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Analyzing the Electricity Consumption and Costs of Electrical-Powered Machines When There is Orepass Failure in Underground Mine

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Abstract

In underground mining environment where the loss of orepasses is a dominant factor, the mine may face a challenge of improving the loading and hauling operations. Some of the options will be to rehabilitate the lost orepasses, or developing the new ones. When the rehabilitation cost is high, alternative strategies should be applied to compensate for the orepasses failure. One of the possible options is to use diesel or electric Load-Haul-Dumps (LHDs). The use of diesel-powered LHDs will increase heat and gas emissions which increase environmental concerns and ventilation costs, while adoption of electric-powered vehicles needs to be analysed. Therefore, this study was conducted at an existing underground mine in Sweden, to determine the electricity consumption and costs of electric-powered LHDs when there is a loss of orepasses. The AutoMod™ discrete event simulation tool was used during the analysis. The results show that, electric-powered LHDs have significant cost saving when used in case of orepass loss to move materials compared to diesel-powered units. However, the source of electricity to fully adopt electric-powered units may need further financial justifications to evaluate the impacts to the environment.

Keywords: Electricity costs; production rate; discrete event simulation; loading operations.

Introduction

In underground mining environment where the loss of orepasses is a dominant factor, the mines may face challenges of improving the loading and hauling operations. Some of the options will be to rehabilitate the lost orepasses, or developing the new orepasses. The actual costs of rehabilitating the orepasses using different alternatives are higher compared with the initial costs of developing new orepass (Hadjigeorgiou and Stacey 2013). When the rehabilitation cost is high and the time to restore the orepass is long, alternative strategies should be applied in order to compensate for the orepasses failure. One of the possible options is to use diesel or electric-powered Load-Haul-Dumps (LHDs).

Diesel-powered machines are flexible with relatively low capital costs, which do not require any additional infrastructure to operate in the mining environment. With the already established market and long tradition in the mining industry, it makes the diesel-powered machines difficult to compete with. However, the decision to use more LHD machines in the production area where loss of an orepass has occurred increases the environmental problems due to high heat and CO_2 emmsions. In such environment, more fresh air needs to be pumped and hence increasing the ventilation costs (Skawina et al. 2018). Continuing to use diesel-powered equipment will force mining companies to investigate the implications of the operational costs on their mine plan and will emphasize their needs to adapt to different situations (Paraszczak et al. 2013). This means that haulage methods that exploit lower energy consumption will be of great significance in the reduction of the operating costs for mining operations (Kecojevic and Komljenovic 2010). As mine depth increases to chase the orebodies which are difficult to access, with diminished grades, the increase in operating costs has a significant impact. One of the possible ways to contain elevated operating costs and provide comfort to work environment is to adopt the elctric-powered vehicles. The use of electric-powered units has fewer strains on ventilation requirements, emit low amount of heat, noise, and adverse particulate matters hence contribute less to the environmental problems and operating costs. The fluctuation in fuel price and the high energy density contained in a diesel fuel (which is twenty times the energy density of equivalent lithium ion or a molten-salt battery) has ignited the suppliers to establish the presence in electric engines (Schatz et al. 2015). The temperature rises when mining goes deeper into the bedrock will necessitate the need to develop the cooling systems and reducing the heat emission resulting to greener mining environment (Fridleifsson et al. 2008). In reaching more energy-efficient ways towards costs reductions, initiatives for energy reduction in mining processes are gaining attention worldwide (Jacobs et al. 2015). The European commissions is anticipated to bring down emission levels to the same as those of the USA and Japan by 2025; that is, < 0.01g/kWh particulate matters (Jacobs et al. 2015). Australia has acted through the introduction of sweeping new taxes on coal and iron ore producers by means of a mineral resources rent tax as well as the introduction of a broader carbon tax in the name of environmental protectionism (Salama et al. 2014).

Electric-powered LHDs can be powered by battery, overhead electric lines, or trailing cables. Battery offers the highest flexibility; however, battery powered vehicles are heavy and the battery must be regularly recharged. Overhead power lines may be feasible for haul trucks where routes remain constant for an extended period of time, but are impractical for LHDs which require a high degree of maneuverability (Paraszczak et al. 2013). A trailing cable plugged into the electrical infrastructure of the mine is currently the most viable way to power electric LHDs. The disadvantage of powering with electric cable is that it reduces the versatility of the LHDs, also presenting problems with cable faults and relocation issues, limited haul range, restricted movement, and cable wear (Paraszczak et al. 2013, Halim and Kerai 2013, Salama et al. 2015). Despite having more advantages compared to diesel-powered units, electric-powered equipment are not commonly utilized but continue to gain attention in mining operations worldwide (Paraszczak et al. 2013).

