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Analysis of the performance of battery powered LHDs in sublevel caving using discrete event simulation

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Abstract: Load-haul-dump (LHD) machines are powered by diesel, electric, battery, or hybrid systems. Diesel LHDs are efficient but produce noise and emissions. Trolley electric lines or cables are impractical for LHDs, while batteries offer high flexibility during operations but require frequent recharging. Despite the advantages of battery LHDs, studies are limited. This study used discrete event simulation to evaluate the performance of battery LHDs focusing on battery swapping stations and energy consumption in traditional and fork production layouts in a sublevel caving mine. The results showed the battery machines are more energy-efficient when working in a traditional layout than a fork layout. The daily energy consumption is 0.64% less in a traditional layout than a fork layout. The results also showed the selected battery swapping stations are optimal because productivity is not significantly affected by changing the swapping locations.

Keywords: battery powered machine; battery swapping; mining production layouts; sublevel caving; discrete event simulation.

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1 Introduction

In hard rock underground mining, load-haul-dump (LHD) machines are used for loading and hauling ore and waste to trucks, orepasses, dumping areas, and crushers (Eger and Godwin, 2013). In sublevel caving, these machines move materials from the draw points to orepasses (Jiang et al., 2022). LHDs can be powered by a diesel, electric, battery, or hybrid powertrain (Freire et al., 2023). Diesel LHDs provide an efficient, robust, and dependable drivetrain and have low costs during operations (Resitoglu et al., 2015). However, they produce noise, heat, gases, and particulate substances which require substantial ventilation (Freire et al., 2023; Paraszczak et al., 2014). These drawbacks mean mines may turn to alternative power source such as electricity. Electric LHDs can be powered using electric lines, batteries, or trailing cables. However, trolley electric lines are impractical because LHDs change their working location (Paraszczak et al., 2014). Electric cables are also used for LHDs, but they have a limited range of movement and problems of cable wear (Kumar et al., 1992; Paraszczak et al., 2014). Batteries offer the highest flexibility in movement, but battery vehicles are heavy and must be regularly recharged. When battery vehicles are used, battery swapping or charging locations must be well established.

There are several aspects to consider in analysing performance of battery LHDs. Some of the challenges in performance analysis of battery LHDs are battery degradation and lifespan, state-of-charge and state-of-health, charging infrastructure and downtime, operational challenges, maintenance requirements, and safety. Nieto et al. (2020) analysed the performance of LHDs powered with battery, electric cable, and diesel in the areas of utilisation, availability, mean time between failures, and mean time to repair. They highlighted the reliability of battery and electric vehicles and the superior mobility

