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REVIEW ARTICLE

# Development of an Underground Haulage System Evaluation Tool for Feasibility Studies

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## Abstract

The mining industry faces many difficult challenges, for example, lower ore grades, smaller and deeper deposits, and longer transportation distances. In the past, there have been remarkable innovations in both equipment and the types of mining methods for which it is used, which have resulted in economies of scale. This has led to an increased use of bulk mining methods, like sublevel and block caving, which has increased productivity and reduced costs. Haulage alone plays a major role. Current haulage techniques are a significant cost driver, which account for between 15 and 30% of the overall capital investment (capex) in a mine and are an increasingly part of the operating costs (opex). The paper introduces a simulation tool of main haulage system in underground mining. Therefore, performances and the costs of the three most common underground main haulage systems, rail, truck, and conveyor, are calculated using a developed modeling tool. The tool was applied and validated in a case study carried out with the LKAB Kiruna Mine in northern Sweden.

**Keywords** Project evaluation · Underground rail haulage systems · Deterministic simulation

## 1 Introduction

Despite the huge challenges for future underground mining operations resulting mainly from lower ore grades and deeper deposits, the worldwide demand for raw materials like iron ore and copper increases steadily. Even the current steel and raw material crisis will not have any sustainable influence on this trend.

Therefore, a lot of capital is provided by the markets to develop new deposits. But the project setting has been changed dramatically over the last decades: In the past, development efforts in the mining business were modest as most operations were surface mines or, in case of underground mines, the projects were developed step-by-step by expanding the underground roadways while production has already started. This was a cost- and capital-efficient approach. After a short time, mining projects could be financed out of the internal cash flow and became independent from the financial markets. In contrast, today's projects are vastly more complex, bear risks that are more technical, and involve significant up-front investments. The general lack of information, such as geological and geotechnical properties or market development, at an early project stage as well as the need to comfort investors leads to comprehensive and long-lasting feasibility studies. One major aim is to shorten this pre-financed period in terms of reducing time-to-market and increase its efficiency. This requires a focus on the major cost drivers of the project, the haulage system. With up to 30% of the overall capex, the haulage system is a major cost driver in mining projects [1].

Especially, rail haulage, equipped with new drive technology (AC instead of formerly DC), its vast automation capability, and having less emissions, can score in this new setup. Moreover, operating costs of these rail and belt conveyor are the lowest. The large up-front investments of rail haulage systems and conveyor belts relativize due to more elaborate infrastructure needed for future mining operations regardless of the choice of a haulage system. In this early stage, a clearly

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preferred haulage system does not exist. Sticking to familiar technology without investigating other options can become a cost boomerang in the long term.

Thus, planning entities and consultant companies in the business react. As most of the available cost databases do not reflect the current technology status of all three haulage systems, suppliers are invited to quote and provide actual information at a very early project stage. However, the provided data quality and quantity vary and the data situation is frequently insufficient—not least because lacking time and capacity. So the early choice for a haulage system that determines the path of the whole project is sometimes made rather randomly and based on experience than on reliable facts and up-to-date cost figures.

An approach to fill this information and efficiency gap is to provide an evaluation tool combining generic design models of main haulage systems in defined environments with project-specific data as production volume and location. The model consists of an input mask to gather all major criteria related to the selection of an underground haulage system. One of the results is an overview on the KPIs of all three different haulage systems. Like that, the major cost factors of the various haulage systems can be identified at a very early project stage with an accuracy complying with the requirements of scoping studies.

The system boundaries of the tool are the underground main haulage system. It is useful for mine plans where the mined material is mucked to a central haulage level or axis, means, in environments where rail haulage and conveyor belts are an alternative. Mining in irregular orebodies do not have structures concerning the underground drift network. They normally require a flexible transportation system which is only achievable by trucks.

The purpose of the tool is to achieve transparency concerning strength and weaknesses of different horizontal haulage options for underground mining operations. A comprehensive case study has been carried out at the LKAB Kiruna mine in Sweden—one of the largest underground mining operations globally—to validate the tool.