Numerous authors have advanced the state of the art in the electric-powered vehicles using various methods in solving underground loading and hauling related problems. Paraszczak et al. (2013) compared the performance of diesel and electric powered vehicles using data from Infomine and Sandvik specifications. In their study, they pointed out that electric LHDs powering with electric cable reduces the versatility of the equipment and presents problems with cable faults and relocation issues, limited haul range, restricted movement, and cable wear. They concluded that electric LHDs can be adopted in mass mining methods such as block and sub level caving, whereby relocations delays can be less critical as the operation is performed along a similar path for an extended period of time. Halim and Kerai (2013) investigated the ventilation requirements for electric powered machines operated in underground mines. They stated that replacing diesel vehicles with electric ones can reduce the ventilation power consumption of up to 40% of total mine power. Hustrulid et al. (2001) analysed the cost-benefit for electric LHDs for Western Australian underground mines, and discussed the issues related to diesel-electric development. They pointed out that despite the fact that elctric-powered machines are not universal solutions, but can offer lower operating costs and contribute to many qualitative benefits especially with respect to reduced exposure to diesel particulate matter. Paraszczak et al. (2014) examined the electric drive as an alternative for the diesel units. They concluded that the electric-powered vehicles have multiple advantages over their diesel counterparts including low heat emissions, and possible ventilation savings. Salama et al. (2015) analysed the energy consumption and gas emissions of diesel and electric-powered LHDs with similar bucket capacities using discrete event simulation. They found that the hourly energy cost generated by electric LHDs was 47% less compared to diesel LHDs of the same size. They concluded that in an environment of increasing energy prices and the increased need to mine at greater depths, minimizing the use of diesel-engine machines and increasing the use of electric machines can greatly benefit on green mining environment and cost reductions. Schatz et al. (2017) conducted a feasibility study on replacement of diesel machines to run into battery power in room and pillar and mining wall operations. They found that LHD vehicles could be adopted to run on battery power. However, larger units will require regular battery recharge which may be not feasible with the current energy content in Li-ion batteries. Most of these studies described the advantages of electric-powered vehicles over its diesel counterparts and pointed out that using these machines benefited the mines in environmental impacts and costs reduction.

The study presented in this paper, is the continuation of the work published by Skawina et al. (2019). In their study, they analysed the ventilation costs when using diesel-powered LHDs in case of the orepass failures. They concluded that the use of more diesel-powered LHDs provided the benefits towards cost reductions and improving throughput compared to rehabilitate the failed or developing the new orepasses. However, using more diesel-powered LHDs increases the ventilation costs and hence leads to environmental impacts and high operating costs. They suggested to use the electric-powered LHDs to reduce environmental problems and ventilation costs.

Therefore, in this study, electric-powered vehicles were analysed to determine the electricity consumption and costs when there is a loss of orepasses. The AutoMod^{TM} discrete event simulation tool was used during the analysis. Discrete event simulation was used to determine the production rates, and the results were used to estimate the electricity consumption and costs.

Materials and Methods

Case study

This study is based on data and information obtained from Kiirunavaara underground mine located in Kiruna, Sweden. The mine uses sublevel caving method to extract the iron ore (Figure 1). The ore reserves are distributed over 20 large and small ore bodies, with 14 ore bodies currently in production. Depending on the type of ore body, the interval between the sublevels varies from 20 to 30 m, with drift spacing of 22.5 m. The ore bodies are divided into blocks and then further into production areas spread over a 5 km long and 2.5 km wide area, each with its own group of orepasses. The orepasses are around 300 m long, have a diameter of around 3 m and dipping around 60 degrees. The drifts are approximately 5 m high and 6.5 m wide. The sequencing of drifts to be extracted is based on the rock stress-related factors, the ancillary activities of the production drifts, distances to the orepasses (depending on the production rate requirement) and the amount of ore left in each of the production drifts. The number of orepasses in the production areas varies between one and four depending on the size of the production area.