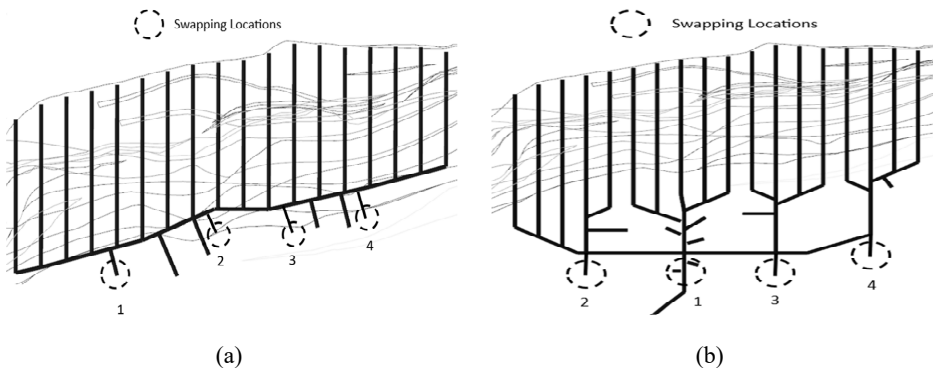
of diesel equipment. Schatz et al. (2017) compared costs and revenues for diesel and battery LHDs. They concluded battery powered LHDs yield more revenue annually per vehicle than diesel LHDs, although diesel LHDs have a higher internal rate of return, on average. Acuna-Duhart et al. (2022) compared battery performance using different slope percentages. They found the net energy consumption of the Rokion R400 utility battery electric vehicle increased with load but decreased at higher speeds, with energy consumption and regeneration affected by grade and speed. Kukkonen (2017) analysed energy consumption of battery electric vehicles, including the charging cycle. The analysis demonstrated that with strategic placement of charging stations and the use of regenerative braking, battery electric vehicles can operate continuously in underground mining environments without the need for additional charging periods. In previous studies on battery powered LHDs, the focus has been on cost analysis and comparative evaluations with diesel-powered machines. However, few studies have evaluated LHDs' performance, productivity, and energy consumption in different battery swapping locations in sublevel caving mines. Such evaluations are essential for achieving efficient battery LHD operations. To achieve efficient operations, production disturbances related to battery swapping such as queues and travel time to swapping stations must be minimised. Without determining the optimal number and locations of swapping stations, it is impossible to effectively plan production for battery powered LHDs. This study analysed the performance of battery-powered LHDs across various swapping station locations and battery energy consumption during different modes of operations, i.e., loading, hauling, and dumping. The goal was to identify potential production disturbances caused by battery swapping and if present, suggest the best possible location and number of swapping stations to mitigate any production losses. It should also be noted that battery swapping can be challenging particularly due to substantial costs of infrastructure demand and large battery fleet (Zhu et al., 2023). Despite these disadvantages, battery swapping is an advantageous option compared to battery charging because currently battery charging takes much longer time than battery swapping for LHDs. The study employed discrete event simulation because this method is a suitable approach for the system of LHD operations to determine the optimal location and number of battery-swapping stations. Several approaches exist for determining optimal solutions, and the choice of method depends on the characteristics of the system being modelled. In this case, LHD operations in production layouts represent dynamic systems where new events are influenced by past events. LHD operations can be effectively modelled as discrete systems because the state of the system changes based on specific events such as the events when the LHD is loaded, unloaded, idle, or off. These characteristics make discrete event simulation an appropriate choice for analysing and modelling this system. Various researchers have used discrete event simulation to study loading operations. Salama et al. (2014) compared two transportation alternatives, i.e., trucks and LHDs, using discrete event simulation. They concluded the technique is very suitable for modelling complex systems and noted that it is increasingly used in various mining operations. Usmani et al. (2014) applied discrete event simulation to the number of loads loaded by LHDs to determine the optimal number of LHDs. Salama et al. (2015) used discrete event simulation to comparatively analyse the energy consumption and gas emission of diesel and electric LHDs with similar bucket capacities. Although discrete event simulation is a widely used method in mining, it has some challenges such as demonstrating financial benefits of it to stakeholders (Collins et al., 2023) and ensuring the credibility and validation of simulation models.

A number of different discrete event simulation software that can be used to model LHD operations. The choice of simulation software is important, and the tool should be chosen based on flexibility, ease of use, and accuracy of results (Law et al., 2007). The Python programming language with SimPy package was used in this study to model battery powered LHD operations in traditional and fork production layouts in a sublevel caving mine. SimPy is a package developed for discrete event simulation and it offers robust compatibility with other packages that can enhance future projects (Nam et al., 2022). The model developed with SimPy was used to evaluate the performance of battery LHDs.

2 The case study

The case study site was the underground iron mine, Kiirunavaara, in the northern region of Sweden. The operational configuration currently uses a traditional production layout. Orepasses are placed near the footwall drive, and crosscuts run nearly perpendicular to the orebody's strike, with a footwall drive connecting them, as illustrated in Figure 1(a). The figure shows four swapping locations along the footwall drive. The LHDs' productivity and energy consumption were determined for each of these swapping locations using discrete event simulation.

Figure 1 (a) Traditional layout (b) Fork layout



To improve the conventional production layout, Quinteiro (2018) introduced a design known as the fork layout [Figure 1(b)]. This layout augments the traditional sublevel caving production areas by introducing improvements in some aspects. For example, orepasses are positioned between the footwall drive and crosscuts, creating LHD operation zones that are separate from activities in other drifts. The aims of this design are to enhance footwall drive stability, reduce the development work required for production, and decrease operational expenses. Figure 1(b) shows a modified version of the fork layout with four swapping locations. As for the traditional layout, the productivity and energy consumption of the LHDs were determined at each swapping location using discrete event simulation.

The aim of this study was to analyse the performance of battery powered LHDs by evaluating their productivity and battery energy consumption at different battery swapping locations during different modes of operations, i.e., loading, hauling, and

dumping, when working in traditional and fork production layouts in a sublevel caving mine.

