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Comparison of Productivity When Running Filled, Near-Empty, or Flow-Through Orepass Using Discrete Event Simulation

Bartłomiej Skawina [1,2,*], Abubakary Salama [3], Johan Gunillasson [4], Mats Strömsten [4] and Thomas Wettainen [2]

1 Department of Civil, Environment and Natural Resources Engineering Division of Mining and Rock Engineering, Luleå University of Technology, 977-54 Luleå, Sweden
2 Luossavaara-Kiirunavaara Aktiebolag (LKAB), 983-81 Malmberget, Sweden; thomas.wettainen@lkab.com
3 Department of Mining and Mineral Processing Engineering, School of Mines and Geosciences, The University of Dar es Salaam, Dar es Salaam P.O. Box 35131, Tanzania; asalama@udsm.ac.tz
4 Luossavaara-Kiirunavaara Aktiebolag (LKAB), 981-86 Kiruna, Sweden; johan.gunillasson@lkab.com (J.G.); mats.stromsten@lkab.com (M.S.)
* Correspondence: bart.skawina@ltu.se; Tel.: +46-725862980

Abstract: Ore passes are often the main part of sublevel caving transportation systems, and they use gravity to move material to lower levels in the mine. During operations, the ore pass structures are exposed to the risk of stoppage and failure, leading to a long-term reduction in operational capacity and affecting productivity. The failed ore passes can be restored or rehabilitated, but the rehabilitation cost is normally high and the time to restore is usually long. To minimize disturbances and stoppage of the ore pass, alternative strategies should be considered. The appropriate design and operation of an ore pass is crucial. Therefore, this study compared running ore pass systems in a filled, near-empty, or flow-through manner using discrete event simulation. The aim was to compare the ore pass operational performance and impact on reaching the daily and 90-day production targets of 76.4 Ktonnes and 6.9 Mtonnes, respectively. The results showed that running the ore pass in flow-through mode, filled manner, and near-empty manner achieved 96%, 80%, and 81% of the production target, respectively. In mining operations where ore pass systems are used to transfer material, running them in a flow-through mode can ensure higher production and fewer hang-ups, as it lessens the chance of blocks arching over a chute throat and leads to less blasting.

Keywords: ore pass; sublevel caving; discrete event simulation

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1. Introduction

Ore passes are often the main part of sublevel caving transportation systems; they take advantage of gravity to move materials to lower levels in the mine. During operations, ore pass structures are exposed to the risk of stoppage and failure, leading to a long-term reduction in operational capacity and affecting productivity [1,2]. Improving productivity can reduce operating costs and increase production. An efficient way to calculate productivity is to utilize simulation programs. The most common ore pass failures are associated with hang-ups and ore pass stress degradation [3,4]. Hang-ups are build-ups that block the passage. Degradation results in the enlargement of the original dimensions of an ore pass, and this influences the wall stability. If the rock mass quality is poor or there is high stress on the wall of the ore pass, together with additional rock mechanically impacting the wall, the enlargement of the ore pass walls can become critical. If not treated in time, the size of the ore pass can even become 20 times the size of the designed diameter [5].

Failed ore passes can normally be restored or rehabilitated back to their operational state [6]. A common method to restore an ore pass with hang-ups is the blasting technique. However, frequent blasting to restore the ore pass and break up the hang-ups can damage the ore pass walls or the chute. Restoring the ore pass and bringing it back to an operational state is also time-consuming and costly. Whether it is related to blasting or filling the ore pass with concrete, the time the ore pass is out of operation can be longer than the time it is operational. Ore pass rehabilitation of a failed pass is very expensive and usually involves the use of rock supports, which are also a challenge, unsafe, and time-consuming [7]. Normally, the rehabilitation costs of an ore pass are high compared to the initial development cost of the ore pass system. Several studies have addressed ore pass transportation problems in underground mines and proposed various techniques to restore and rehabilitate the ore pass [1,6,8,9]. Stacey and Swart [6] suggested the use of liners, especially in weak or closely jointed blocky rock, to prevent uncontrolled growth of the ore pass dimensions. The liners may be useful as a prevention measure prior to the use of the ore pass or after the repair to increase longevity. A study of 18 international mines in the Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future found most mines with ore pass problems have opted to develop new ones rather than restore or rehabilitate the existing passes. The mines claim that the process of restoring an ore pass is expensive and time-consuming, and this, in turn, reduces production [1,8,9]. As the rehabilitation cost is normally high and the time required to recover the ore pass to its operational state is long, alternative strategies should be considered to determine the one that can minimize disturbances and stoppages.