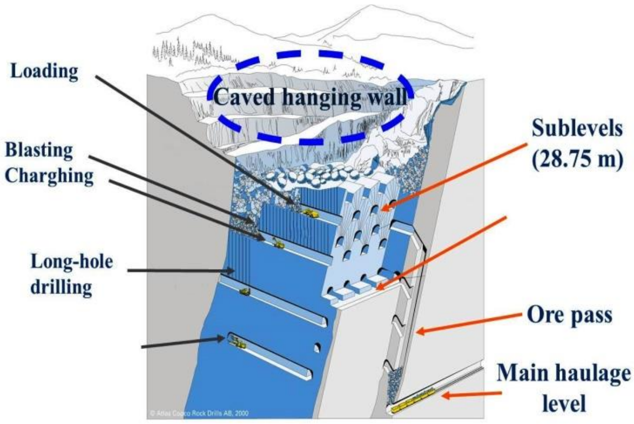

Figure 1: A large scale sublevel caving mining method (modified after Epiroc 2018).

The current loading practice in the mine is based on the use of manually operated diesel LHDs with a 21-tonne bucket capacity. In the smaller production areas, there is usually one LHD in operation. In larger production areas, between one and two LHDs are used simultaneously. The ore is transported from the draw points to the orepasses. From the orepasses, the ore is collected on the main haulage level by trucks and then hauled to the crusher, where the rock is fragmented and further transported via conveyor and then hoisting system to the surface.

Discrete event simulation modelling

The method used in this study is discrete event simulation. Discrete event simulation is a technique whereby variables change at discrete points in which the events occur (Banks et al. 2010). Discrete event simulation is currently widely used and a suitable method for analysing dynamic systems in mining. One of the key advantages when using simulation is that it does not disturb the existing system and enables evaluation of the designed system without building and interfering with the existing system (Dugardin et al. 2007). Also, since it represents the behaviour of the real system as it enables the users to understand the logic much easier (Spearman and Hopp 1996). The discrete event simulation method was chosen due to the existence of many uncertain operational elements and the random behaviour of the system. Discrete event simulation approach was considered as the most appropriate technique to deal with such operations and is known for its advantage of more accurate accounting for the real-world uncertainty and diversity to the variability of the interdependent components within the operations (Banks et al. 2010).

In this study, the AutoMod^{TM} discrete event simulation tool was used to simulate the underground loading operations and the results were used to determine the electricity consumptions and costs. The production area shown in Figure 2 was modelled. During modelling, the production rates and energy consumptions were modelled. The production rates were determined using machines specifications and the energy consumptions were determined by modelled Equations 1 to 4 using AutoMod^{TM}.

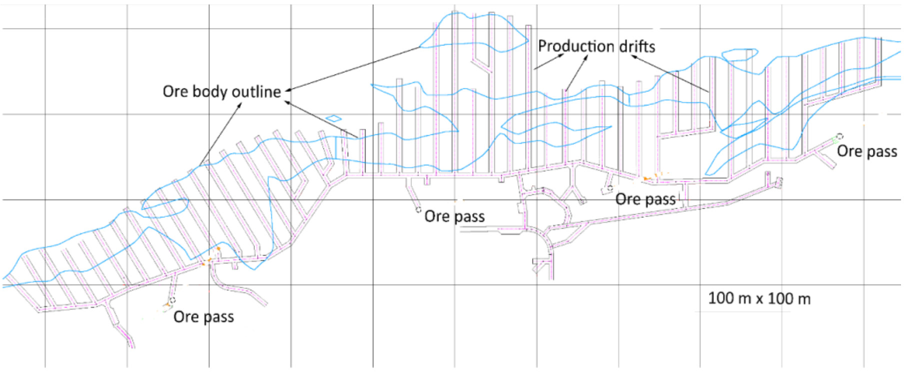

Figure 2: The plan view describing the model configuration.

Energy consumption is measured by the amount of fuel used during a specific period of time. The most accurate method of determining the energy consumption is through onsite measurements. Onsite measurements are the most accurate methods of determining fuel and power consumption; however, they are very expensive since continuous monitoring is required. In cases where there is no enough data from the field measurements, the fuel consumption can be estimated based on Equations 1 to 2 (Frank and Filas 2009).

$$C_f = EBP \text{ x } Fl \text{ x } UCF \quad (1)$$

Where; C_f stands for fuel consumption (L/h), EBP is the engine brake power (kW), F_l represents engine load factor (in decimal), and UCF is unit conversion factor 0.3 (L/kWh). Standard engineering calculations of the vehicle energy model can be written as seen in Equation 2 (EEO 2010):

$$E = E_{idling} + \frac{1}{\eta u \,(Eaero + Eroll + Eaccel + Eclimb + Ebrake + Eancill)} \quad (2)$$

Where; E is the total energy used by the vehicle, E_{idling} stands for energy used by idling, η_u is the energy efficiency of the engine and transmission, E_{aero} represents aerodynamic resistance, E_{roll} is the rolling resistance, E_{accel} is the energy required for acceleration (overcoming inertia), E_{climb} stands for energy required for climbing, E_{brake} is the energy dissipated in braking, and E_{ancill} is the energy consumed by ancillaries (e.g., alternator, air compressor).