3 Model setting

In the simulation model created for the study, LHDs handle material transport to orepasses in both traditional and fork layouts. In this operational sequence, LHDs load material from designated points in the drifts and transport it to the designated orepass; after unloading, the workflow proceeds depending on the necessity for further mucking operations. A 15-minute shift break is allocated in the model for operator change in the afternoon shift. The model assumes the battery is fully charged at the beginning of operations. The battery has an energy capacity of 300 kWh. After unloading, the LHD is sent for battery swapping if the energy consumed is less than or equal to 17 kWh. The model also assumes batteries are available for swapping at the swapping locations, and LHDs are assumed to be switched off when waiting for battery swapping if there is a queue for swapping.

Productivity was calculated as an average tonnage produced per day for each LHD. The manufacturer of LHDs provided power requirements for different LHD operations, i.e., hauling empty, hauling loaded, mucking, and dumping. Energy consumption in kWh was calculated using the duration of operations obtained from the simulation runs and the kW provided by the manufacturer.

Table 1 Scenarios for different swapping locations to determine the effect on productivity and the adequacy of the number of swapping stations

<i>Scenario</i>	<i>Layout</i>	<i>Number of LHDs</i>	<i>Location of swapping</i>
1	Traditional	1	1
2	Traditional	1	2
3	Traditional	1	3
4	Traditional	1	4
5	Fork	1	1
6	Fork	1	2
7	Fork	1	3
8	Fork	1	4
9	Traditional	4	1
10	Fork	4	1

4 Designed scenarios

Table 1 shows ten scenarios created to study the effect of the location of battery swapping on productivity (scenarios 1–8) and to determine whether the number of swapping stations is sufficient for four LHDs while maintaining the productivity at the same level (scenarios 1, 5, 9, and 10). Productivity and energy consumption were examined for all ten scenarios. The scenarios included varying production layouts (traditional, fork), numbers of LHDs, and locations of swapping. Eight swapping

locations were considered for traditional and fork layouts (four for each type of layout) along the footwall drive (Figure 1). The number of LHDs was either one or four.

5 Data collection

The simulation model used battery powered machine model ST 14. Table 2 shows the various specifications, including battery swapping time, power requirements for loading, hauling, dumping, and battery capacity. These data were collected from the manufacturer and used for model development and as input to calculate energy consumption. The energy consumption rates correspond to a specific loaded tonnage. This data was deterministic and did not include variability. Also, vehicle speed does not follow a distribution because the speed settings were intended to remain consistent with those in the previous validated model. As a result, no probabilistic distribution was applied to account for uncertainty in these input data. The kinematic data for battery powered LHDs and bucket capacity are shown in Table 3. These data were also provided by the manufacturer. The payload data were taken from the mining equipment company; payload was assumed to be constant in the simulation model.

Table 2 Swapping model setting

ST14	
Battery swapping time (min)	7
Loading (kW)	160
Hauling – loaded (kW)	210
Dumping (kW)	100
Hauling – empty (kW)	160
Energy at which LHD is (kWh) sent for swapping	17
Battery capacity (kWh)	300

Table 3 LHD kinematics data

ST14	
Max speed loaded	24 km/h
Max speed empty	26 km/h
Loading time	40 s
Dumping time	5 s
Capacity	4.6 m ³

6 Verification and validation

Verification is guaranteeing that the conceptual model has been faultlessly translated into a working computational implementation (Sargent, 2020). In this paper, the simulation model was verified through several debugging processes so that entities in the simulation model behave as intended. During verification process, the model was examined through various events such as loading, hauling (loaded and empty), dumping, and battery

swapping. The progress of each entity was traced by checking timing of events, logical sequence of events, the start and end of shifts, and the routing of vehicles. The expected behaviour of entities was compared to the behaviour resulted in the simulation runs.

Validation is the process of ensuring the accuracy of the model by testing how well it represents the behaviour in real world case (Robinson, 1994). According to Robinson (1994), validation procedures can be classified into three main categories: face validity, comparison with a real system, and comparison with other simulation models. To validate a simulation model, various tests such as degenerate tests, extreme condition tests, face validity, and internal validity are suggested by Sargent (2010). Salama et al (2015) and Skawina et al. (2015) performed these validation tests on a simulation model of diesel and electric LHDs in a traditional sublevel caving layout using automod software. The simulation model presented in this paper was validated using the 'comparison with similar simulation models' approach proposed by Robinson (1994). Specifically, it was compared to the simulation model created by Salama et al. (2015) and Skawina et al. (2015). However, the current simulation model incorporates different LHD capacities and velocities, an additional battery-swapping logic, a traditional and a new layout. Battery LHDs are tested using a non-existing layout referred to as fork layout. In this study, validation using historical data was not feasible because there is no existing data for battery LHDs or the fork layout in the Kiruna mine. Nonetheless, validation could be done if certain changes are made in a validated simulation model. Simulation models are often used to explore alternative designs or changes in input conditions. According to Banks et al. (2014), confidence in a model's accuracy can be transferred when changes to the operational model are minor. Some minor changes are adjusting parameters such as machine speed and arrival rates, etc. and statistical distribution changes such as changes in service time or failure time distributions whereas major changes are modifying a subsystem's logic such as changing queue discipline or scheduling rules and implementing entirely new designs (Banks et al., 2014). In this study, changes to the model were in kinematic properties and capacity of the vehicle, which is considered minor change. A battery swapping logic and energy consumption calculation were also added into the simulation model. However, the fundamental behaviour of the vehicles within the layouts remained unchanged.

