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Comparative analysis: Evaluating battery and diesel load haul dump (LHD) units' productivity in a block cave mine using discrete event simulation (DES)

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ABSTRACT

The use of Battery Electric Vehicles (BEVs) in underground hard rock mines is gaining traction due to their ability to improve working conditions by removing diesel exhaust gases, Diesel Particulate Matter (DPM), and reducing air temperatures. This would make the mines easier to comply with increasingly stringent Occupational Health & Safety (OH&S) regulations and make the underground mine environment healthier. Moreover, BEVs consume less energy than diesel machines due to their higher energy efficiency. All these examples would improve the efficiency of an underground mining operation. Diesel machines have been used for a long time in mining because of their high productivity. It is still unknown whether the current generation of BEVs can match the productivity of diesel machines. When using BEVs, aspects such as the required number of batteries and charging stations, the swapping time, and the swapping interval are aspects that can affect their productivity. As a result, Discrete Event Simulation (DES) analysis was carried out with Arena software using mine design data from a block cave mine that is in the feasibility study stage. The purpose of the analysis was to evaluate the productivity of two equivalent 18-tonne Load Haul Dump (LHD) units: diesel- and battery-powered, using two different hauling strategies, varying availability, and the speed of the machines. The results suggest that hauling strategy and speed have a significant impact on the required number of machines and that when using equivalent gear, battery machines can achieve on average between 6.5% and 10.3% higher productivity than equivalent diesel machines. The work was done as part of the Next Generation Carbon Neutral Pilots for Smart Intelligent Mining Systems project (NEXGEN SIMS, www.nexgensims.eu), which is funded by the European Union.

1 INTRODUCTION

Battery Electric Vehicles (BEVs) provide various advantages over diesel-powered machines in deep hard rock mines. BEVs emit no harmful gases or Diesel Particulate Matter (DPM), and they produce less heat and noise (Halim et al., 2022). Moreover, a field trial program found that BEVs consume significantly less energy than their equivalent diesel machines (Halim, 2024). In underground mining, traditional loading and hauling processes performed with diesel machines consume a significant amount of fuel (Salama et al., 2015), where diesel fuel consumption in underground mines can account for 27% to 34% of the total energy used (Engeco Pte Ltd, 2021). Halim (2024) did two comparative trials of Epiroc's BEVs and their diesel version. He found that the diesel version consumes four to five times more energy than the battery version when operating on a horizontal track, and 10 times more energy than the battery version when operating on an inclined track.

Many activities are involved during the loading and hauling operations in underground mines, and each takes a certain amount of time depending on the activity at hand and the surrounding conditions. These include waiting, queuing, loading, dumping, hauling, availability of drawpoints, extraction drives, and other related tasks. Owing to the discrete nature of these events or actions (Banks et al., 2014), discrete event simulation can be used among others to identify bottlenecks in production or differences when using machines with different specifications to execute the required tasks. For example, in our case, we compared battery LHDs with equivalent diesel LHDs. This study aims to determine how productivity changes when battery or diesel LHDs are utilized, how many machines are needed for each simulation scenario, how much battery swapping time affects the overall productivity, and the number of chargers or batteries needed within each scenario. The terms *battery bay* and *charger* are used in this article. Battery bay refers to the location where the LHD's batteries are swapped and recharged. A charger refers to the device that charges a battery. In the simulations, a maximum of two chargers were used within one battery bay.

1.1 Case study, anonymous block cave mine

The case study block cave mine used in this study is in the planning stage and is located in Australia. Due to the request from its owner, the mine is made anonymous in this paper. The mine will be extracted in two production blocks, block cave 1 (BC1) and block cave 2 (BC2), where BC1 includes the first eight extraction drives (drives 1 – 8) and BC2 contains the remaining six extraction drives (drives 9 – 14). BC1 will be extracted first followed by BC2; however, there will potentially be some overlap, where both will be producing at the same time. The study outlined in this paper focuses on the results of the simulations of BC2.

2 METHODOLOGY

With simulations, it is possible to replicate real-world systems and operations and employ proven models to study the outputs of interest, which can be divided into continuous and discrete (Banks et al., 2014). Continuous systems, such as ore throughput in the crusher or the level measurement of the cement silo or acceleration chemical tank, change continually over time. On the other hand, discrete systems, where the states change discretely over time, include, among others, aspects such as the number of loaders queuing up to swap their batteries. The simulations in this study were conducted using the discrete event simulation software Arena, developed by Rockwell Automation Inc. First, base case scenario assumptions were identified and defined with the assistance of the mine staff, the original equipment manufacturer's specifications, and a discrete event simulation expert.