To convert the fuel consumed (FC) into kilowatt hours (kWh), Equation 3 was used (Packer 2011):

$$E_D = \frac{FC \text{ x } A}{B} \quad (3)$$

Where; E_D is the diesel energy consumption (kWh), A is the 38.6 MJ/L–amount of heat released by the combusted fuel (conversion factors), and B stands for 3.6 MJ–heat used to produce 1 kWh. The energy consumption can be derived from the Energy Mass Balance model, estimated based on the loading cycles as seen in Equation 4.

$$E_C = \frac{(TR * g * [(V_W + B_C) * V_L + (V_W * V_E)])}{1000 * t} \quad (4)$$

Where: E_C is the energy consumption (kWh), TR is the total rolling resistance (tonne), g represents acceleration due to gravity (m/s^2), V_W is the gross vehicle weight (t), B_C is the bucket capacity (tonne), V_L stands for vehicle speed when loaded (m/s), V_E is the vehicle speed when empty (m/s), and t is the loading cycle time (hours).

During simulation modelling, the electric-powered LHDs were ordered to travel to one of the production drifts and then assigned to one of the orepasses. The LHD operators chose their destination by finding the closest orepass with the less queue. If all orepasses are unavailable, the LHD operators wait until an orepass is available. This affects the LHD cycle time when waiting in the production drift for the orepass to become available. Each simulation ended when the production level was mined out. It was assumed that there was enough blasted material for loading at the faces at all times. During operations, the electric-powered LHDs encountered delays whenever production disturbances or breakdown of the vehicle took place, thus reducing the operating time. Whenever breakdown of a vehicle took place, the vehicle stopped at its current location. Based on the experience from this mine, it was assumed that LHDs will be available for operation 90% of the total time and the production disturbances were estimated to be 20% of the total time. During the breaks, the LHDs were sent to the closest parking space.

Data collection

The kinematics data for three different types of electric-powered vehicles were collected (Table 1). These machines are LH 10E, LH 14E, and LH 21E. The aim of using machines of different bucket sizes was to analyse the possibility of meeting the desired production rates in the areas where there is problem of orepasses. The data were received from Sandvik equipment manufacturer and the operating mine in Sweden. It consisted of LHD capacity, speeds and machines operating weight. The average speed at gear three for all LHD machines was used for the analysis. Gear three was chosen because of the recommendations of mine safety procedures and regulations.

Table 1: Kinematics and machine specifications

LHD type	Bucket capacity (m^3)	Empty speed (km/h)	Loaded speed (km/h)
LH 10E	4.6	15.8	15.1
LH14E	5.4	15.5	15
LH21E	9	13.5	12.7

The operational data are shown in Table 2. These data were collected from the mine on several different occasions through video recordings, documentation and time studies. The loading and dumping times were analysed using a Minitab statistical tool by fitting in probability distributions that characterize the uncertainty and randomness of the operations. The drive power and vehicle weight for each machine were obtained and used in the determination of the energy costs.

Table 2: Technical parameters for electric LHDs

LHD type	Vehicle operating weight (t)	Drive power (kW)	Loading time (sec)	Dump time (sec)
LH 10E	28.2	132	30-35	5-10
LH14E	38.5	243	30-35	5-10
LH21E	58.4	283	35-40	5-10