7 Results and discussion

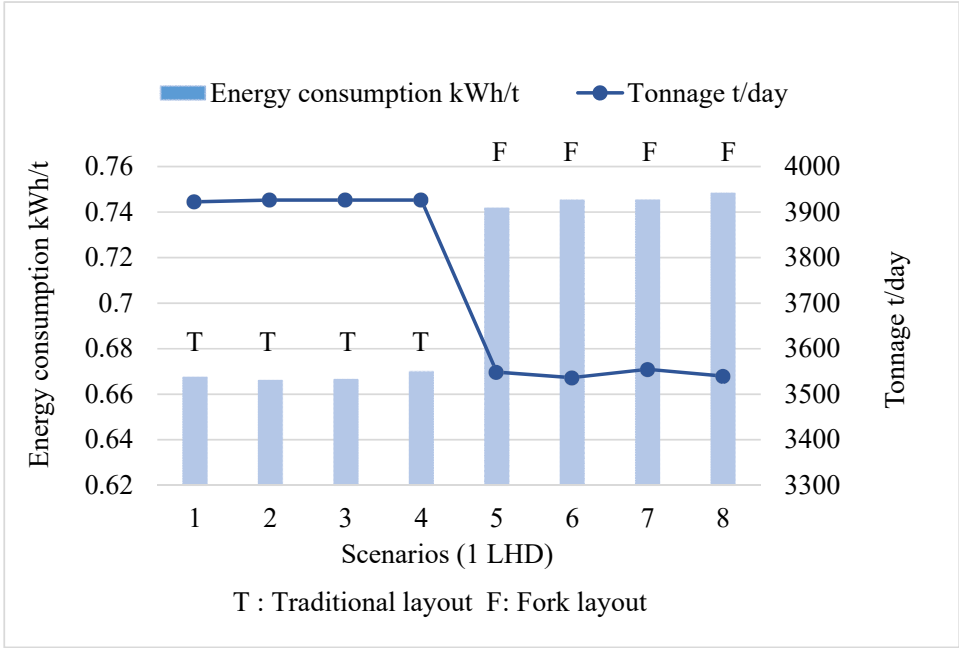
The study analysed the performance of battery powered LHDs by evaluating the productivity, appropriate location of swapping, hourly battery energy consumption, and daily battery energy consumption during different modes of operations, i.e., loading, hauling, and dumping, for traditional and fork production layouts. The scenarios were run for 90 days, and the results are given as average values per day. The results of simulation runs are shown in Figures 4, 5, and 6. Ten scenarios were simulated with different battery swapping locations (Figure 4) and different numbers of LHDs (Figure 5).

As seen in Figures 4, 5, and 6, the production rate in tonnes/day, the energy consumption in kWh/day, and energy consumption in kWh/t per LHD vary slightly across ten scenarios with different battery swapping locations in both traditional and fork layouts, but the differences are negligible. Battery swapping locations along the footwall drive have no significant impact on operation duration or production (Figures 4 and 5). The energy consumption in kWh/t is higher in scenarios 1 and 5 than 9 and 10, because

LHDs travel longer distances per cycle in the former. Overall, the productivity in traditional and fork layouts are 3,927.7 t/day and 3,553.3 t/day, respectively due to more cycles of LHDs in a shift. For scenarios 1, 5, 9, and 10, the average daily production rate per LHD in traditional and fork layouts when using four LHDs is 3,936.5 t/day and 3,586.6 t/day, respectively, and this is 14.0 t/day and 37.9 t/day higher than when one LHD is used (Figure 5). Increasing the number of LHDs does not adversely affect productivity, which indicates that one swapping station is sufficient.