The productivity of diesel LHDs and equivalent battery LHDs were simulated starting with base case scenarios. Base case scenarios were simulated using two different hauling strategies: direct hauling (Figure 1) and loop hauling (Figure 2).

Direct hauling is the traditional LHD hauling strategy where LHDs use the same extraction drive to make a return trip from a drawpoint to the crusher. In this scenario, only one LHD can be inside the extraction drive at a time (Figure 1).

In the loop hauling strategy (Figure 2), the LHDs' route of the return trip from a drawpoint to the crusher follows a loop where the extraction drives are configured as entry and exit drives, with the entry drives having even numbers (2, 4, 6, 8, 10, 12) and the exit drives having odd numbers (1, 3, 5, 7, 9, 11 and 13). Drives are numbered from West to East. It has been assumed that the loops only operate in a clockwise direction for simplicity. For example, an LHD enters the loop at drive 4 and exits at drive 3. It can muck at any drawpoint within this loop (within drive 4 or drive 3). This allows multiple LHDs inside a particular extraction drive. If the adjacent drive is not available due to rehabilitation/maintenance, the simulation logic was programmed to allow the LHD to choose the nearest westbound exit drive that is available. In the previous example, when drive 3 is unavailable, the LHD can choose to exit via drive 1 if it is available. When no westbound exit drives are available, the simulation logic allows the LHD to choose the closest exit drive on the east side, and it is allowed to make a counterclockwise loop. In this situation, *a time penalty for traveling counterclockwise* is added to the machine's tramming time. The time penalty is used to simulate the possible effect of traffic when traveling against the traffic flow within the southbound loop area. In addition, an LHD is not allowed to pass another LHD while the latter is mucking a drawpoint. The former must wait until the other LHD finishes mucking. In this situation, a delay to the machine after waiting on the other machine loading is added to the former's tramming time.

In the simulations, the battery bays were placed between the drawpoints and the crusher, as shown in Figures 1 and 2. This was found to be the most suitable placement in order to allow the LHDs to meet the production target since they do not require to detour when they have to swap their battery.

