which is all done within the charging station. This implies that such a charging station must be larger in comparison to one equipped with a crane, to enable moving the BPM inside the station.

Figure 3. Lowered LHD battery and visible hooks on the machine (Company 2).

The procedure for battery swapping in this case comprises of the following steps:

- Arrival and parking of the BPM in the charging station;
- Disconnecting the charged battery from the charger;
- Moving the machine to the location for the lowering of the discharged battery;
- Lowering of discharged battery;
- Moving and manoeuvring the BPM to the charged battery;
- Hooking and lifting the battery onto the machine;
- Parking the machine;
- Connecting the discharged battery to the charger;
- Driving the machine from the charging station.

As in the previous case, this procedure is effortless, and it can be performed by the BPM operator. However, the OEM is unclear on the required personnel for the charging station.

Considering the above, battery swapping shall be a common procedure in every underground mine which operates battery-powered machines. This procedure can be performed several times during the shift, depending on the routes of the trucks, battery capacity, LHD's bucket volume, road conditions and other factors. One of the mentioned OEMs suggests that 6 min is required for the swapping procedure.

Battery-powered machines are a fairly new technology in the underground mining industry, and it is becoming more and more common. Therefore, there is a necessity to identify the hazards related to the application of such machines in underground mining. However, battery swapping is an activity typical for BPM, and it is very frequent, meaning that it will occur numerous times during the day. Further on in this study, we will focus on the hazards related to battery swapping.

3. Identification of Hazards and Risk Assessment During Battery Swapping

Risk assessment is a fundamental process in OH&S that systematically identifies hazards, evaluates the risks they pose, and, when necessary, provides measures for risk reduction. This process involves risk analysis of identified hazards associated with various tasks, assessing their probability and consequences within an established acceptance criteria framework. A flowchart of this process is shown in Figure 4.

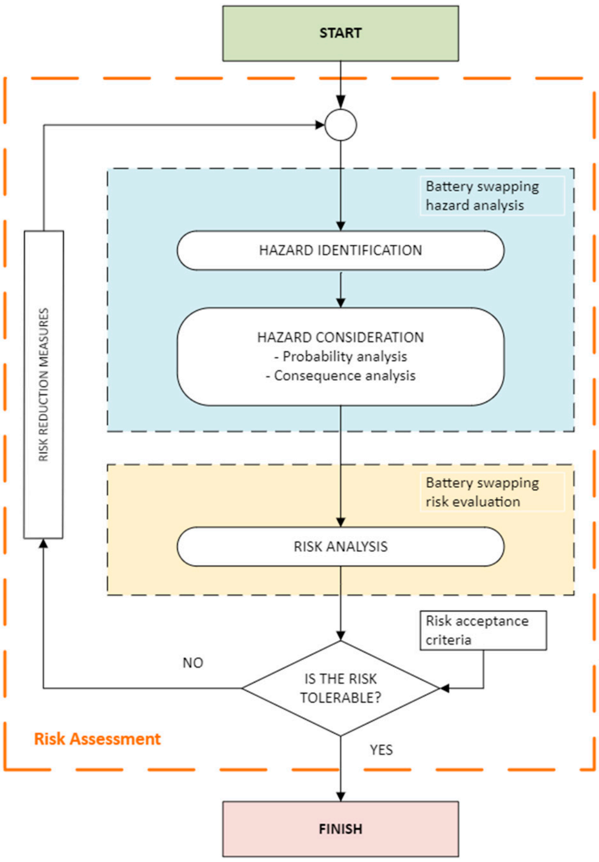

Figure 4. Scheme of risk assessment procedure.

The risk assessment process described in this section will follow the sequence shown in the figure above. The first step is hazard identification, which is performed according to standard safety practices and available information [21–24], as well as during several rounds of sessions with safety experts and OEM personnel.

In the next step, the probability of a hazard occurring is assessed by the frequency of personnel and equipment exposure to specific hazards. Similarly, consequences are evaluated according to hazard exposure scenarios. Probabilities and consequences are also the topic of discussion rounds with safety experts and OEM representatives.

Finally, the risk level is assessed with a 5 by 5 matrix according to probability and consequences.

The presented approach has inherent subjectivity, since this is a new technology in underground mining conditions and due to the lack of safety-related metrics.

So far, it is understood that there are two systems for battery swapping available from the major manufacturers. Both systems are located in single-entry chambers. One utilises an overhead crane for manipulating the batteries (Company 1), while the other features a vehicle-based system for the same purpose (Company 2). Both companies envisaged one worker for completing the task of battery swap—a machine operator, but it is unclear if there are additional workers in the charging station.