## 2 General Aspects of Underground Main Haulage Systems

Planning of a main haulage system is one of the most important parts of the mine planning process. Poor planning can result in fluctuating and low production rates, performance that declines over the mine's life, and an unexpected economic burden. A main haulage system must consider the mine development including identified and well-known bottlenecks in the system; it should be flexible enough to react to minor changes and include strategies for high equipment availability [10].

According to Goldratt and Cox [6], the output rate of every process is restricted by a single bottleneck. Therefore, the output rate can be adjusted by changing the mass flow at the bottleneck. In mining, it is important to ensure a constant flow of material, which results in a stable output from the mine. A steady mass flow can be achieved by using buffer systems in the mining processes. This also decouples the single mining process. Typical examples of such buffer systems are ore passes, stockpiles, and silos. [4]

The haulage equipment, the necessary infrastructure, the loading and unloading stations, and the upstream or downstream crusher units must all be considered when a new haulage system is designed. The technical planning process for the system is based on production rates, mine life, applied mining method, and the lateral and vertical transportation distance. Additional factors like the operating license, development costs, and revenues must be considered as well. The haulage system is finally selected based on a comparison of different haulage options which takes into account calculated cost, safety issues, and flexibility [5, 9]. There are several options for transporting ore from the mining sections to an underground main bunker. In the mining industry, rail systems, trucks, and conveyor belts, or a combination of these, are normally used.

Rail haulage systems are mostly used in underground mines, which have high production rates and a long mine life. By describing rail haulage as a track-bound system with limited curve mobility and high initial capex, the most common disadvantages of this option are pointed out. Currently, motive power is delivered by either conventional diesel or electric power systems; the diesel systems offer two variants—electric traction motors or hydrostatic drives. Equipped with electric traction motors, energy can be supplied by a diesel generator unit, catenary system, batteries, or combinations of them (hybrid solution). Electric systems are preferred for underground applications because they have less emission, which leads to a reduction in ventilation requirements. Their functional simplicity requires less maintenance which in turn produces a reduction in opex. The demand for electric systems will grow due to deeper mines and rising ventilation costs and bottlenecks. For the hard rock market, the machine's flexibility is improved by making the unit an electric/electric hybrid, effectively a battery/trolley combination. This allows onboard battery charging from the overhead catenary while on the main haulage loop and switching the locomotive to battery power once off the catenary and into the development headings [9].

The obvious advantage of rail haulage systems in large projects is the reduction in operational cost compared to use of diesel underground trucks. In some situations, rail can be only 10% of the opex of trucks (AMC [1]). The savings are most marked where rail haulage can be used and manpower requirements can also be reduced. Many new projects achieve this by, for example, using automated haulage trains. Another advantage is the long lifetime of rail systems with low-maintenance efforts.

Another potential benefit of rail systems is in respect to ventilation. Emissions are greatly reduced compared to those from diesel trucks; therefore, the necessary ventilation infrastructure is also reduced. This could include using smaller fans and smaller ventilation shafts. Rail can also mean that smaller drift cross sections can be used which reduces the cost of ground support.

Rail is less attractive for smaller operations, where only a few thousand tons per day are moved or the hauling distance is short, simply because the effort for building the infrastructure and the capital spend are ineffective. These smaller mines usually have the facilities in place, such as fuel bays and underground shops, required to service diesel rubber-tired vehicles [8]. In this situation, it makes sense to continue with the actual system rather than putting in the additional service capability needed for rail. Haul trucks have a long-term advantage, over the life of mine (LOM), in that operations can be easily scaled up or down. Using haul trucks also reduces the risk of breakdowns as, in contrast to rail and conveyor haulage systems, the truck fleet presents a parallel backup.

Currently, the only established continuous system for large volume movement is a belt conveyor system [5]. The high capex for the system as well as the opex for control, servicing, and maintenance, can be divided by the volume of tons conveyed which produces an ever-reducing cost to performance ratio. This is the main disadvantage for mining operations with relatively low production. Conveyor belt systems are characterized by less-specific emissions coupled with electrical energy efficiency. In respect of employee safety however, the positive effect of unattended operations is counteracted by the fire hazard caused by the continuously running electrical motor drives and rollers, which is difficult to monitor.