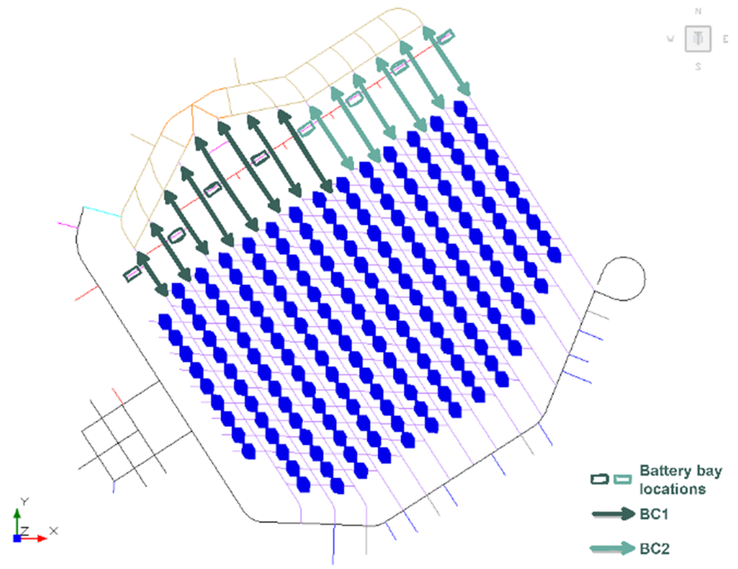


Figure 1 **Direct hauling to the crusher.**

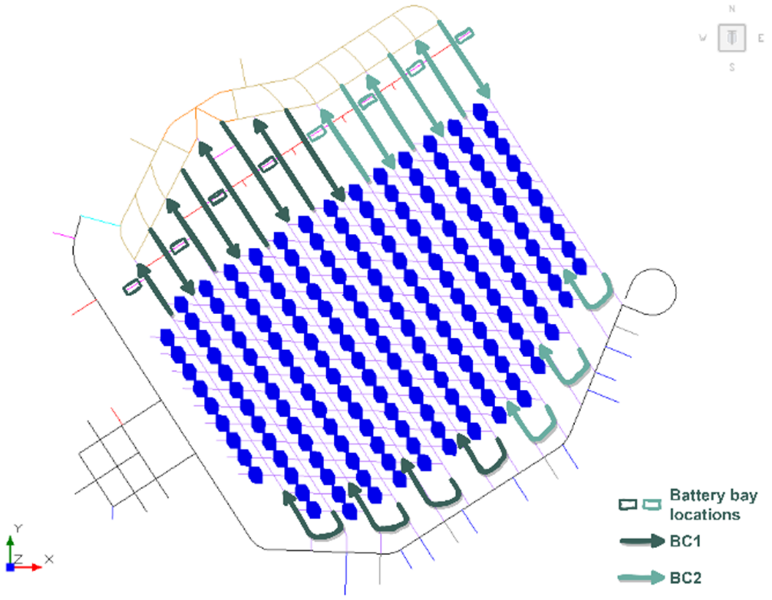


Figure 2 **Loop hauling to the crusher.**

2.1 Simulation simplifications and assumptions

Base case scenarios were simulated with the assumptions and simplifications presented in Figure 3. It was assumed that each battery bay has two chargers, which makes the total number of chargers equal to eight. Then, scenarios with a reduced number of chargers and a limited number of batteries were simulated. This was performed to determine the minimum number of chargers and batteries required to achieve the production target. The simplifications and assumptions when limiting the number of batteries and chargers are presented in Figure 4.

Simulated LHDs were battery and diesel versions of Epiroc ST18 using actual load carried as 16.5 tonnes and a battery duration of 4 hours. This is based on observations during the field trial at Kittilä mine (Halim et al., 2022) where the ST14 Battery was observed to carry one tonne less than its payload and battery to last for approximately four hours. Therefore, it was assumed that each version of the ST18 carried a tonne less than its payload of 17.5 tonnes. LHDs' speed when they are loaded, and empty, is the speed on the 2nd, 3rd, and 4th gear (Table 1 and Table 2).

Table 1 **Speeds of ST18 SG Battery on horizontal track (grade 0%) (Epiroc, 2023)**

Status	gear	km/h	m/s
Empty bucket	2nd	10.5	2.9
	3rd	17.2	4.8
	4th	31.2	8.7
Full bucket	2nd	10.7	3.0
	3rd	17.0	4.7
	4th	31.9	8.9

Table 2 **Speeds of ST18 Diesel on horizontal track (grade 0%) (Epiroc, 2022)**

Status	gear	km/h	m/s
Empty bucket	2nd	9.2	2.6
	3rd	15.3	4.3
	4th	27.7	7.7
Full bucket	2nd	9.2	2.6
	3rd	15.3	4.3
	4th	27.4	7.6

The assumed availability values were based on the observed values during the field trial at Kittilä mine (Halim et al., 2022), where the trialled BEVs were observed to have approximately 80% availability. This value was varied to 75% and 70% to simulate worse case scenarios.

Base case scenario

First the simulations were run with the base case scenario settings to find out the required number of LHDs in each scenario. The following scenarios were simulated:

- ST18 diesel LHD, changing the availability and maximum operating gear
  - Direct hauling
  - Loop hauling
- Battery-powered ST18 SG LHD, changing the availability and maximum operating gear
  - Direct hauling
  - Loop hauling

Base case scenario assumptions and simplifications

- Production target: 8 million tonnes per annum (Mtpa)
- Working days: 352
- Actual load carried by an LHD: 16.5 tonnes
- Loading time: 40 seconds (triangular distribution ± 10%)
- Dumping time: 15 seconds (triangular distribution ± 10%)
- Maneuvering time: 30 seconds
- Other time: 20 seconds to include accelerations and deceleration
- Equal tonnage of caved ore is drawn from each drawpoint
- Battery duration: 4 hours (triangular distribution ± 10%)
- Battery swapping time: 10 minutes (triangular distribution ± 10%)
- Machine availability: 70%, 75% and 80%
- A charged battery is always available in the battery bay whenever ST18SG arrives to swap its battery
- Operating time per shift for ST18 SG is 9 hours on and 3 hours off and for ST18 diesel model 8.75 hours on and 3.25 hours off
- One extraction drive is always unavailable for 5 hours every day due to rehabilitation and maintenance
- Valid for loop hauling
  - Time penalty for traveling counterclockwise: 20 seconds
  - Delay that LHD traveling needs to wait after another LHD has finished mucking in the same extraction drive: 10 seconds
  - Maximum three LHDs at a time can be inside the same extraction drive
- Valid for direct hauling
  - Only one LHD at a time can be inside the extraction drive

Figure 3 Simplifications and assumptions used in the base case scenarios.