2. Ore Pass Running Modes

Recent research studies dealt with simulating productivity issues of the ore passes [1,2,9]. Two studies [1,2] focused on the effects of ore pass loss on production (fewer ore passes available for the operation) and, in the other, simulation models were run to test the effects of equally reducing the number of ore passes in operation and their buffer storage capacities while progressing deeper [9]; in those studies, no specific ore pass loading rule was applied. However, in this study, different ore pass loading rules are introduced (filled, near-empty, flow-through, and special case).

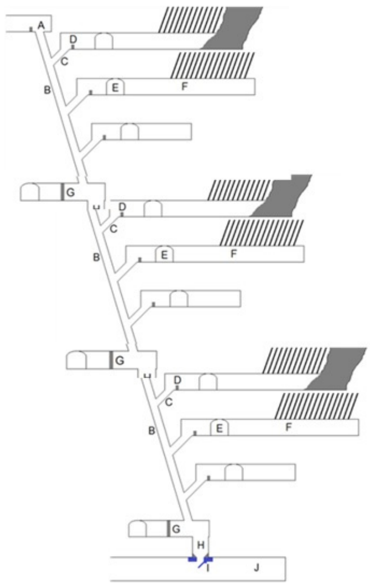
Running ore passes in a filled manner is the process whereby ore passes are not allowed to have too much empty space. This increases the risk of hang-ups but decreases the level of ore pass degradation and seismicity near ore pass walls. The method is also used to curtail gravity failures [10]. The distance between the place where the material is dumped into the ore pass and the level of the ore pass that is filled is much shorter, so the impact is much less. Running the ore pass in this system improves the stability and prevents enlargement of the ore pass, especially in places where the rock mass quality is poor [5,11]. However, running the ore pass filled could cause problems, especially if there is a lot of water. Mud-rush is likely to flood the discharging stations and disturb operations. If the material is not being drawn from the ore pass for longer periods, the system might encounter more hang-ups due to the settling of fine materials at the bottom, material oxidation, and interlocking boulders [10]. A preferable working practice would be to make sure that those ore passes that are kept filled are continuously drawn.

Running ore passes in a near-empty manner is the process whereby ore passes are run as empty as possible with the minimum amount of material inside. Running ore passes in a near-empty manner ensures fewer hang-ups, as it lessens the chance of blocks arching over a chute throat and leads to less blasting (especially arching). Blasting takes time and increases the damage to the pass walls [11]. Rock falling by gravity crashes at the bottom, leading to better fragmentation and greater compaction of the material. However, high impacts can cause severe structural damage [10].

Swedish practice also uses a flow-through ore pass system configuration and, in special cases, the ore passes with some very fragile sections caused by stress interaction are kept filled. Running ore passes under this condition helps to improve performance, but creates other risks associated with water interaction. These include cohesive hang-ups and the risk of in-rush of material below the discharging bin. In the past, when ore passes were run in a flow-through manner, the number of blasts was 3 to 4 per week, while in ore passes run in a filled case, there were as many as 96 blasts per week [12].