Bearing in mind the described procedures for battery swapping, a total of 21 hazards are identified, occurring in 25 instances (some hazards are occurring in separate circumstances). These are listed below.

1. Crushing/Impact—the risk of injury by crushing the operator by fixed and moving object (battery).
    - This hazard occurs during the battery handling—load lifted with the overhead crane. The estimated probability rank of this hazard is 2, and the consequence rank is 5;
    - The same hazard occurs during machine movement in situations when other people are present in the charging station. The estimated probability rank of this hazard is 3, and the consequence rank is 5;
2. Moving equipment—risk of equipment damage by moving objects;
    - Hazard similar to the previous one, but in regard to the equipment and assets present at the site. The estimated probability rank of this hazard is 2, and the consequence rank is 3;
3. Pinch points—the risk of pinching the part of the human body between two objects.
    - Pinching hazard is present during connecting and disconnecting the power supply cables to the battery. The estimated probability rank of this hazard is 2, and the consequence rank is 2;
    - Pinching can occur during the suspended load handling and fitting the slings and ropes to the load (battery). The estimated probability rank of this hazard is 2, and the consequence rank is 3;
4. Static stability—risk by disrupting the static balance (equilibrium) of forces by adding or removing the weight;
    - Adding and removing the weight (battery) impacts the static stability of a battery-powered machine by moving the machine's centre of gravity. The estimated probability rank of this hazard is 2, and the consequence rank is 5;
5. Dynamic stability—the impact of dynamic forces and velocity on the system;
    - Manipulating the battery with an overhead crane generates dynamic forces in lifting ropes/chains (swinging) and the load-bearing structure. The estimated probability rank of this hazard is 3, and the consequence rank is 3;
6. Mechanical strength—the strength of all load-bearing components;
    - Load-bearing components, such as steel beams of the overhead crane and hooks for lifting/lowering the battery, must have sufficient mechanical strength for expected loads during the battery handling. The estimated probability rank of this hazard is 1, and the consequence rank is 4;
7. Roll over—risk of tipping;
    - The hazard of battery tipping occurs during battery handling with an overhead crane (lifting and lowering). The estimated probability rank of this hazard is 2, and the consequence rank is 3;
8. Wearing and Scraping—risk of equipment wearing;
    - Frequent connecting and disconnecting of power supply cables to the battery creates the hazard of the cable's insulation wear and tear. The estimated probability rank of this hazard is 1, and the consequence rank is 3;

9. Fall at level—tripping hazard for the operator;
   - A tripping hazard at the level is present during the suspended load handling when the attention of the operator is focused on the suspended battery. Additional obstacles (cables lying on the ground) contribute to the hazard. The estimated probability rank of this hazard is 3, and the consequence rank is 3;
10. Fall from height—the risk of falling while working on the height;
    - Some activities during battery swap are performed at height (connecting and disconnecting the battery on the machine, crane inspection), and such situations represent the falling from height hazard. The estimated probability rank of this hazard is 3, and the consequence rank is 4;
11. Falling object—the risk of an object falling from a height;
    - A falling battery suspended on the crane represents a hazard for the operator and other equipment and assets on the site. The estimated probability rank of this hazard is 1, and the consequence rank is 5;
    - Falling of the battery from the lifting and lowering mechanism due to the failure of the mechanism or inappropriate battery hooking. The estimated probability rank of this hazard is 1, and the consequence rank is 5;
12. Roll away—the risk of uncontrollable machine movement;
    - This hazard occurs when parking the machine on a sloped surface. The estimated probability rank of this hazard is 3, and the consequence rank is 5;
13. Confined space—the risk of performing the tasks in small and enclosed areas;
    - This hazard is somewhat difficult to describe but it is common in underground mining. All tasks to be performed must be planned with limitations generated by this hazard (for example, the charging cables should not be longer than necessary since it would contribute to the risk—tripping, cable wear, generating larger heat loads, and similar). The estimated probability rank of this hazard is 2, and the consequence rank is 1;
    - A specific confined space hazard, which is not directly related to battery swapping, is a completely discharged battery. A battery-powered machine with a completely discharged battery is blocking the roadway for other traffic, thus disrupting the regular operations in the mine. Removing such machines would include options such as towing, mobile chargers and similar. The estimated probability rank of this hazard is 2, and the consequence rank is 1;
14. Pedestrians—the risk of injury to personnel in case of their presence;
    - This hazard is related to the presence of other personnel at the site, not directly related to the battery swapping. The presence of personnel is increasing the level of hazard due to the increased possibility of risks occurring described in this list. The estimated probability rank of this hazard is 3, and the consequence rank is 4;
15. Remote activities/Isolation—tasks performed on remote sites and in isolation;
    - As said above, OEMs are suggesting that battery swapping can be performed solely by the operator of BPM. Working in isolation is a relevant hazard, especially in the case of an incident when an injured operator requires medical attention. The estimated probability rank of this hazard is 2, and the consequence rank is 5;