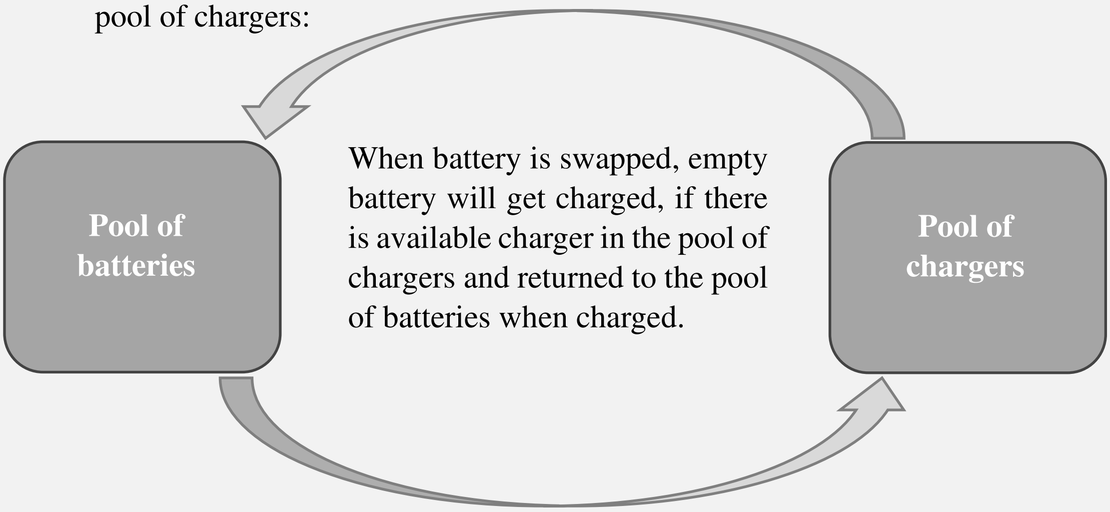
Limiting the number of batteries and chargers

From the base case scenario, the results with 80% availability were simulated further, to find the minimum number of chargers needed per scenario. The following scenarios were simulated:

- Battery ST18 SG LHD
    - Direct hauling with 3rd and 4th gear speeds
    - Loop hauling with 2nd, 3rd, and 4th gear speeds
- Simulations were started by first finding out the minimum number of chargers that is required to achieve production target
- After that, the number of batteries was reduced until the minimum possible that is required to achieve production target

Assumptions and simplifications added

- Batteries and chargers were set up to the model as a pool of batteries and a pool of chargers:



When battery is swapped, empty battery will get charged, if there is available charger in the pool of chargers and returned to the pool of batteries when charged.

- Battery swapping time: 3 minutes (triangular distribution ± 10%)
- Battery charging time: 3 hours
- Updated schedule: 4.5 hours on and 1.5 hours off

Figure 4 **Simplifications and assumptions used when limiting the number of batteries and chargers.**

Individual machine movements were monitored within the drawpoints and extraction drives in the simulation model. The distances between the extraction drives and the southern connecting drives, battery bays, and the crusher were set up as distances in the simulation model.

Simulations were conducted by assuming consistent speed for each gear. The simplified workflow of how the model works is presented below (Figure 5) and the same model is used to simulate all the scenarios, with diesel and battery LHDs, only the parameters are changed accordingly.

After the base case scenario simulations, the scenarios with battery LHDs with 80% availability that were able to achieve the production target were chosen to further simulate the required number of chargers and batteries (bolded in Figure 6).

When simulating with the limited number of chargers and batteries, the chargers and batteries were considered as a “pool” of chargers and a “pool” of batteries (Figure 4). Their locations are within battery bays as shown in Figure 1 and Figure 2. Therefore, an LHD could swap its battery whenever a battery bay is available, having a total of four different locations in BC2. When its battery is required to be swapped, the LHD is assigned to the closest bay. If that bay is occupied by another LHD, the LHD will queue until the LHD ahead of it has swapped its battery. After that, the LHD can start swapping its battery. If there is no charged battery in the “pool”, the LHD will wait until a charged battery is available.