Model verification and validation

In order to be able to sufficiently test the scheduling system, the simulated environment has to be verified and validated. This is to ensure the acceptable level of confidence for the actual system under study (Schelsinger 1974). Verification is the process in which various tests are undertaken in order to ensure that the conceptual model is correctly translated into an operational model (Banks et al. 2010). Validation is the process in which the operational model is confronted with the real system in order to demonstrate the acceptable correspondence between them (Banks et al. 2010). In this study, for verification purposes, the following tests were performed: debugging of the computer program, internal logic of the model and comparison of the program output with the conceptual. In cases where error or discrepancy of the faulty functionality was observed, the model was corrected. For this useful subroutine in form of the error message provided a handy way of picking up the errors. For validation, the review of the designed model was made by experts and the simulated mine was validated against historical data from the mine. All the simplifications and assumptions were outlined, discussed and accepted in detail by mining engineers. In certain cases, flow charts and additional explanations were added and presented to an expert group selected for the purpose of this study. When it comes to simulation experiments and comparison of the runs, the model was tested based on the information obtained from the mine. Part of the logic for the modelled operations is schematically shown in Figure 3. The simulation model was run for two shifts whereby for the first shift the electric-powered machines were working from 6 a.m. until 10 p.m. before blasting, and second shift started from 10 p.m. to 6 a.m. and the simulation was stopped when electric-powered machines moved all the mined out materials.

```
begin the P_vehicle arriving procedure
        call F_FindNextWorkLoc(VvehPtr(Ai_ID))
        set VvehPtr(Ai_ID) A_WorkLoc = A_WorkLoc
        call F_SetOperParam(VvehPtr(Ai_ID))
        dispatch VvehPtr(Ai_ID) to A_dest
        while A_Done = 0 begin
                if V_locData(A_Drift, A_PointIndex) > 0 begin
                set VvehPtr(Ai_ID) A_destIndex = A_destIndex
                dispatch VvehPtr(Ai_ID) to A_WorkLoc
                wait to be ordered on OL_vehicle(procindex)
                wait for u Vload_mean, Vload_STD sec
                if V_locData(A_Drift, A_PointIndex) < VvehPtr(Ai_ID) A_Capacity then set VvehPtr(Ai_ID)
                A_current_amount to V_locData(A_Drift, A_PointIndex)
                else set VvehPtr(Ai_ID) A_current_amount = VvehPtr(Ai_ID) A_Capacity
                dec V_locData(A_Drift, A_PointIndex) by VvehPtr(Ai_ID) A_current_amount
                if VvehPtr(Ai_ID) defined velocity <> 0 then
                call F_SetSpeed(VvehPtr(Ai_ID),Vr_Machine_speed(Ai_ID,Loaded),Vr_Machine_acc(Ai_ID,
                Loaded))
                dispatch VvehPtr(Ai_ID) to A_dest
                wait to be ordered on OL_vehicle(procindex)
                if V_orepass = 2 then begin
                        wait for u Vdump_mean, Vdump_STD sec
                end
                else
                        call F_boulder(V_boulder(A_destIndex), VvehPtr(Ai_ID) A_destIndex)
                        wait for u Vdump_mean, Vdump_STD sec
                end
                inc V_received(A_destIndex) by VvehPtr(Ai_ID) A_current_amount
                increment C_tonnage by VvehPtr(Ai_ID) A_current_amount
                inc C_cycles by 1
                call F_SetSpeed(VvehPtr(Ai_ID),Vr_Machine_speed(Ai_ID,Empty),Vr_Machine_acc(Ai_ID,
                Empty))
        end
        call F_FindNextWorkLoc(VvehPtr(Ai_ID))
        call F_update(VvehPtr(procindex))
end
```

Figure 3: AutoMod^{TM} codes created for the analysed production area.

Scenarios

As shown in Table 3, fifteen different combinations for each of the three electric-powered vehicle types used to load and haul materials to four orepasses were analysed, and these combinations are termed as scenarios. In the Table, 'FL' stands for the orepass located in the far-left side of the studied production areas, 'CL' stands for the orepasses located in the center-left position, while 'CR' and 'FR' stand for center-right and far-right, respectively. The aim is to determine the electricity consumption and costs when used in case of the orepass losses. The number of operational orepasses varied between one and four, while the number of each electric-powered vehicle type was varied from one to three and then to six. The number of vehicles was varied for each scenario to observe the variations in electricity consumption and costs in the current infrastructure in case of orepass loss. The maximum number of six LHDs was used in this study since a larger number of machines would result in very extensive waiting times and would be highly unpractical. In all the scenarios, the production rates and operating times are obtained from simulation analysis. The electricity consumption and costs are then calculated based on the simulated operating times.

Table 3: Scenarios modelled during simulation

Scenario	No. of LHDs	No. of available orepasses	Sequence of the orepasses			
			FL	**CL**	**CR**	**FR**
1	1 - 6	4	1	1	1	1
2	1 - 6	3	1	1	1	
3	1 - 6	3	1	1		1
4	1 - 6	3	1		1	1
5	1 - 6	3		1	1	1
6	1 - 6	2	1	1		
7	1 - 6	2		1	1	
8	1 - 6	2			1	1
9	1 - 6	2	1			1
10	1 - 6	2	1		1	
11	1 - 6	2		1		1
12	1 - 6	1	1			
13	1 - 6	1		1		
14	1 - 6	1			1	
15	1 - 6	1				1

Results and Discussion

The discrete event simulation analysis was conducted for all the 15 scenarios. During simulation runs, the number of operational orepasses varied from one to four, while the number of electric-powered vehicles of each type was set to one, three and six. The AutoMod™ simulation software was used during the analysis. All the scenarios were run to analyse the production rates, electricity consumption and costs when LH 10E, LH14E, and LH21E are used in case of orepass loss. The results of production rates for these equipment are shown in Figures 4, 5, and 6.