16. Ambient heat/Heat stress/Radiant heat—heat emitted from the equipment;
    - The battery charging process is closely related to the heat emission. Considering the size of the charging stations, this hazard may become relevant both regarding legally regulated temperatures for the human working environment and the equipment's operational temperature ranges, which is of high relevance for the lithium-ion batteries. The estimated probability rank of this hazard is 4, and the consequence rank is 2;
17. Ventilation—the requirement of providing a sufficient amount of fresh air and to create acceptable temperature at the work site;
    - This is closely related to the previous hazard. Supply of fresh air is not seen as a major hazard, since there is no air consumption during the battery charging process. However, ventilation may be influenced by the requirement to secure specific room temperatures inside the charging station due to numerous heat emission sources. In some cases, air conditioning (cooling) may be required to create acceptable working conditions. The estimated probability rank of this hazard is 3, and the consequence rank is 1;
18. Contact—contact with hot or cold surface;
    - In general, no sizable items with high or low temperatures will be present inside the charging station. However, specific smaller components such as connecting sock pins, components of the charger or components of air-cooling equipment (if used) may be at temperatures which could cause an injury. The estimated probability rank of this hazard is 2, and the consequence rank is 1;
19. Pushing and pulling—the risk of injury during manual work;
    - This risk is related to handling the battery as a load (fixing the ropes/chains/slings to the battery) and handling the power supply cable for connecting and disconnecting. Both activities require some level of manual work, during which injury can occur. The estimated probability rank of this hazard is 2, and the consequence rank is 1;
20. Short circuit—the hazard from the unintended current path;
    - This is usually related to the abnormal electrical connection between two or more conductors, where batteries with low internal resistance are capable of generating dangerously high currents in case of short circuits. Short circuits in charging stations can occur due to equipment malfunctions and environmental factors (humidity, dust, debris, etc.). It can result in major to catastrophic consequences to humans and equipment. The estimated probability rank of this hazard is 3, and the consequence rank is 4;
21. Arcing (arc flash)—the electrical hazard of current flow through the air;
    - Current flow through the air can occur between conductors or from one conductor to a grounded object due to malfunctioning insulation or an accidental short circuit. The consequences of this hazard can be very serious for workers and can also damage the equipment. The estimated probability rank of this hazard is 3, and the consequence rank is 5;

Risks associated with the above hazards are assessed with a well-known 5 $\times$ 5 matrix [25]. This matrix is visually represented by a table with five categories of probability (the likelihood of a specific risk occurring) and five categories of consequences (the impact of the risk once it occurs).

Categories of probability with associated values (in brackets) are:

- Rare (1)—highly low probability of hazard, negligible;
- Unlikely (2)—low probability of hazard to occur, not negligible;
- Possible (3)—moderate probability of hazard to occur. Such a hazard is not uncommon, but also is not frequent;
- Likely (4)—a high probability of hazard to occur, occasionally, or repeatedly;
- Almost certain (5)—the highest level of hazard to occur, frequently.

It is expected that battery swapping (replacing the discharged battery with a charged one) will take place once to twice per shift, meaning that identified hazards will occur frequently. Some activities will be performed several times during the battery swapping (connecting and disconnecting cables), and others are continuously present (confined space and ambient heat).

It should be noted that all of the hazards listed above can be grouped as Occupational Health and Safety (OH&S) hazards or as Economic hazards. A Occupational Health and Safety hazard is associated with the personnel, while an Economic hazard is associated with the assets (fixed and mobile), operational effectiveness, impact on production volumes, and similar. Therefore, a common scale of consequences will be more detailed. Categories of consequences with associated values (in brackets) are:

- Minor (1)—OH&S hazard: Reversible health effects of little concern. Economic hazard: Minimal consequence to the asset (easy to repair) without impact on the operations;
- Medium (2)—OH&S hazard: Reversible health effects of concern that would typically result in medical treatment. Economic hazard: Little damage to the asset, reparable, slight delay in operations;
- Serious (3)—OH&S hazard: Severe, reversible health effects of concern that would typically result in a lost time illness. Economic hazard: Significant damage to the asset, replacement required, delays at the scale of one to two shifts, and some impact on production volumes;
- Major (4)—OH&S hazard: Irreversible health effects or disabling illness. Economic hazard: Major damage to the asset, delays at the scale of days, and impact on production volumes;
- Catastrophic (5)—OH&S hazard: Fatality or serious disabling illness to multiple people. Economic hazard: Asset replacement required with associated delays, impact on production volumes.