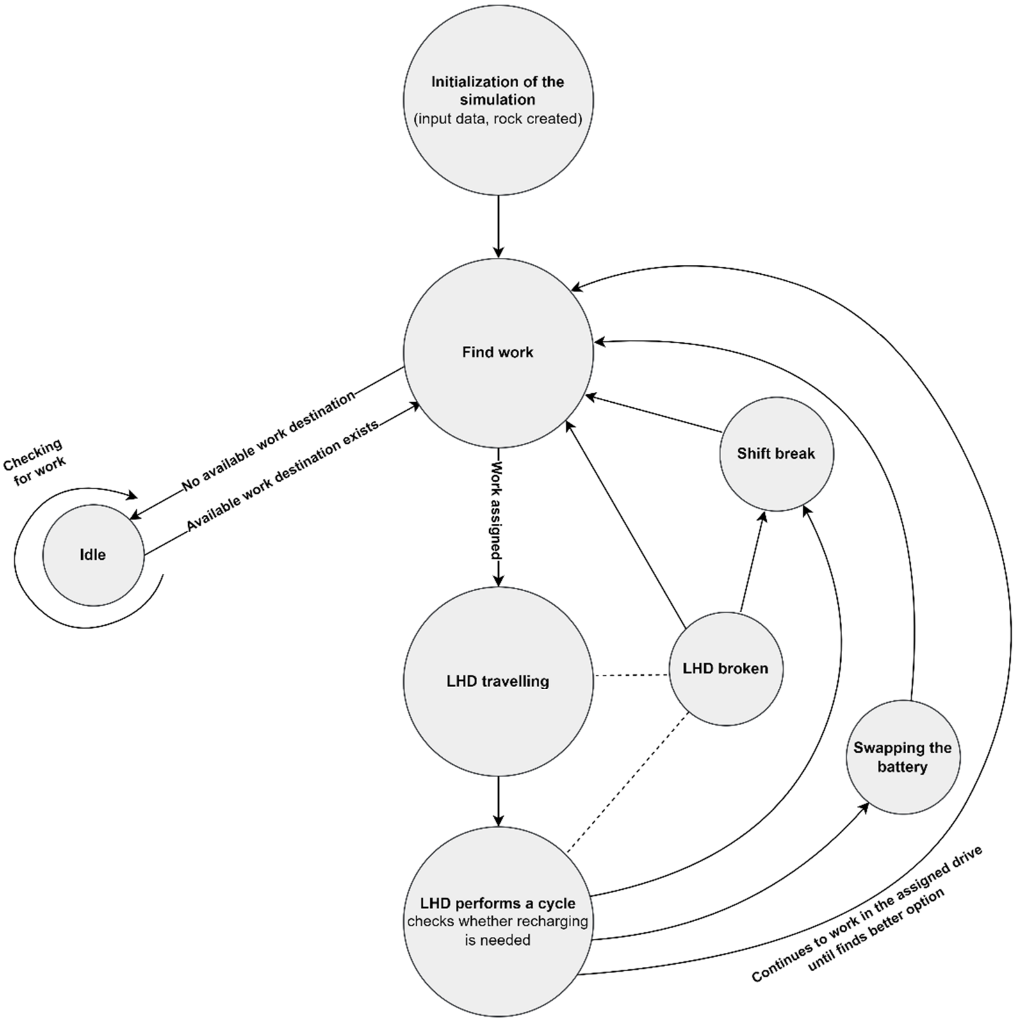


Figure 5 Simplified workflow of the simulation model.

3 SIMULATION RESULTS

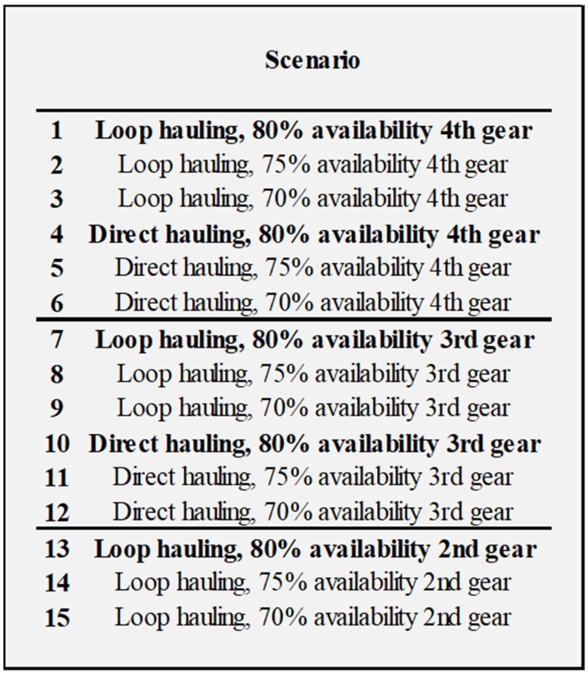
3.1 Base case scenario

Base case simulations were first performed to determine the necessary number of LHDs in BC2. The scenarios that could meet the production target of 8 Mtpa are compiled in Figure 6 and results are shown in Figure 7, which shows the relative number of required machines and average productivity per machine.