3. The Case Study: Kiirunavaara Ore Pass System

The Kiirunavaara underground iron mine located in Sweden uses the sublevel caving method. In this method, development drifts are opened first, followed by the drilling of the ore passes. The geology of the mine area is composed of igneous and metamorphic rocks, with syenite porphyry being the most commonly occurring. The orebody strikes north–south with an eastwards dip of about 60 degrees. The orebody width varies from a few meters to 200 m with unknown depth. The dominant joint orientations have been documented for most levels. The ore passes extend near-vertically from the current mining area down to the bottom of a new mining area, where a transportation level is located. Horizontal sublevels are created, including crosscuts that provide access to the crosscuts. The mine is divided into 10 main production areas, called blocks, which extend from the uppermost mining level down to the current main level. Each mined block consists of 10 sublevels. Each block is 400 to 500 m-long and has a group of ore passes located at the center of the production area and extending down to the main haulage level. Ten ore pass groups are grouped in TappGrupp (TG) systems. A TappGrupp consists of 2–4 ore passes in a block, with a drawing station at the bottom of the ore pass where trains are being loaded. The ore passes are comprised of three 100-m vertical sections and a discharging bin located at the bottom of the ore pass, a 3-m design diameter, and an angle of around 60 degrees. In Sweden, the inclination of most rock passes ranges from 60 to 70 degrees [12]. Vertical ore passes are not considered favorable, as they could lead to increased pressure, resulting in increased air blast [13] and making the pass more difficult to regulate and maintain [11]. From the bottom of the ore passes, trains operating on the main level transport the ore to a crusher. The crushed material is stored in ore bins and transported on a conveyor belt to the hoisting system. Figure 1 shows a schematic of the bottom of an ore pass section. The bottom entry to the ore passes is mainly used for inspections and clearing the ore passes of hang-ups and blockages.



A. Top ore pass entry used for development, inspections, and maintenance
B. Ore pass
C. Finger raise
D. Tipping blockade
E. Footwall drift parallel to the orebody
F. Crosscuts
G. Intermediate ore pass entry used for monitoring, inspections, and maintenance
H. Chute
I. Control gate
J. Main haulage level

Figure 1. Ore pass.

This study analyzed running the ore pass systems in a filled, near-empty, or flow-through manner using discrete event simulation (DES). DES is widely used in accounting for real-world uncertainty behavior [14–17] and is a suitable method for analyzing dynamic and complex rock transportation systems such as the equipment selection, the effects of disturbances of the system, scheduling, sequencing, and optimizing processes as well as when assessing, managing, and evaluating the studied system or testing alternative approaches/scenarios/input generation. In DES, a system, which is a collection of objects and components, is modeled through occurring events. The system is represented by a collection of variables in which the state of variables changes at a discrete set of points in time as opposed to a continuous system in which the state of the variables' changes occur continuously over time [17].

4. Discrete Event Simulation Model Settings

Various types of DES software can be used to model mining systems. This study used the AutoMod^{TM} simulation software. The tool has the advantages of modelling the rock transportation systems of the selected mines with the necessary level of detail; it is also a commonly used simulation language environment capable of satisfying the characteristics necessary for this study. The AutoMod^{TM} software consists of a built-in material movement system and simulation environment [16]. The graphics offer two modes: static and dynamic. In the latter mode, moving objects can be observed during the simulation run. The software is flexible because of the AutoMod^{TM} syntax and built-in environments. There is a possibility of modifying various parameters via AutoMod^{TM} syntax or directly in the movement system, such as speed, turning speed, acceleration, or deceleration [14,17].