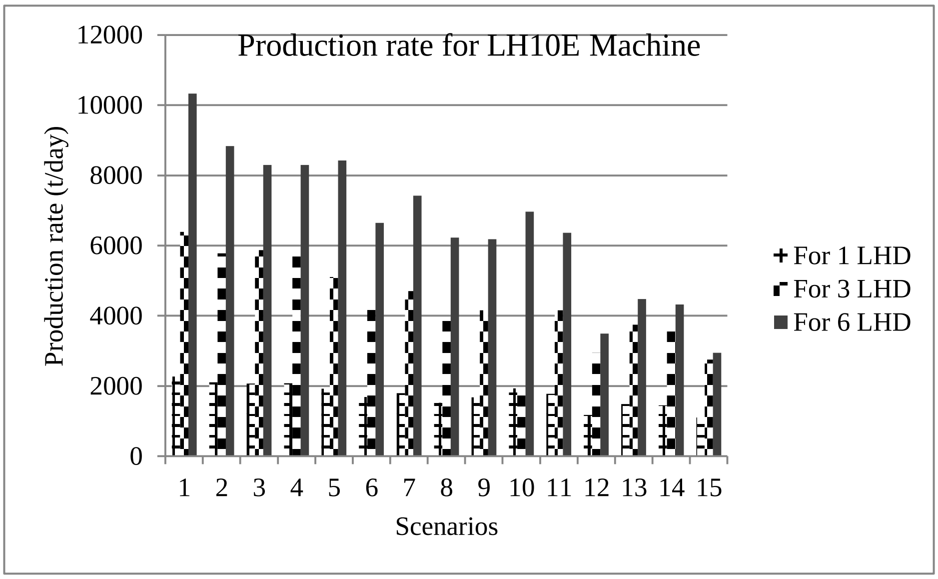

Figure 4: Production rate for LH10E LHDs when an orepass loss has occured.

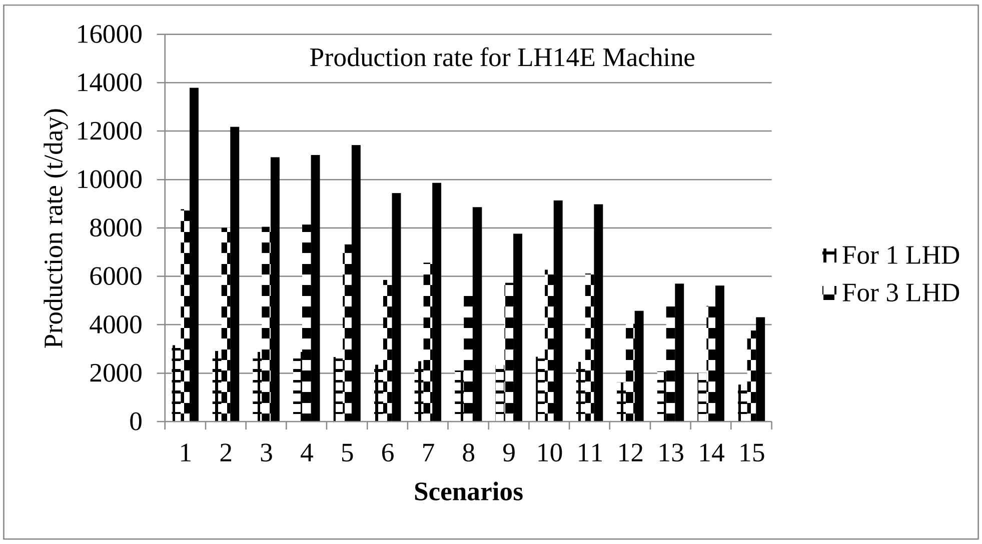

Figure 5: Production rate for LH14E LHDs when an orepass loss has occured.

