Production rate comparison using different Load-Haul-Dump fleet configurations: Case study from Kiirunavaara Mine

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Abstract
The constant increase in mining depth creates new demands on the various mining processes and unit operations. The aim of the mine haulage system is to move the rock masses from one location to another in the most efficient manner by minimizing the long and short-term operational costs while meeting production targets. Underground loaders are used for this type of operations. Depending on the chosen approach, the efficiency of moving the rock mass will vary and by evaluating and selecting one or more of the hauling options, the production rate can be improved. This paper aims to estimate the rate at which the ore can be hauled by comparing the use of different diesel and electric Load-Haul-Dump (LHD) machines form draw points to the ore passes using Discrete Event Simulation (DES). The study has been done for Loussavaara Kiirunavaara AB (LKAB) mine in Sweden, where one of the largest iron ore deposits in Europe is being extracted using sublevel caving. The study shows the production of the different fleet configuration based on the number, size and type of LHD machines. The study is concluded by identifying the fleet configurations that fulfill the 10 000 (tonnes/day) production target. The option of using two 18-tonne diesel LHDs was the closest to reach the production target. Furthermore, if smaller drifts are required when mining progresses deeper, operation can be managed and possibly improved by using 18-tonne LHD machines.

Keywords: load-haul-dump machines; production; discrete event simulation; fleet configuration

Introduction
As mining progresses downwards, towards greater depths, a new haulage system may prove to be necessary in order to maintain the production rate. Underground loaders, such as Load-Haul-Dump (LHD) machines are generally the first machines used in the haulage system unit operations. LHD machines move the ore from the draw points to the ore passes or load the ore directly to the hauling equipment. Depending on the position of the draw points and the dumping areas, the tramming distances will vary. However, efficiency and effectiveness will also vary depending on the type of the vehicle (Salama, et al., 2014). Selecting the wrong LHD may limit the loading performance and purchasing of inappropriate equipment may lead to increased operational costs and lower mine output (Salama, et al., 2014). This study analyses the practice and performance of both electric and diesel LHD machines operating in the mine based on the changing conditions due to increased depth. By modeling the loading operations the production rate for different sized diesel and electric LHD machines is compared using DES. The aim of the analyses was to identify the fleet configuration which enables the closest production rate of 10 000 (tonnes/day) and the performance of the LHD machines operating at greater depths. The study was financed by the I² Mine Project (Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future) and created baseline for the future studies, possible alternatives and improvements that can be made in the underground transportation systems.

Load-haul-dump machines
Currently both diesel LHD machines and electric LHD machines are used to load and haul the material in the Kiirunavaara mine. Also, automated LHD machines are being used under certain conditions and in certain areas of the mine. The diesel LHDs have a 21-tonne bucket capacity and are semi-automatic, enabling the possibility to load ore in noxious atmosphere, shortly after the blasting. A single operator can also control more than one unit at a time (Chadwick, 1996). The electric LHDs have 25-tonne bucket
capacity, and are less flexible due to their size and their cable movement restriction. According to Chadwick (1996), “electrically powered LHDs are often a better choice than diesel units because there are no emissions and because of their low noise and heat levels”. The collective name LHD includes machines of different types, designs and sizes. One example (of a Sandvik LHD) can be seen in Figure 1.

Figure 1    LHD (Sandvik, 2014)

Kiirunavaara mine
The Kiirunavaara mine, located in northern Sweden is an iron mine using the sublevel caving method to extract the ore from the underground. The orebody is around 4.5 km long and 80 meters thick on average. For production planning reasons, the orebody is divided into ten blocks, each around 450 meters long. One block has several production levels. In the studied production area, 17 production drifts of varying length are connected to the main drift. The current main level is located at 1045 meters (see Figure 2), whereas the deepest new haulage level is located at 1365 meters.

Figure 2    One of the haulage levels (LKAB, 2014)
The extraction processes are separated according to unit operations for productivity reasons (Heden et al., 1982). Slice drilling is normally performed a long time in advance, before charging takes place and just after the development is completed. Fan drilling is used to slice the levels with a spacing of approximately three meters. According to Heden et al. (1982), “Normally, two levels are mined at the same time, while two levels are being drilled and three levels are developed”. The production follows a cyclical pattern, where charging and later blasting are performed every morning around 1:30 a.m. Next, the loaded rock mass is hauled to the ore passes, where secondary breaking takes place. Secondary breaking of oversized material is done using grizzlies and rock breakers. A grizzly is a sizing device used to ensure a maximum passing size of material and to protect the crusher. Grizzlies also act as a metal scavenger to trap rock bolts, wire mesh, drill steels, and cables. These are removed from the ore stream periodically by a loader from the top of the grizzly (Bloss et al., 2011). Fixed or mobile rock breakers are often used in conjunction with a grizzly (Bloss et al., 2011). Rock breakers are employed to prevent oversized rock entering or blocking the ore pass. The ore in the Kirunavaara mine, from the draw points to the ore passes, is loaded by either electric or diesel-driven LHDs. Current loading practice is based on using manual electric vehicles during the day and semi-automated diesel vehicles at night. Generally, only one vehicle at a time is allowed to work in one of the main production areas. The sequencing of drifts to be extracted is mainly based on the rock stress related factors, the working of the production drifts, distances to the ore passes (depending on the production rate requirement) and the amount of crude ore left in each of the production drifts.