The studied production area is presented in Figure 2. The figure shows the ore pass groups, the train haulage level, and the hoisting system. Each simulation was run for 90 days. The procedure of building the model began by importing the planned layout into the graphical environment. The next step was to define all the necessary parameters such as performance characteristics of the equipment, rock properties (ore/waste), mining cycles, shift schedules, blasting times, speeds, maintenance stops, and transportation system logic. Further actions included implementing necessary procedures and interactions between the operating machines and systems, such as loaders, ore passes, train, conveyor, and hoist system. It was also necessary to incorporate the programming code. A base case model was developed to benchmark against the planned development/production rate. Further steps involved running alternative scenarios and verification and validation of the models using physical and statistical tests. The model is considered valid when the conceptual model has been determined to represent the existing system. When running the simulation, the same input data and boundary conditions were used with the number of repetitions and the length of the run so extensive that no major changes of the results occurred (that is, when changing the seed number). The results from the simulation were then compared with the results from the calculations. The validation was carried out by comparing the output from the simulation model with the output from the existing system. Further, debugging techniques, animations, model inspections, and running the model under varying conditions were carried out. During the process of model development, the reporting and documentation of various optimization scenarios was determined, including variations such as additional equipment, shift, or different performance characteristics.

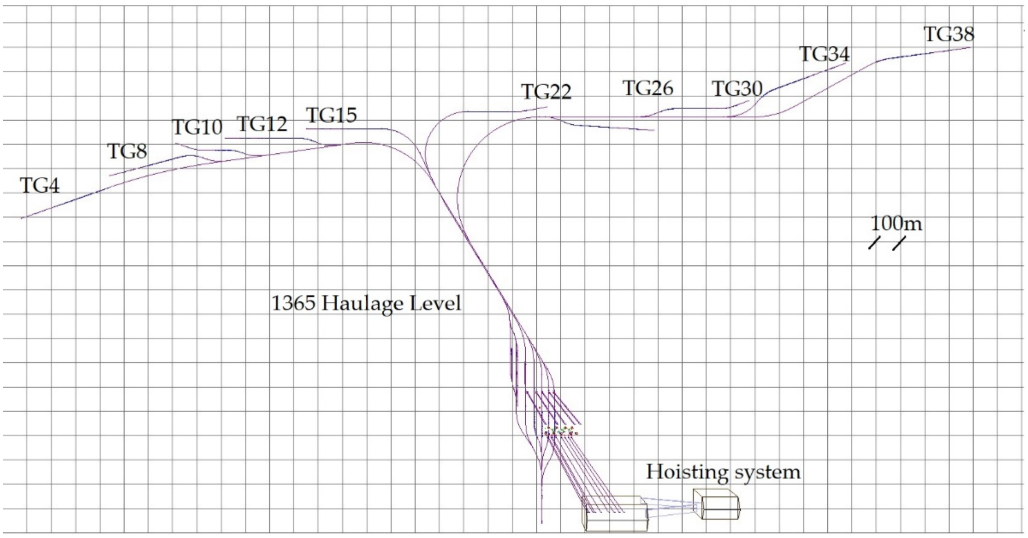


Figure 2. Simulation model (3D top view).

5. Input Data

Data and information were obtained from Kiirunavaara underground iron mine. The input data used in AutoMod^{TM} software included historical data and baseline mapping of the mine site, including disturbances associated with loading the material, ore passes, train, and hoisting system.

5.1. Loading System

Electric-driven 10 m^3 bucket-size LHDs were used in the study. The productivity of the loaders was estimated as 450 ± 45 tonnes/hour/LHD. The LHDs were scheduled to operate for 18 h/day, with an operational time ranging between 11 and 13 h/day. The loading fleet was adjusted to match the productivity required for each ore pass. At the end of the shift, the information was checked again to see if there was a need to reposition the loader in another ore pass to support an underperforming pass.

5.2. Ore Passes

In all 10 ore pass group systems, a total of 33 individual ore passes were modelled during simulation (Table 1). An additional shorter ore pass, TG41, located in the far south, was excluded from the study. As seen in Table 1, the total daily production target was set by the mine planning team for ore passes in all groups to 76.4 Ktonnes/day. If the simulation is run with this production target for 90 days, a total of 6.9 Mtonnes is expected. Shaft capacity varies depending on the design, compaction, ore-to-waste ratio in the bucket dumped into the ore pass, any enlargements of the passes, and the current operation level from which the material is being dumped. Once the mining progresses downward to lower sublevels, the capacity of the ore pass is reduced. The length of the complete section of a single ore pass is around 100 m, and its capacity is around 2309 tonnes plus a buffer capacity of approximately 45 tonnes; it takes three to four train trips to empty the pass. During production, some of the ore passes are undergoing renovation, and some are blocked or not functional; therefore, more than one ore pass should be in operation in each ore pass group.