The results for energy consumption in kWh/t per LHD show the energy consumption per tonne is higher in the fork layout than the traditional one when there is one LHD and swapping stations are in different locations (Figure 4). The average energy consumptions are 0.75 kWh/t and 0.67 kWh/t for the fork layout and the traditional layout, respectively. The average energy consumption per tonne is lower in the traditional layout than the fork layout because tonnage produced in the traditional layout is higher and energy consumed in the traditional layout is more or less the same as in the fork layout in a day.

Figure 4 Energy consumption (kWh/t) and productivity/day of LHDs considering different battery swapping locations (see online version for colours)



In scenarios 1–7, 8, 9, and 10, the average number of swaps per day is 9, 8.8, 8.3, and 8.4, respectively; total swapping durations are 1.05, 1.02, 0.96, and 0.99 hr/day, and queuing times for battery swapping are 0, 0, 0.21, and 0.23 hr/day, respectively (Table 4). The queuing times are zero in scenarios 1–8 because only one LHD is operating, while the queuing time is not zero in scenarios 9 and 10 because four LHDs are operating simultaneously with one battery swapping resource in the simulation model.

The results for the energy consumption of LHDs in different operational states, i.e., hauling loaded, hauling empty, mucking, and dumping states, are shown in Figure 6. The figure indicates the daily average energy consumption per LHD. The average energy

consumption in hauling loaded, hauling empty, mucking, and dumping states is 1,181.5 kWh/day, 899.9 kWh/day, 500.0 kWh/day, and 39.1 kWh/day, respectively. The average energy consumption for all scenarios is 2,620.4 kWh/day. The variations in energy are due to the different kW requirements for each activity based on the technical properties of the LHD and the duration of the activity.

Figure 5 Energy consumption (kWh/t) and productivity/day of LHDs considering adequacy of battery swapping (see online version for colours)