**Analysis of the loading operations**

The analysis of different types of LHDs aims to show the production rate with the total time required to finish the whole production area. Selection of the appropriate equipment is determined by the production requirements (Sweigard, 1992). Scenarios shown in Table 2 depict different types of LHDs selected depending on their type (diesel, electric, bucket capacity, etc.), number of machines allowed to work in the production area and the length of time they can work. Smaller LHDs are considered, as, when the mine depth is increasing, a smaller drift size may be required. The AutoMod discrete event simulation was used in the study to model and analyze the real system over time. The scenarios generated were run in order to see the changes in the production rates and the interaction of the model with these changes. The base case model was appropriately adjusted to the underground hauling mine system and used to produce the scenarios.

**Data collection**

Collection of data was done between 13 November 2013 and 31 January 2014. The collected data were checked and validated with the assistance of specialists in the mine. Night shifts were also included in the study, where semi-automated LHDs are used to work shortly after blasting. The scale of the investigation consisted of one of the main production areas. The production was assumed to not encounter any disruption from not having blasted material ready to load. The collected data consist of layout, LHD, ore pass, rock breaker and train information and include the distances from the work location to the destinations, delays that the LHD machine encountered during the working process and LHD parameters. These parameters, such as speeds of the vehicles, acceleration, deceleration (loaded or empty), rotation velocity, and their bucket capacities differ depending on the type of the LHD used (see Table 1).

**Mine layout**

Figure 3 presents the layout of the production area used in this study. The drifts are approximately 5 meters in height, approximately 7 meters wide and with a length up to 138 meters. Spacing between drifts is usually 25 meters and height between production levels is approximately 30 meters.
Loading equipment
In the study, four types of machines were considered for the specified hauling operations, two electric-driven LHDs and two diesel-driven LHDs. One of the diesel-driven LHDs is semi-automated. Semi-automated LHDs have a bucket capacity of 21 tonnes and operate in both manual and automated modes. The diesel LHDs with an 18-tonne bucket capacity are manual. The first type of electric LHD has a bucket capacity of 25 tonnes and the second type of electric LHD has a bucket capacity of 14 tonnes.

Table 1 shows the vehicle speeds for different LHDs. For the 21-tonne diesel and 25-tonne electric, the values were estimated based on the real data, whereas for the 14-tonne electric and 18-tonne diesel theoretical data was collected from the suppliers.

Table 1 Vehicle speed specification for diesel and electric LHDs

<table>
<thead>
<tr>
<th>LHD type</th>
<th>Forward/Reverse speed</th>
<th>Acceleration</th>
<th>Deceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Empty (km/hr)</td>
<td>Loaded (km/hr)</td>
<td>Loaded/Empty (m/s²)</td>
</tr>
<tr>
<td>25-tonne electric</td>
<td>18</td>
<td>16</td>
<td>1.58</td>
</tr>
<tr>
<td>21-tonne diesel</td>
<td>25.5</td>
<td>22.4</td>
<td>1.2</td>
</tr>
<tr>
<td>14-tonne electric</td>
<td>23.5</td>
<td>20.5</td>
<td>1.2</td>
</tr>
<tr>
<td>18-tonne diesel</td>
<td>24.7</td>
<td>23.7</td>
<td>1.58</td>
</tr>
</tbody>
</table>

The availability of the LHDs is approximately 90%, based on the input data from the Kiirunavaara mine. The estimated loading time was 40 seconds, the dumping time was five seconds and the different vehicles speeds, also based on the data from the Kiirunavaara mine. Loading and dumping time was assumed the same for all LHD types, as the 14-tonne and 18-tonne LHDs are not in operation yet, thus no data are available. Additionally the production area availability was estimated to 80%.