Table 1. Selected production plan to study for the ore pass system (taken from the actual mine plan in Kiruna).

Ore Pass Group:	**TG4**	**TG8**	**TG10**	**TG12**	**TG15**	**TG22**	**TG26**	**TG30**	**TG34**	**TG38**
No. of ore passes	4	4	2	4	4	1	2	4	4	4
Daily target (Ktonnes/day)	0.3	0.8	16.4	11.9	1.6	5.9	2.3	12.9	12.2	12.1

5.3. Train System

At Kiirunavaara underground mine, there are 7 trains each with 21 cars that can load an average of 650 tonnes per train. Trains are scheduled to operate 24 h/day, during which they encounter disturbances; these were included in the simulation. Speeds of the trains and crossings were adjusted according to current regulations and procedures in the mine. In this study, the train dispatch selected the ore pass group system with the longest waiting time. During analysis, ore passes that had a small amount of material had reached the minimum required level of the ore passes, required maintenance, or had disturbances were given less selection priority.

5.4. Hoisting System

The hoisting system considered in this analysis is built out of 5 active hoists and consists of two parts: an upper part with 8 hoists and a length of 869 m; a lower part with 5 hoists and a length of 796 m. The capacity of each skip that is hoisted up is estimated as 34 tonnes for the lower hoisting system and 2 × 24 tonnes or 1 × 40 tonnes for the upper hoisting system. The cycle time of the lower part is approximately 84.4 s per trip, and the upper part is approximately 175.2 s per trip in case of 1 × 40 (single skip) or 86.3 s per trip in the case of 2 × 24 (double skip).

6. Scenarios

As seen in Table 2, four scenarios were considered during the simulation based on the scheduled production plan. The aim of simulating these scenarios was to evaluate the running of the ore pass in a filled, near-empty, or flow-through mode to help in the decision-making process and make necessary adjustments in the final production plan. The first scenario was run with varying levels, with the minimum and maximum capacity of each ore pass set to 325 and 2309 tonnes, respectively. In the second scenario, the ore passes were kept filled, and in the third scenario, the ore passes were run near-empty. In the fourth scenario, a special rule was applied whereby only critical ore passes were kept filled and other ore passes were run as scenario 1. In this case, the ore passes in TG26 and TG34 were the critical ore passes, and they were kept filled. These groups were considered critical because they are located in unfavorable locations with high rock stresses and poor ground conditions. Therefore, to reduce the wear progression and fallouts from the walls, these ore passes were filled.

Table 2. Scenario list.

Scenario No.	Rule	Description	Running Case
1	Varying levels	Varying the ore pass levels with the maximum value of 2309 tonnes and minimum value of 325 tonnes to be unloaded by train.	Flow-through manner
2	Filled ore passes	The minimum value of 2000 tonnes/orepass. The maximum value is kept the same, 2309 tonnes.	Filled manner
3	Near-empty ore passes	Minimum 325 tonnes per TG to send train, and the maximum amount in the ore pass is 400 tonnes; after that, loading is stopped. Therefore, the maximum capacity is set to 400 tonnes.	Near-empty manner
4	Special rule	Only critical ore passes kept filled (TG26 and TG34) and run as scenario 2; others are run as scenario 1.	Filled and flow-through manner

7. Results and Discussion

This study evaluated the extreme cases when ore passes were run in a filled or near-empty manner. In a normal situation, there is an attempt to meet a certain capacity according to the daily production plan. A simulation model using AutoMod^{TM} was prepared and validated in four scenarios: when the levels of materials varied between 304 and 2309 tonnes in a flow-through manner (1st scenario); when the ore passes were kept filled (2nd scenario); when the ore passes were kept near-empty (3rd scenario); and when only critical ore passes were kept filled while others were run as scenario 1 (4th scenario). The aim was to compare the operational performance of all modes and the impact on reaching a daily and a 90-day production target of 76.4 Ktonnes and 6.9 Mtonnes, respectively.