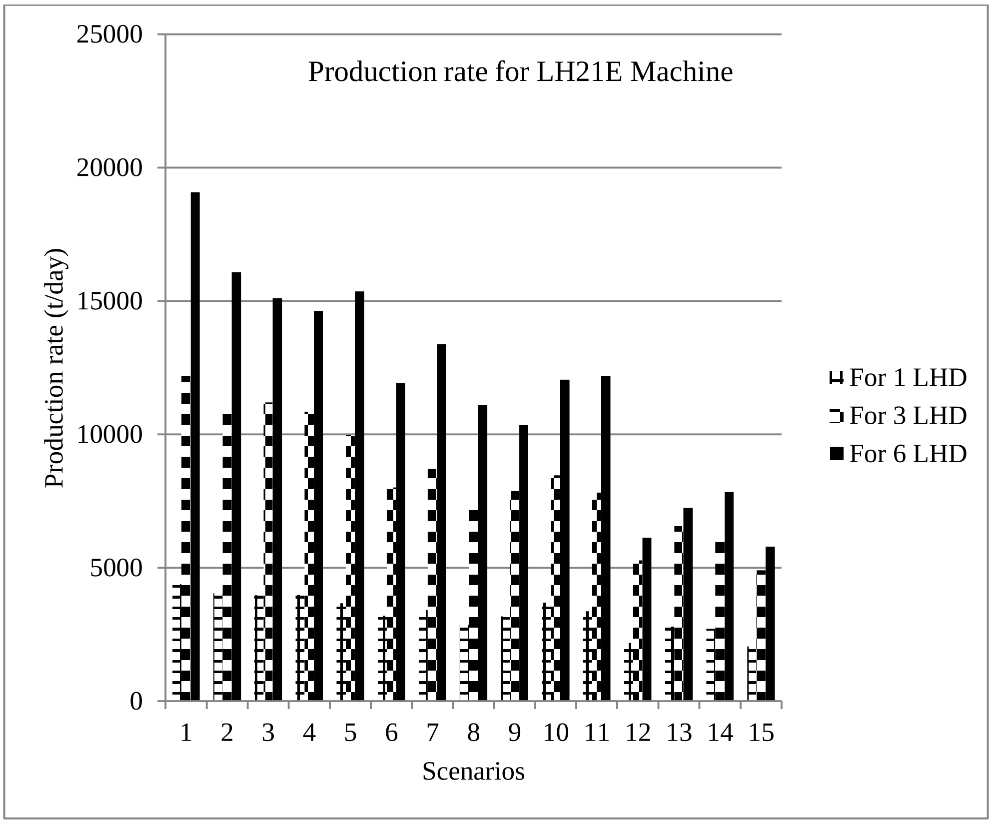

Figure 6: Production rate for LH21E LHDs when an orepass loss has occured.

As seen in these Figures, it shows that in each scenario, the production rate is observed to increase with an increase of the number of electric-powered LHDs. Depending on the scenario number, the production rate is not constantly increasing, as in some cases it tends to decrease, especially when six LHDs are in operation. This is due to the large number of traffic in the drifts and the longer waiting times for the machines when waiting on the cross cuts to give way to each other. As expected, the highest production rate was observed as 19,065 tonnes/day when six LH 21E LHDs are in operation, whereas the lowest production rate was 1,100 tonnes/day when one LH10E LHDs is in operation. In the area where only one orepass remains in operations, the production rate is much affected compared to when all the orepasses are operating. It also shows that despite the fact that smaller-bucket machines consume shorter cycle times when moving materials from loading to dumping points, but the larger-bucket machines were able to transport more ores. This means that LH21E which has 21 tonne bucket capacity moved more ores compared to LH10E which has a 10 tonne capacity. This is because of machines waiting time at the dumping point especially when the number of active orepasses is less. In comparisons to 21 tonne diesel machines (from the results published by Skawina et al. 2019), diesel-powered LHDs observed to move more materials per hour than the electric-powered LHDs of similar bucket sizes because diesel machines travel faster and have higher versatility, resulting in shorter cycle times than electric-powered machines.

Based on the production rates for all the analysed electric-powered machines, it was observed that with the current required production for the mine, only LH21E can be adopted when there is an orepass failure. Recognizing that moving ore is one of the mining’s most energy-intensive activities and that energy costs are large contributors to the operation costs, then we analysed electricity consumption and costs for LH21E when there is long term orepass failure. Results from discrete event simulation and the empirical formulas shown in Equations 1 to 4 were used during estimation (Table 4).