Ore pass
The ore passes are 300 meters long and have a diameter of around 3 meters. The ore passes dip around 60 degree. Common boulder size is 1.35 meter in diameter and the largest boulder encountered was 3.5 meters in diameter. The size of the boulders, which can pass through is limited to around 1.5 by 1.16 meters.
**Rock breaker**
The rock breaker operations are modeled as waiting time in the dumping operation. Boulder frequency was estimated to be one boulder per every 10 dumps. Average rock breaking time was set to triangular distribution with a minimum of 1 minute, average of 5 minutes and maximum of 30 minutes. If the time to wait for the boulder to be broken exceeded 5 minutes the machine used another ore pass until the boulder was fixed.

**Simulation model settings**
The layout of the main production area is presented in Figure 3. In the model, two parking spaces are created. The model work sequence moves the LHD from the first defined location in the production drift to the next location. If none of the work locations are found, the LHD goes to the parking space to wait for the next assignment. In the working process, lunches, times when the machine is functional but not working and movement of the machine to parking when going off for the break, are included. After every blast, the length of the drifts is assumed to be reduced by approximately three meters. The LHD shift schedule is 22 hours, consisting of two shifts of eight hours (including two breaks of 45 minutes each), one night shift of 2.5 hours and automated shift of 3.5 hours. Work is performed seven days a week. The shift time includes the time for trammimg, hauling and dumping from a draw point to an ore pass. The 21-tonne diesel LHD is allowed to work after 2:30 am because it can operate in automated mode in the still polluted area, whereas the other types of LHD presented in this study are only operated in manual modes. Due to this, the vehicle shift hours in respective scenarios are changed to 4:00 am to 6:00 am.

In this study, five production scenarios have been analyzed (see Table 2) in which either one or two vehicles were allowed to work simultaneously in the production area. In the scenarios with two vehicles, the first vehicle was working on the left side of the production area and the second vehicle was working on the right side of the production area. The two LHD machines are working independently of each other. In all cases, machines were ordered to travel to one of the production drifts and then directed back to one of the ore passes. No more than two LHD machines were allowed to work at the same time in the same production area. This is due to the fact that if more vehicles worked in the same area more problems would arise from queuing of the vehicles; equipment constraints (electric cable restriction), for example, would mean that that solution was not feasible. Simulation ended, where there was no longer any material left to be loaded, meaning production level was completed after moving 6.17 Million tonnes of the rock mass. The smaller LHDs are under consideration since smaller drift size may be required when the mine depth increases.

**Simulation**
An increase in number of LHDs was simulated to show the scenario where there would be no need to decrease the size of the drifts, while mining deeper underground, thus providing a possible way of increasing the production rate. In case of the need to decrease the size of the drifts due to the rock stresses while mining deeper, the smaller machines scenarios were simulated. In case the production drifts should be downsized the 21-tonne diesel LHDs are used, in order to analyze by how much the production rate varies from the base case scenario. Furthermore, if the production drifts would be even further downsized, the 18-tonne diesel and later 14-tonne electric are used.

First, Table 2 shows both 25-tonne electric and 21-tonne semi-automated diesel loaders. The aim of first scenario was to shows by how much the production rate differs when the number of vehicles increases. The second scenario is the same as first scenario but this time from 6:00 to 10:00 am, two 25-tonne electric LHDs are replaced by two 21-tonne diesel LHDs. The third scenario has two 18-tonne diesel LHDs instead of two 25-tonne electric LHDs and one 21-tonne diesel LHD instead of two 21-tonne diesel LHDs, as the production rate in the two 21-tonne diesel LHDs (scenario 2) went over 10 000 tonnes day. The fourth and fifth scenarios look at using either two 14-tonne electric LHDs or two 18-tonne diesel LHDs with smaller bucket sizes when excluding work after the blasting and considering the smaller drifts.

<table>
<thead>
<tr>
<th>Table 2 Scenarios for diesel and electric LHDs</th>
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<tbody>
<tr>
<td><strong>Shift schedule</strong></td>
</tr>
<tr>
<td><strong>Scenario</strong></td>
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<td>2</td>
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### Model verification and validation
Verification was assured in accordance with the conceptual model. In verifying the model, comparison of the conceptual model with the simulation model, a debugger, an animations check and systematic scanning of the logic and specialist assistance were used.

Validation was assured by comparing the base case scenario with the real system and using expert assistance. For 25-tonne electric LHD 426.9 (tonnes/hour), in average, the 426 (tonnes/hour) was achieved and for 21-tonne diesel 415 (tonnes/hour), in average, the 415 (tonnes/hour) was achieved. Moreover, different LHD scheduling options were considered, in order to see the influence in total time, when extracting the production drifts, and this resulted in differences of only a few hours. Although different LHD scheduling does not affect the total haulage time, if considering shorter periods of time, a possible increase or decrease of speed in choosing different drifts is possible, as the distances between the drifts vary. Additionally, when considering random number distribution, several runs were made and compared with each other and the results also differed by no more than few hours.