First, the simulation was run for each scenario to evaluate the 90-day production target of 76.4 Ktonnes/day. The results are shown in Figure 3. The results show that the 1st and 4th scenarios kept the production close or sometimes over the daily target of 76.4 Ktonnes, while the 2nd and 3rd scenarios had low production. The low production was due to loaders not being able to load when the ore pass reached the limit of 2309 and 400 tonnes, for the 2nd and 3rd scenarios, respectively. As a result, the LHDs were not utilized in the best manner, leading to delays in loading material; consequently, the trains were delayed in their operations.

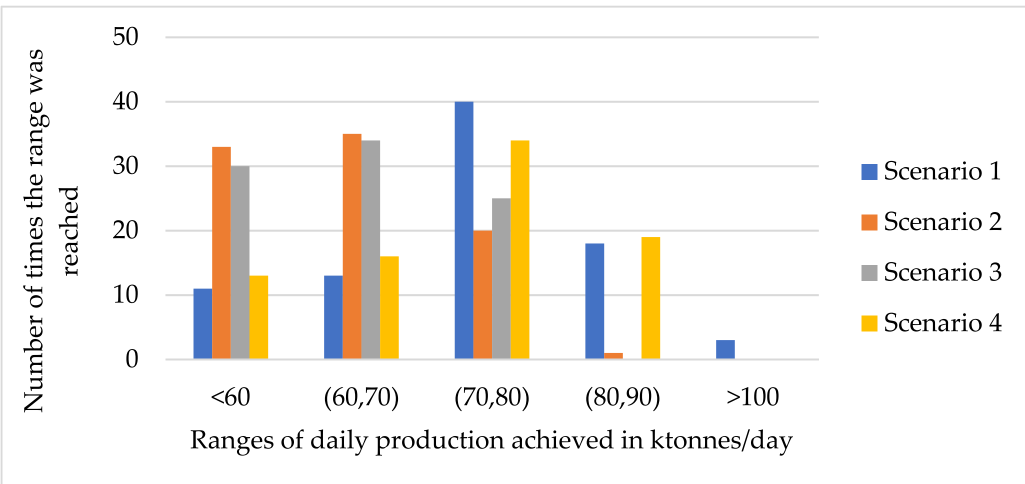


Figure 3. Daily production for each scenario.

The simulation was then repeated for each scenario to evaluate the 90-day production target of 6.9 Mtonnes for all ore pass modes. The results are shown in Table 3. After 90 days, production was observed to be 6.6, 5.5, 5.6, and 6.4 Mtonnes for scenarios 1, 2, 3, and 4, respectively. The highest production was achieved in scenario 1 (96% of the production target), while the lowest production was achieved in scenario 2 (80% of the production target). The high production in scenario 1 was the result of allowing LHDs and trains to load and draw the material from the ore passes more often than in the other cases. In scenarios 2 and 3, the trains and the loaders were under-utilized in the sense that they often did not have work in the given block and had to wait for the ore pass to meet a specific condition. This means they became more dependent on the status of the ore pass than in scenario 1. The instantaneous capacities of the trains (650 tonnes) were also much higher than the capacities of the LHDs (approx. 25 tonnes/bucket).

Table 3. Results for different scenarios.