Figure 7 shows that when tramming on 2nd gear, the production target can only be met with loop hauling strategy for both versions of the LHD. When tramming on 3rd gear, the target can only be achieved using direct hauling strategy with battery LHDs but not with diesel LHDs. Battery LHDs have higher productivity than diesel LHDs in every base case simulation scenario, mainly because of the higher speed of the battery version in each gear.

With the assumptions made that in each battery bay there is always charged battery available, the battery LHDs have 6.5-6.9% higher productivity than diesel LHDs when using the loop hauling strategy with 4th gear speed. With 2nd gear speed, where the target could be only met using the loop hauling strategy, battery LHDs have 10.3% higher productivity than equivalent diesel LHDs.

When comparing the productivity differences between loop hauling and direct hauling strategies (both versions running at the 4th gear), battery LHDs have 12.1% higher productivity, and diesel LHDs have 11.6% higher productivity when utilizing the loop hauling strategy. Productivity differences between loop hauling and direct hauling increase as the speed of the machine increases.



	Scenario
1	**Loop hauling, 80% availability 4th gear**
2	Loop hauling, 75% availability 4th gear
3	Loop hauling, 70% availability 4th gear
4	**Direct hauling, 80% availability 4th gear**
5	Direct hauling, 75% availability 4th gear
6	Direct hauling, 70% availability 4th gear
7	**Loop hauling, 80% availability 3rd gear**
8	Loop hauling, 75% availability 3rd gear
9	Loop hauling, 70% availability 3rd gear
10	**Direct hauling, 80% availability 3rd gear**
11	Direct hauling, 75% availability 3rd gear
12	Direct hauling, 70% availability 3rd gear
13	**Loop hauling, 80% availability 2nd gear**
14	Loop hauling, 75% availability 2nd gear
15	Loop hauling, 70% availability 2nd gear

Figure 6 Base case productivity simulation results with 80%, 75%, and 70% availabilities for BC2, with the minimum number of required machines to reach the production target. Scenarios bolded are simulated further.