### Results and discussion
The total amount of material transported from the production drifts to the ore passes was 6.17 Million tonnes in all scenarios, which is the number of theoretical tonnes available in the defined production area.

The production rate for the base case was 6 143 (tonnes/day) and 260 377 cycles to finish extracting the whole production area within 1 004 days.

The production rate measured as tonnes per day, for the different scenarios are presented in Figure 4. The production rate showed an average value of the whole production area. The range falls between 6 143 tonnes to 12 007 tonnes per day.

![Figure 4] Simulation results for the different scenarios

In Figure 5, the total production time was compared with different scenarios. The times to complete the production area (excluding the base case scenario) vary between 1.4 to 2.2 years for the different scenarios.
The reason for the consequent increased production rate, with increased number of LHDs is that two LHDs work independently of each other, thus causing no delays or queues. Even the ore passes are separated between the LHDs, so every LHD has two ore passes to use. For scenarios, when only one LHD works, the LHD can use the whole production area and all four ore passes.

Scenario 1 where one additional machine was allowed to work in the production area, the time to finish the whole production area was only about 50% of the base case scenario. Adding an extra vehicle in scenario 1 to the production area reduced the production time by almost 50% from around 1004 days to around 514 days. If only 21-tonne diesel vehicles were used in the mine (scenario 2), the total time to extract the production area increased by 9 days and the production rate drop was from 12 007 (tonnes/day) to 11 793 (tonnes/day), when comparing scenario 1 with scenario 2. The production time increased by 130 days and the production rate drop was from 11 793 (tonnes/day) to 9 452 (tonnes/day), when comparing scenario 2 with scenario 3. In this scenario number of 21-tonne diesel LHDs was reduced from 2 to 1 during the evening and night. If the fleet would be completely changed to only new machines used for the load haul and dump operations, two 18-tonne diesel were faster than two 14-tonne electric LHDs. In all cases, all the scenarios shown require less time to finish total production area. The 18-tonne diesel LHDs (scenario 5) had around 200 days of advantage in production time compared with 14-tonne electric LHDs (scenario 4).

When considering the 10 000 tonnes per day goal, scenario 3 and scenario 5 are the ones closest to reaching the goal. The scenario 3 production rate needs an increase of only around 548 (tonnes/day) and scenario 5 needs a decrease of around 156 (tonnes/day) to reach the production rates to 10 000 (tonnes/day).

**Conclusions**

The production rate for different types of LHDs has been analyzed using the AutoMod simulation tool. Various scenarios in terms of haulage equipment fleet were simulated based on the machine sizes, tramming speeds, acceleration, deceleration, delays and shift breaks. The results show that the base case load, haul and dump operation, which consists of a 25-tonne electric and a 21-tonne diesel machine, achieves the production rate of 6 143 (tonnes/day) and requires around 1 004 days to transport the total of 6.17 Million tonnes of rock mass from the production drifts to the ore passes.

Among all simulated scenarios, the aim was to identify the fleet configuration with the closest production rate of 10 000 (tonnes/day). The option of using 18-tonne diesel LHDs (scenario 3 and scenario 5) was the closest to reach the goal of 10 000 (tonnes/day). The total amount of time saved would be equal to around 351-396 days. This reveals that the total time to transport material is decreased by almost 35-40% (0.96-1.08 year) of the initial time required to finish the production area.
Taking into consideration the smaller drifts, due to the increased depth for example (resulting in not being able to accommodate 25-tonne electric LHDs and 21-tonne diesel LHDs), the analysis show that the scenario with only two 18-tonne diesel LHDs (scenario 5) resulting in the production rate of 10,156 (tonnes/day), is the closest to fulfill the current production performance targets. Therefore, if smaller drifts are required when mining progresses deeper, operation can be managed and possibly improved by using 18-tonne LHD machines.

Future research

Particular areas of interest are to look at the performance of the LHD machines operating at greater depths, with main focus on smaller LHD machines and also emissions of particulate matters and their operating cost. Additionally, increasing rock stresses with depth may require a downsizing of the drifts and openings which will affect the size of the production machines. Moreover, additional studies should be made based on the flexibility of the machines to handle a new environment, their cost and maintenance. In future studies, more focus should be put on the emissions, alternative loading systems, increasing the number of machines and changing the type of LHD machines.

References