Table 4: Electricity consumption and costs for LH21E

	1 LHD		3 LHD		6 LHD	
Scenario	Consumptions (kWh/cycle)	Costs (US $/tonne)	Consumptions (kWh/cycle)	Costs (US$/tonne)	Consumptions (kWh/cycle)	Costs (US $/Tonne)
1	16.72	0.10	18.03	0.10	22.90	0.13
2	18.18	0.10	19.77	0.11	27.37	0.16
3	18.53	0.11	19.51	0.11	28.66	0.16
4	18.45	0.11	20.19	0.12	29.70	0.17
5	20.03	0.11	21.90	0.13	28.37	0.16
6	22.98	0.13	27.44	0.16	36.65	0.21
7	21.49	0.12	25.22	0.14	32.43	0.19
8	25.66	0.15	30.37	0.17	39.33	0.22
9	23.13	0.13	27.67	0.16	41.62	0.24
10	19.91	0.11	25.97	0.15	36.30	0.21
11	21.84	0.12	28.08	0.16	35.90	0.21
12	33.67	0.19	41.90	0.24	71.91	0.41
13	26.29	0.15	33.69	0.19	60.47	0.35
14	27.13	0.16	34.83	0.20	55.87	0.32
15	35.90	0.21	44.99	0.26	75.72	0.43

It shows that the electricity consumptions increase with the decrease in number of active orepasses with the higher consumptions when six electric-powered LHDs are in operations. For example, when six LHDs are in operations, the electricity consumption is 75.72 kWh compared to 35.39 when one LHD was simulated. Table 4 also shows the electricity costs when LH21E was used in case of orepass failure. The electricity price was assumed as $ 0.12/kWh (US EIA 2019). It shows that the average electricity cost is observed to increase when the number of LHDs in operation increases, while the number of active orepasses decreases. For example, when all four orepasses and six LHDs are in operation, the electricity cost is $ 0.13 per tonne. This cost increased to $ 0.43 per tonne when six machines are used in one active orepass. This means that when there is orepass failure, the demands of more electric-powered LHDs will increase power consumptions as well as costs.

The results published by Skawina et al. (2019) using the same underground mine shows that diesel-powered machines have high operating costs. The costs are observed to be higher when six diesel LHDs are operated in one active pass. As for electric-powered LHDs, no ventilation will be required to dilute fumes or diesel particulate matters. It will also need less ventilation costs for geothermal control and to provide oxygen to workers. This will make electric-powered machines to have low operating costs.

Analysis of these results shows that electric-powered LHDs have significant cost saving when used in the case of orepass loss as they need less electric energy per tonne to move materials compared to higher fuel consumption per tonne for diesel engines. The main concern is the source of electricity which may have high impacts to the environment. Electricity can be generated using several alternatives such as coal, hydro, natural gas, solar, and nuclear energy. When electricity is produced from burning of coal, the emissions is very high compared to when produced from other energy sources. Under assumptions that electricity produced from less emissions methods, electric-powered LHDs becomes a real substitution to replace diesel engine machines in underground mine operations. In a situation that a mine aimed at operating under cost reduction scenario, the use of electric-powered LHDs may gain a boost on acceptance especially for a mine which has a long operational life. However, the acceptance requires further analysis on financial justification if the increase in capital costs of electric-powered machines might be recuperated by the additional saving gained.

Conclusions

This study was conducted at an existing underground mine, to determine the electricity consumptions and costs of electric-powered LHDs when there is a loss of orepasses. The AutoMod^{TM} discrete event simulation tool was used during the analysis. The results indicated the following:

- For the studied case, the production rates were observed to increase especially when six electric-powered LHDs were in operation with high production when LH21E was used compared to other analysed machines. For example, the production rate increased to 19,065 tonnes/day when six LH 21E LHDs were in operation whereas the lowest production rate was 1,100 tonnes/day when one LH10E LHDs was in operation. Based on the production rates for all the analysed electric-powered machines, it was observed that, with the current required production for the mine, only LH21E can be adopted to use when there is an orepass failure.
- The electricity consumption increases with decrease in number of active orepasses with the higher consumptions when six electric-powered LHDs are in operations.
- Based on the electricity consumption, it can be seen that in the area affected by an orepass loss, when all four orepasses and six LHDs are in operation, the electricity

cost is $ 0.13 per tonne. The cost increased to $ 0.43 per tonne when six machines were used in one active orepass. This means that by increasing the number of electric-powered LHDs in the areas affected by orepass loss generated higher electricity costs compared to areas which are not affected by orepass loss.

- In the situation that a mine is experiencing a long term orepass failure, the decision to increase the number of electric-powered LHD machines may lead into slighlty lower production rate and increases the electricity costs.
- Electric LHDs have significant cost saving when used in case of orepass loss as they need less electric energy per tonne to move materials compared to higher fuel consumption per tonne for diesel engines. However, the source of electricity may have high impacts to the environment.

Future research should include emission costs from different energy sources and electric-powered capital costs.

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