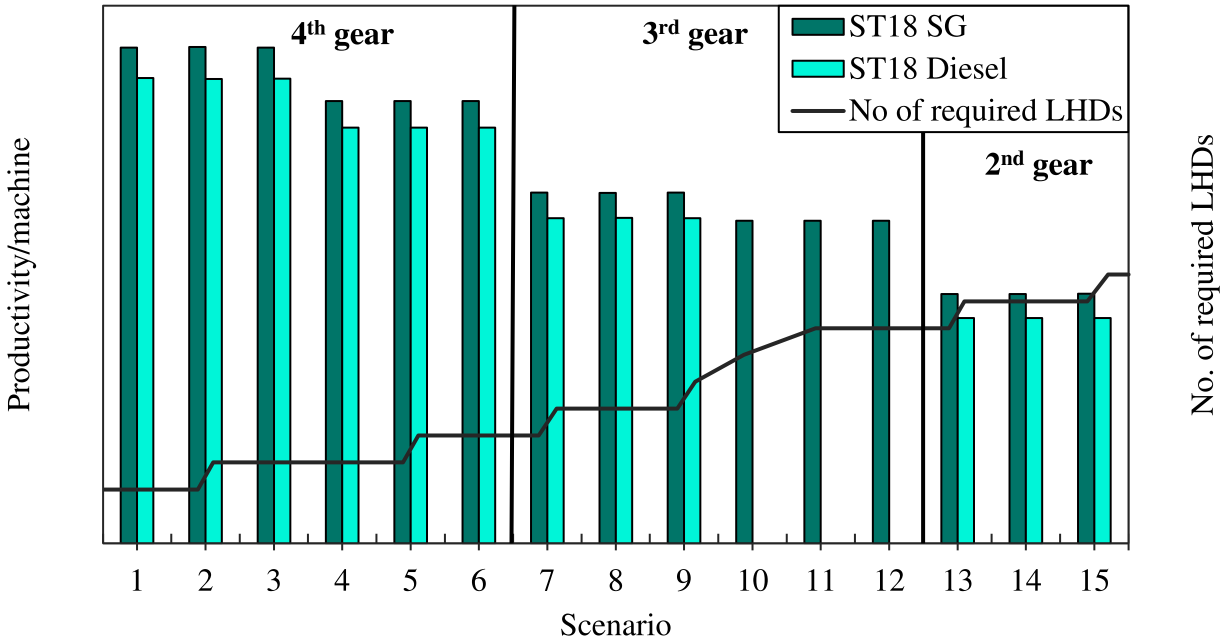


Figure 7 **Base case productivity simulation results with 80%, 75%, and 70% availabilities for BC2, with the minimum number of required machines to reach the production target.**

Figure 7 shows that more diesel LHDs are required than battery LHDs to achieve the production target because the productivity of battery LHDs is generally higher than that of diesel LHDs in all base case scenarios.

The availability and speed of the machines have a significant impact on the required number of machines and productivity. When running at the lowest speed (2nd gear), battery LHDs can reach the annual target with 80% availability, but when the availability is reduced to 75%, additional one LHD is required to reach the production target. The productivity per machine is 37.2-42.9% higher when traveling in 4th gear instead of 3rd gear and when travelling in 3rd instead of 2nd gear 41-44.4% higher productivity can be achieved.

In addition, the battery LHDs in the base case simulation scenarios 1, 4, 7, 10 and 13 (Figure 7) were also simulated using a more realistic schedule of 4.5h on and 1.5h off. This was done because, under the simplified schedule (9 hours on and 3 hours off), batteries are assumed to be switched every four hours, and each battery is charged for three hours. If a battery is dropped to the charger immediately before the break or off time, it will be fully charged during this time, which could lead to overly optimistic results. For diesel LHDs, it was assumed that they would require 15 minutes to refuel in each shift, which includes the travel time to the fuel bay. It was identified that the modified schedule will increase productivity by approximately 0.5t/h in the base case scenario of battery LHDs simulation results, with a median value of zero.

3.2 *Limited number of available batteries & chargers*

Further simulations using battery LHDs adopted this modified timetable, even though it has very little impact because it is more realistic and does not include potential implications for future simulations when limiting the number of chargers and batteries available. The bolded base case scenarios 1, 4, 7, 10 and 13.1 (Figure 6) were chosen for further investigation, to determine the minimum number of chargers and batteries required to achieve production target. The equivalent simulation scenarios using a limited number of batteries and chargers are named 1.1, 4.1, 7.1, 10.1 and 13.1. These simulation results are presented in Figure 8 where an updated schedule is then used.

While conducting the simulations while reducing the number of chargers and batteries, it was noticed that an additional attribute that keeps track of the maximum number of batteries queuing to be charged at any given time during the simulated production days (140 days) needed to be added. 140 days simulation time was seen to be a long enough time to add variability to the model results and to minimize any impact of drift maintenance and other short disturbances. With the *Maximum number of batteries queuing for charging* attribute, it was possible to determine that the number of batteries that needed to be charged did not increase over time and that the proportion of the number of LHDs to the number of chargers was stable. When running the simulations, the minimum number of chargers required for each scenario was determined with the help of the previously mentioned attribute *Maximum number of batteries queueing for charging*. To ensure that the maximum number of batteries in the charging queue would not be at least significantly more than the simulated number of LHDs, each simulation scenario was started with a very high number of batteries. By doing this as phase 1, we were able to determine the minimum number of chargers required to support the specified number of LHDs in each scenario. As a second phase, the overall number of batteries was reduced until the fleet couldn't transport the requisite annual production with the minimum required chargers used from phase 1. This allowed us to determine the minimum number of batteries required.

The simulations used two battery swapping times, 10 and 3 minutes, which are based on the designed time from Epiroc and Sandvik, the two largest underground mine BEV manufacturers in the world (Halim et al., 2022) (*Sandvik mining and rock solutions.*2022). This was done to determine whether and to what extent the battery swap time affects to the required number of chargers and batteries.

According to the simulation results, BC2 requires three batteries per charger when employing loop hauling in the fourth gear despite the battery swapping time (Figure 8). The production target can be met by a battery LHD with one battery less in the remaining simulations when the battery swapping time is 3 minutes instead of 10 minutes.