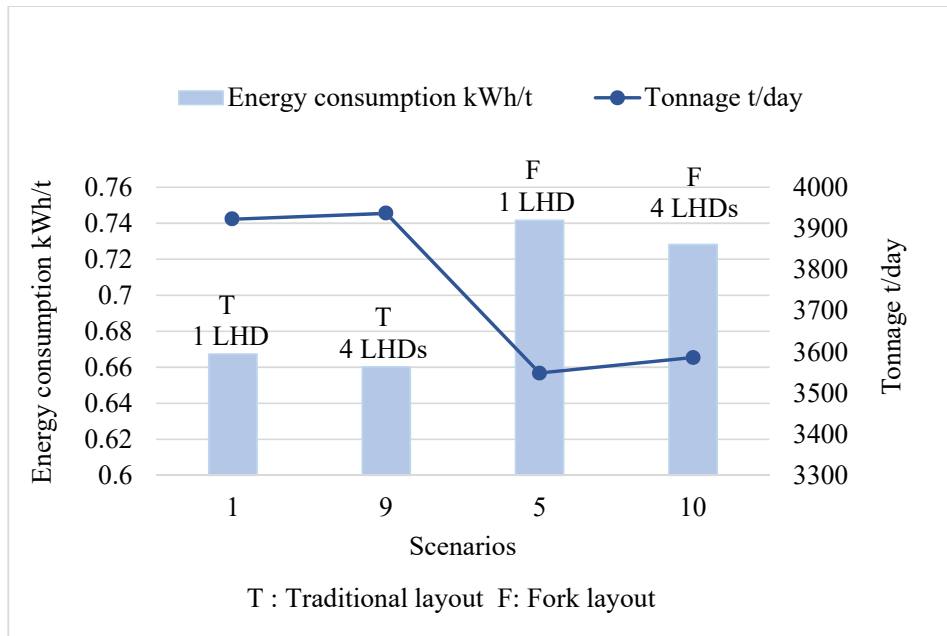


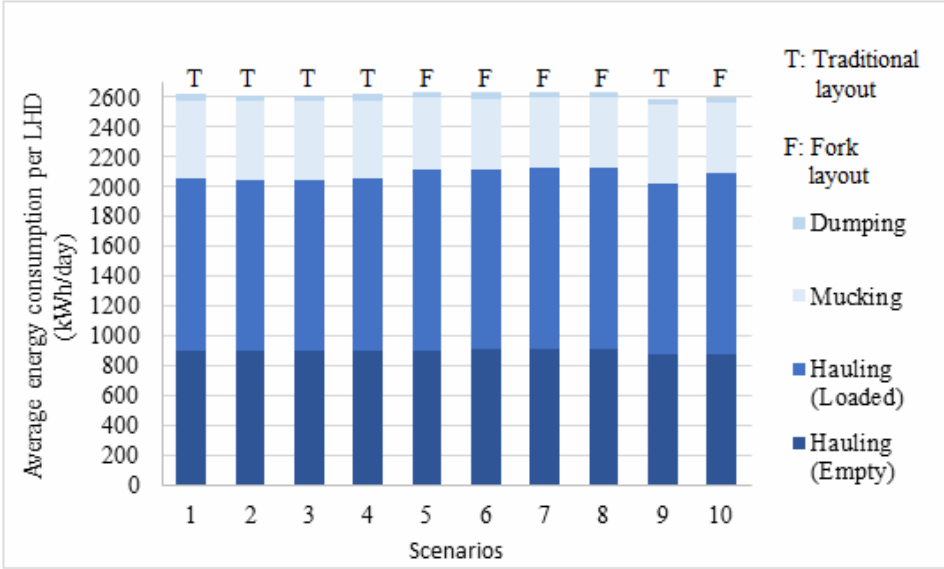
Table 4 Number of battery swaps per day and average queueing time (hr/day)

Scenario	Number of swaps per day	Queueing time hr/day
1–7	9	0
8	8.8	0
9	8.3	0.21
10	8.4	0.23

As expected, the highest energy consumption occurs during hauling in a loaded state. The traditional layout is the most energy efficient configuration with lower energy consumption per tonne compared to the fork layout. Moreover, scenarios 1 to 8 (Figure 4) indicate negligible productivity impact when battery swapping locations are considered. This implies a certain degree of flexibility in swapping stations placement without compromising overall operational efficiency. Figure 5 confirms the current number of battery swapping stations is adequate. Using one LHD instead of four increases energy use due to longer travel distances per cycle. The average queueing times for battery swapping are 0, 0.21, and 0.23 hr/day in scenarios 1–8, 9, and 10, suggesting no

significant queueing or productivity difference when battery swapping locations are changed along the footwall drive, and one battery swapping station is sufficient.

Figure 6 Energy consumption (kWh/day) of LHDs considering LHD operation status: hauling (empty), hauling (loaded), mucking, and dumping (see online version for colours)



8 Conclusions

The study analysed the performance of battery powered LHDs using the SimPy discrete event simulation framework in Python. The aim was to evaluate the LHDs' productivity, appropriate location of swapping, and battery energy consumption during different modes of operations, i.e., loading, hauling, and dumping, in traditional and fork production layouts in a sublevel caving mine. The study obtained the following results:

- The average productivity per LHD in traditional and fork layouts is 3,927.7 t/day and 3,553.3 t/day, respectively. The higher productivity in the traditional layout is due to the lower distance travelled per cycle.
- When the location of swapping is changed in traditional and fork layouts, average production differences in t/day are 0.1 % and 0.2–0.3%, respectively. The location of battery swapping stations has no significant impact on productivity when stations are located along the footwall drive. The number of battery swapping stations is sufficient because the queueing time for swapping is in the range of 0 to 0.23 hr/day, and production is not substantially affected. Since the current location and number of swapping stations do not significantly impact productivity, it could be recommended to maintain current swapping station configuration.

- Average energy consumption is 1,181 kWh/day when hauling with a full load, 900 kWh/day when hauling empty, 500 kWh/day when mucking, and 39 kWh/day when dumping. The highest energy consumption occurs when hauling in the loaded state.
- The traditional layout is a more energy efficient configuration than the fork layout. The difference between traditional and fork layouts is 0.08 kWh/t when using one LHD and 0.07 kWh/t when using four LHDs. For mining operations seeking to employ battery power, traditional layouts could be preferred option as they have an advantage over fork layouts.
- The efficient placement of battery swapping stations reduces disruptions to mining operations. Placing them near production areas reduces travelling time and downtime and thus reduces the duration of production disturbances.
- If battery swapping capacity is not determined properly, queueing and waiting times can increase, and this, in turn, will impact productivity and the utilisation of equipment and productivity.

Future work could include other types of production layouts. It could also propose approaches to reduce energy consumption or compare productivity for battery charging versus battery swapping. In addition, conducting a cost-benefit analysis for these methods is essential to identify the most economically, operationally and environmentally efficient approach particularly in underground mining where these aspects significantly impact overall productivity.

Declarations

There are no conflicts of interest to disclose regarding this research.

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