Scenarios	Lowest (Ktonnes/Day)	Highest (Ktonnes/Day)	90-Day Run (Mtonnes)
1	23.9	123	6.6
2	20.4	82.9	5.5
3	26.1	75.8	5.6
4	25.7	97.1	6.4

The simulations then evaluated the daily production target for 90 days by considering each ore pass group (TGs). The results for the ore passes in TG 10 are presented in Figures 4–7. In these figures, the brown dots represent the production target of 16.4 Ktonnes (see production target for TG 10 in Table 1), and blue dots represent the production achieved in Ktonnes on every day of the run. For TG 10, scenario 1 achieved the production target only 35 times (Figure 4). A similar behavior (39 times) was obtained in scenario 4 (Figure 7). In scenarios 2 and 3 (Figures 5 and 6), the production target was never achieved. In scenario 2, LHDs had more delays loading materials to the ore pass and in a near-empty scenario, trains had to wait longer to be able to travel to that location and load the material.

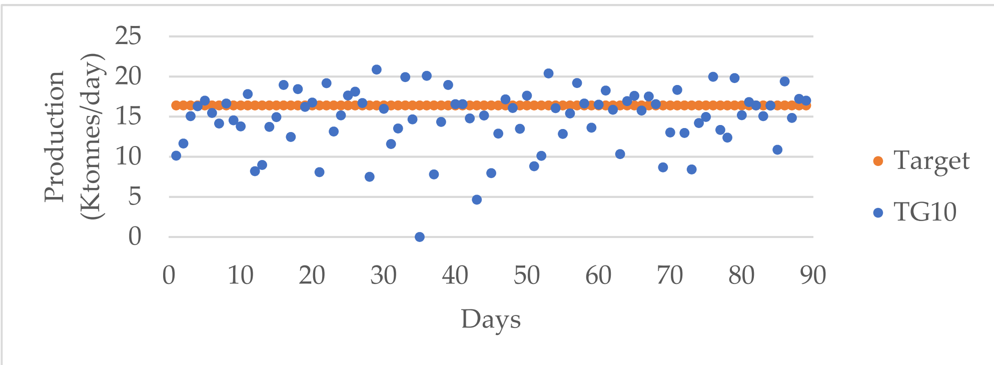


Figure 4. Scenario 1—Ore pass group—TG10.

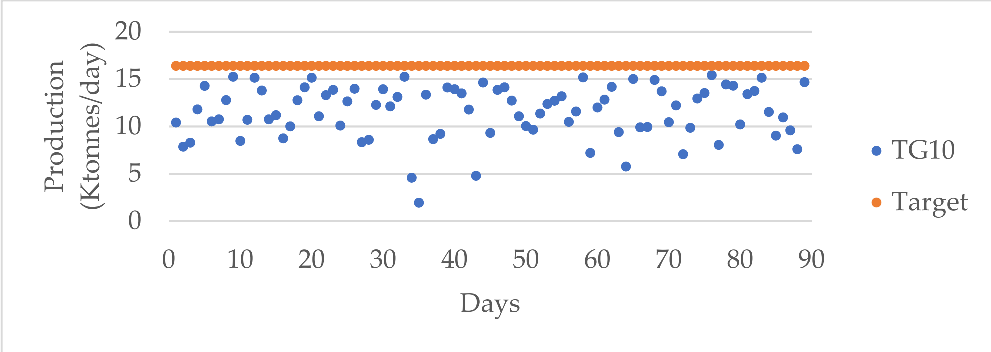


Figure 5. Scenario 2—Ore pass group—TG10.

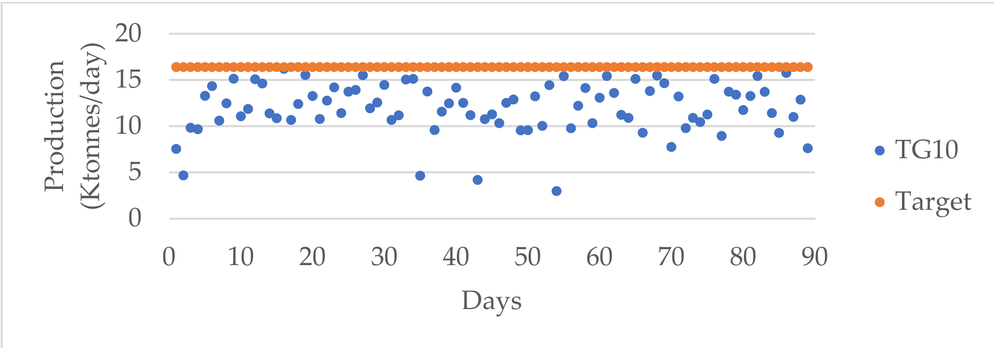


Figure 6. Scenario 3—Ore pass group—TG10.