The risk is then calculated by multiplying the values of probabilities and consequences. For this purpose, extra weights are associated with the major and catastrophic consequences, as given in Table 1.

Table 1. Consequence/likelihood matrix for battery swapping in underground mine.

		Probability				
		1	**2**	**3**	**4**	**5**
Consequence	5	Medium	High	Critical	Critical	Critical
	4	Medium	High	High	Critical	Critical
	3	Low	Medium	High	Critical	Critical
	2	Low	Low	Medium	High	Critical
	1	Low	Low	Medium	High	High

As can be seen, due to the associated weights, the priority rating of the matrix is not symmetrical. We accepted four level priority ratings which can be linked to the risk management response. These ratings (risks) are color-coded, with the following explanations:

- Critical (in red)—Risk which is significantly higher than the acceptance level and requires immediate attention;
- High (in orange)—Risk which is higher than the acceptance level and requires proactive management;
- Medium (in yellow)—Risk on the acceptance level and requires active monitoring. Additional measures can be implemented to further reduce the risk;
- Low (in green)—Risk on the acceptance level.

Finally, the results of risk assessment for identified hazards are presented in Table 2, with recommended measures for risk reduction, when necessary.

Table 2. Risk assessment and suggested measures for reducing the risk.

Hazard Number	Probability	Consequence	Risk (Priority Rating)	Measure
1b	3	5	Critical	Restrict access to the site.
4	2	5	Critical	Prevent unexpected movement of the machine (parking brake, wheel blocks, etc.).
12	3	5	Critical	Prevent unexpected movement of the machine (parking brake, wheel blocks, etc.). Proper training.
20	3	4	Critical	Proper training. Adhering procedures.
21	3	5	Critical	Regular inspection of installation and insulation. Proper training.
1a	2	5	High	Training for lifting loads in confined space. Clear instructions.
9	3	3	High	Clear instructions. Rested workers, enough breaks during shifts.
10	3	4	High	Training for works on heights. Use of personal protective equipment.
14	3	4	High	Restrict access to the site.
15	2	5	High	Including distress caller and underground locator as mandatory personal protective equipment.
16	4	2	High	Video monitoring site. Sufficient ventilation of the site. Protective equipment that reduces heat.

Table 2. *Cont.*

Hazard Number	Probability	Consequence	Risk (Priority Rating)	Measure
2	2	3	Medium	Active monitoring. When necessary additional planning and training
3b	2	3	Medium	Active monitoring. Training for lifting loads in confined space. Clear instructions.
5	3	3	Medium	Active monitoring. Training for lifting loads in confined space. Clear instructions. Regular inspection of steel structure.
6	1	4	Medium	Regular inspection of steel structure.
7	2	3	Medium	Regular crane inspection. Active monitoring of battery movement.
11a	1	5	Medium	Active monitoring. Regular crane inspection.
11b	1	5	Medium	Proper training. High concentration. Enough breaks during shift.
17	3	1	Medium	Ensuring technical ventilation is adequate. Periodical ventilation measurements.
3a	2	2	Low	-
8	1	3	Low	-
13a	2	1	Low	-
13b	2	1	Low	-
18	2	1	Low	-
19	2	1	Low	-

A risk relevant to battery-powered machines is battery fires. This risk is not analysed in detail in this paper, since it requires research of a completely different approach. The risk of battery fires must be assessed and proper safety procedures must be developed with the introduction of battery-powered machines into underground mining.

4. Discussion

This study provides a case study of the practical challenges of technological innovation within a high-risk industrial environment. It describes the current state of battery swapping technology for underground electric-powered trucks, highlighting the approaches taken by two major OEMs and Company 2. Both companies recognise the limitations of onboard battery charging in terms of time and operational efficiency, opting for a battery swapping system to maintain the continuous operation of their vehicles.

Company 1's solution, utilising an overhead crane, presents a more straightforward but potentially less efficient method. The flexibility of placing the vehicle either in front of or inside the charging station chamber offers some adaptability, but it introduces a reliance on complex machinery and potentially increases the risk of accidents associated with crane operation in a confined space. The approach with an overhead crane requires the engagement of lifting equipment and more specialised workers.