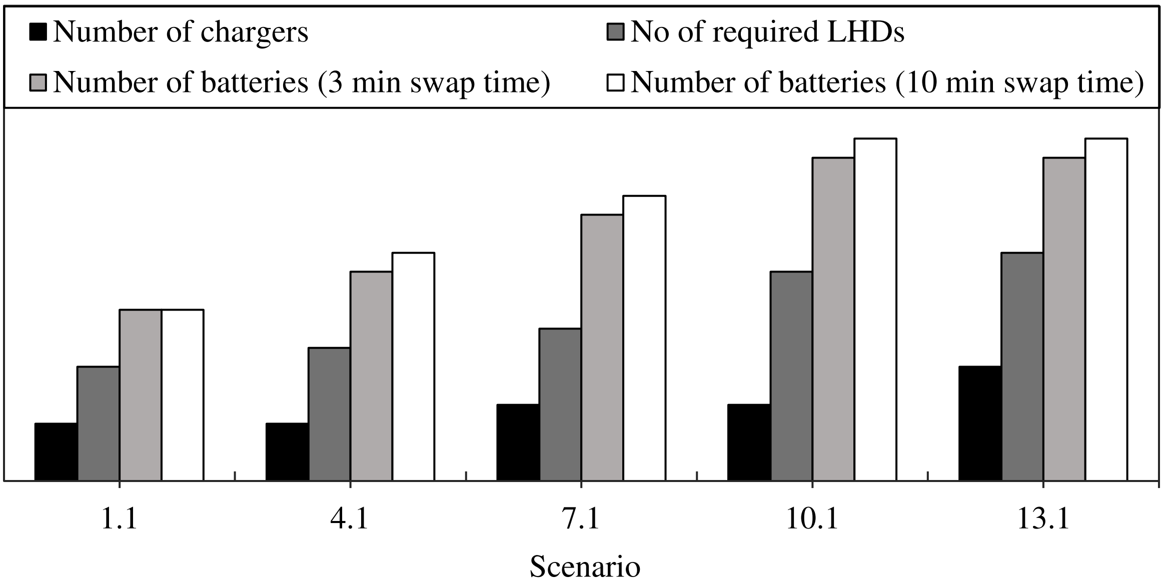


Figure 8 BC2 simulations results with 80% availability, the minimum number of batteries and chargers required for each scenario with the required number of ST18SG LHDs defined in base case scenarios 1, 4, 7, 10 and 13.

In each simulated scenario (Figure 8) the required number of batteries per machine (battery-machine ratio) is less than two. The minimum battery/machine ratio of 1.4 is in scenario 13.1 with 3 min swapping time and the maximum of 1.9 is in scenario 7.1 with 10 min swapping time.

When comparing the required number of batteries and chargers between the loop hauling and direct hauling with equivalent gear, with 4th gear speed the required number of chargers stays the same even though one additional LHD is required in direct hauling, but additional 2-3 batteries are needed to reach the production target. When travelling in 3rd gear speed, one additional charger is needed than in 4th gear speed. But when comparing the loop hauling with direct hauling in 3rd gear speed, additional three LHDs and three batteries are required to haul the target in direct hauling, while the required number of chargers is the same.

In all the simulated scenarios with loop hauling a smaller number of LHDs are needed towards a charger (machine-charger ratio) than in direct hauling. With loop hauling the machine-charger ratio is two while in direct hauling it varies between 2.3-2.75.

4 CONCLUSIONS AND FUTURE WORK

The simulation outlined in this paper indicates that the battery LHDs can match or better than diesel LHDs, providing that battery bay is placed for every two extraction drives between the drives and the crusher. It appears that the battery swapping times, whether it is 10 minutes or 3 minutes, does not have a significant impact on the overall efficiency or to the required number of chargers or batteries.

In the future, the simulation should be repeated when real data is available, because our simulations are based on a conceptual design. Sensitivity analysis on the assumptions used should be conducted to find the key parameters that enable most optimal design solution. Also, aspects such as costs, energy utilization, and emissions should be considered.

The analysis of other differences between battery and diesel LHDs should be further researched and studied when running the machines in a real underground mine environment. Do the failure rates or repair times differ, and if so, how much does this impact the overall productivity? Also, when considering sustainability, it would be useful to compare the overall emissions “produced” by BEVs with those produced by diesel machines over the course of the machines' lifetimes, which includes, among others, emissions produced during the manufacturing of the batteries and the diesel fuel production.

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