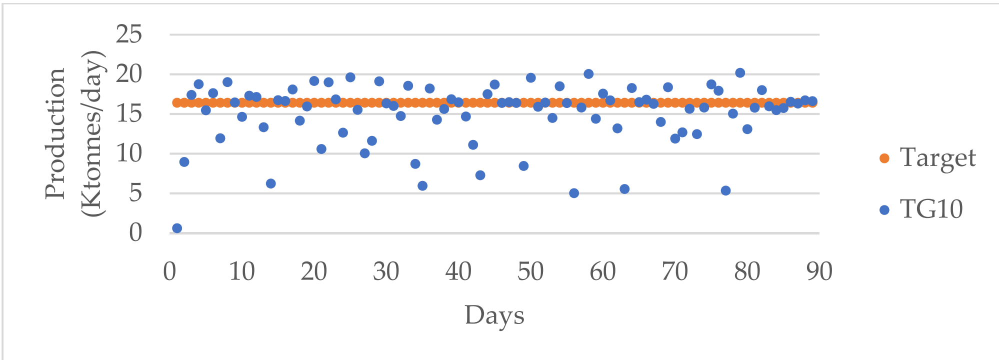


Figure 7. Scenario 4—Ore pass group—TG10.

This study evaluated ore pass systems operated in a flow-through, near-empty, or filled manner to compare operational performance and productivity. These ore passes were loaded by LHDs and unloaded by trains. The results showed that running ore passes in a flow-through manner led to higher production than when ore passes operated under filled conditions. The flow-through mode also allowed full utilization of the LHDs and train during loading and unloading without delays. When a filled mode was used, LHDs had more delays loading materials to the ore passes, as the ore passes were not allowed to have too much empty space. Therefore, in mining operations where ore pass systems are used in material transfer from one mine level to the other, running them in a flow-through mode can ensure higher production than running them in a filled mode.

8. Conclusions

The study presented in this paper was based on the Luossavaara-Kiirunavaara Aktiebolag (LKAB) Kiruna mine in Sweden. The aim was to compare the ore pass operational performance and impact on reaching the daily and 90-day production target of 76.4 Ktonnes and 6.9 Mtonnes, respectively, with the following conclusions:

- The results show that the 1st (flow-through) and 4th (critical passes filled; others flow-through) scenarios achieved production close to the daily target of 76.4 Ktonnes, while the 2nd (filled) and 3rd (near-empty) scenarios had low production.
- The results for the 90-day simulation show that running the ore pass in a flow-through mode achieved the production target of 6.6 Mtonnes (96% of the production target), while the filled mode achieved 5.5 Mtonnes (80% of the production target).
- Setting the ore pass groups (TGs) to high production target levels should be avoided if possible; if the production target is set too high, the current system might not be able to transport that amount of material from the given location. Other relocation options might be considered. Relocation would mean increasing the Ktonnes in other areas (i.e., other TGs). However, sequencing the ore pass groups is often necessary because of safety and mining constraints.
- Whether to operate ore passes in a filled, near-empty, or flow-through manner should be considered independently of the area where the ore passes are located and treated separately.
- The results indicate that running ore passes in a flow-through manner leads to higher production than when they are operated under filled or near-empty conditions. The flow-through mode also allows full utilization of the LHDs and trains during loading and unloading without delays. However, if there are high stress conditions or poor geotechnical conditions in the vicinity of the ore pass, the strategy would be to run the system in a filled manner, thus providing confinement for the ore pass walls.

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