Company 2's approach, while more compact, introduces a different set of challenges. Integration of the battery swapping mechanism directly into the truck minimises the need for external equipment and potentially reduces the space required for the charging station. However, this approach necessitates a more complex mechanism on the vehicle itself, increasing the potential for mechanical failures. Also, the temporary reliance on a smaller auxiliary battery during the swap procedure increases the risk of unexpected power failures during the manoeuvring.

The generality and replicability of the performed risk assessment methodology employed in this study has been designed to ensure both transparency and reproducibility. The identification and evaluation of hazards were conducted using a structured approach grounded in expert input from relevant domains and using the approach suggested in [26,27], where the risk matrix approach is well discussed: *"Risk matrices are referred to in the informative sections of various international standards such as ISO 17776 (2002), IEC 60812 (2006), and ISO 31010 (2010) and industry sector or several national risk management practices, for example (DNV, 2009, Carter, Hirst et al., 2003, PPRT, 2005)"*. The process, including risk scoring criteria and consensus procedures, is described in detail to enable replication in similar operational contexts. While the study focused specifically on battery swapping operations in underground mining environments, where operational constraints such as confined spaces, ventilation challenges, and emergency response limitations are particularly pronounced, the identified hazards and associated risks are, to a significant extent, generalizable. Many of the risk categories (e.g., electrical hazards, thermal events, mechanical failures, and human–machine interaction errors) are inherent to battery swapping technologies across various sectors, including logistics depots, construction sites, and industrial EV fleets. Nonetheless, we acknowledge that the severity and likelihood of specific risks may vary based on environmental, regulatory, and technological conditions, and we have delineated these contextual boundaries where relevant.

Moreover, hazard identification and risk analysis underscore the inherent problems associated with both approaches. The meticulous identification of 21 distinct hazards, ranging from crushing injuries and pinch points to electrical risks and confined space issues, is a testament to the potential dangers present in this environment. The use of a 5×5 risk matrix provides a structured framework for assessing these hazards, assigning probability and consequence scores to help prioritise mitigation efforts.

The matrix highlights the high-risk levels associated with several aspects of the battery swapping procedures, notably the handling of heavy batteries, the operation of overhead cranes (in Company 1's method), and the confined nature of the charging chambers. The critical risk ratings assigned to certain hazards, such as those associated with crane operation or the unexpected movement of the vehicle, emphasise the need for stringent safety protocols.

The suggested mitigation measures, such as thorough training programs, clear operating instructions, and regular equipment inspections, are practical and demonstrate a proactive approach to managing these risks. The emphasis on restricting access to the charging area is also crucial in controlling the human element, a key factor in preventing accidents.

In conclusion, the contrast between Company 1's and Company 2's approaches, coupled with the comprehensive hazard analysis, reveals a critical interplay between technological innovation and operational safety. This study effectively illustrates that even with the promise of improved sustainability through electric vehicles, thorough risk assessment and the implementation of robust safety measures are paramount for successful implementation in a demanding environment like underground mining of mineral resources.

Further research will be oriented to quantitative and qualitative analysis of the impact of these technologies in real-life cases, paying particular attention to the disruption EV charging stations can produce on the overall safety of the underground mines.

5. Conclusions

The transition to electric vehicles in the underground mining of mineral resources presents a compelling opportunity for enhanced sustainability and reduced operational costs. However, as described in this study, this transition introduces significant safety challenges that require careful consideration and proactive mitigation strategies. The contrasting approaches of two major OEMs to battery swapping highlight the diverse technological solutions available but also emphasise the inherent complexities of operating in confined, high-risk environments.

Examination of these distinct approaches reveals a trade-off between simplicity and compactness. Company 1's crane-based system offers a simpler, potentially more robust solution, but with increased space requirements and the added risk associated with lifting equipment. Company 2's integrated system minimises the need for external equipment but introduces potential mechanical failures and relies on a smaller auxiliary battery for manoeuvring, creating other potential hazards.

Comprehensive hazard analysis underscores the importance of a meticulous safety plan. The identified hazards, ranging from crushing injuries to electrical risks and confined space issues, highlight the potential for serious incidents. The use of a risk matrix effectively prioritises these hazards, enabling the allocation of resources to the most critical areas. The proposed mitigation strategies, emphasising training, clear instructions, access control, and regular maintenance, provide a roadmap for minimising risks.

Ultimately, the successful integration of electric vehicles in underground mining demands a holistic approach that considers both the technological advancements and the inherent safety challenges. A rigorous risk assessment, coupled with robust safety protocols and continuous monitoring, is essential to ensuring efficient, sustainable, and above all, safe operations.

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