Conveyor belt systems are extremely inflexible because they are unable to negotiate curves, and therefore, additional transition stations are necessary. Depending on the ore size, there may be a higher requirement for crushers which is also a disadvantage when compared with rail and truck haulage systems [5]. This depends on the expected fragmentation. Generally, a conveyor needs to be three or even four times the width of the largest ore blocks [8]. A further disadvantage is the ongoing wear-and-tear caused by abrasion. The benefits of the system are reduced in many mining operations. This is mainly because of the increased complexity and the inherent breakdown hazard where there is no parallel backup system. Special conveyor products such as the Rail-veyor or conveyor belts with increased curve mobility have lower application potential for larger operations in particular due to their low conveying rate.

## 3 Simulation and Evaluation Methodology

A dynamic spreadsheet model has been developed for use in scoping or pre-feasibility studies and decision making. The model simulates the underground haulage systems that have been discussed. The simulation structure is schematically shown in Fig. 1. The input data and fixed (assumed) parameters are the basis for sub-process calculations.

**System Boundaries and Mine Layout** To compare haulage solutions, clearly defined system boundaries are necessary. The model covers a haulage level, which consists of the total transport infrastructure and includes ore passes with loading stations, as storage bins, which are filled from a production level above. Crushing facilities are considered as well as the essential drifting costs of the haulage system [2].

A simplification of the mine is required for the model to be universally applicable. The mine layout is configured to simulate up to five mining sections with different transport distances and production rates. It is possible to have multiple loading points at one section. All drifts from the production areas are linked to a shared roadway that leads to the dumping points.

Individual additional transport infrastructure is required for different transport systems (see Fig. 2). Rail haulage systems are designed with extra turnout tracks and sidetracks. Parking and evasion slots are needed for truck systems. Crushing units are considered at the dumping spots except for a conveyor system which requires material with a consistent grain size. The cost for those is included as well.

The input data, which can be entered individually for each mine site, includes production data, shift system information, mine layout dimensions, and financial data. A hybrid cost estimation approach is based on assumptions, available databases [7], and—especially for rail systems—company data [11]. This data can also be entered manually. The sub-process calculations are as follows:

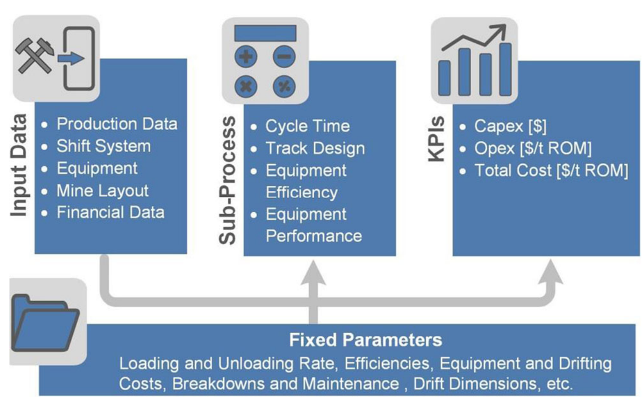


**Fig. 1** Model structure

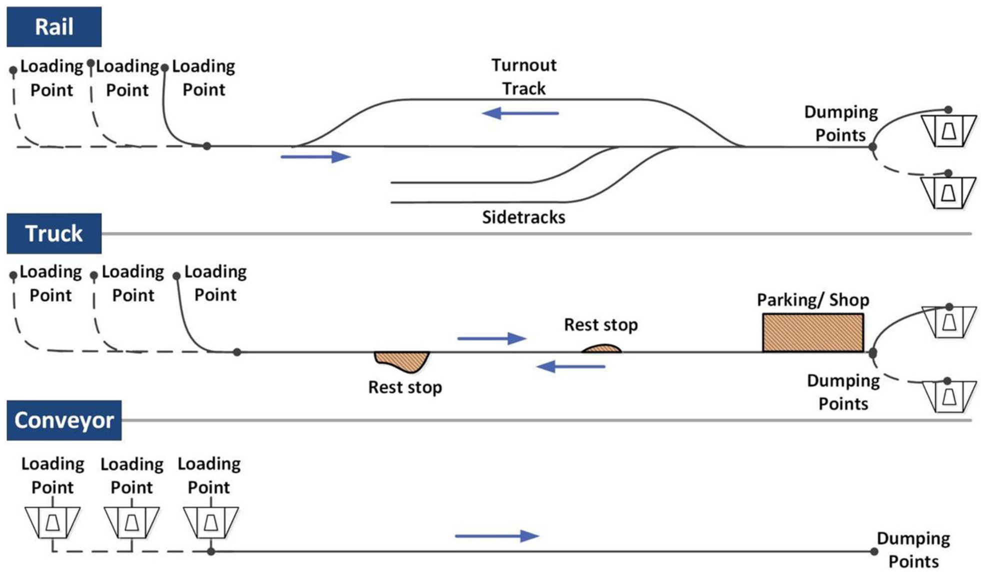


**Fig. 2** Simplified haulage systems with three mining sections for modeling

**Transport Distance** The mine layout is characterized by the individual distances from the mining sections and can be specified in the input. The total length of the transport distance results from the haulage distance and loading and dumping zone distances. An individual distance factor for each haulage system is added to the total length where drift design makes a truck system most flexible. Due to the fact that truck systems are flexible and rail and conveyor systems are limited by curve mobility, the development planning would differ. The distance factor considers this aspect and reduces the total length of the drifting in case of a truck system to 80% as a default setting. But, this can be altered by the user to the specific needs of the project to be evaluated.

For the following production calculations, the haulage distance is simplified from multiple loading points to one loading station with one haulage track. The transport distance is a weighted mean calculated from all single haulage ways by taking the production distribution into consideration.

**Performance and Production Calculation** Because of the different methods of operation (continuous or discontinuous haulage), the performance calculation and equipment selection are not the same. Discontinuous systems are determined by cycle time, single unit performance, and required hourly production, while the continuous systems (conveyor belt) depend on the belt width and speed. The conveyor selection is taken from pre-calculated equipment tables which are provided by the Mine and Mill cost guide [7]. Selection parameters are the hourly production and bulk density. Regression analyses are used to make the calculations dynamic.

The following cycle time calculations ($t_{total}$) are used for the rail and truck haulage system. They cover loading ($t_{loading}$), travel ($t_{travel}$), and dumping time ($t_{dumping}$) as well as working efficiency ($\eta_{Job}$). The travel considers speeds when loaded and unloaded. The transport distance is taken from a theoretical focus/main operating point with the result that all distances that are weighted by the individual production rates.

$$\frac{t_{total} = t_{loading} + t_{travel} + t_{dumping}}{\eta_{Job}} \tag{1}$$

The hourly production rate ($Q_{unit}$) for one single unit (one train or truck) results from the payload of one unit ($q_{unit}$) and the total cycle time.

$$Q_{unit} = \frac{q_{unit}}{t_{total}} \tag{2}$$

The following calculation is given as an example for a rail haulage system. The payload for one train ($q_{rail}$) is calculated by taking into account the number ($n_{OC}$), volume of ore cars ($q_{OC}$), filling factor ($\eta_{filling}$), and density of the bulk material ($\rho_{ore}$).

$$\frac{q_{rail} = q_{OC} \times \eta_{filling}}{\rho_{ore} \times n_{OC}} \tag{3}$$

Placing Eq. 3 in Eq. 2 gives the following production rate:

$$\frac{Q_{Rail} = q_{OC} \times \eta_{filling}}{\rho_{ore} \times t_{total} \times n_{OC}} \tag{4}$$

Finally, the total number of trains ($n_{Rail}$) can be determined by dividing the production rate of one train ($Q_{rail}$) by the production rate of the mine ($Q_{prod}$).

$$n_{Rail} = \left\lceil \frac{\frac{q_{OC} \times \eta_{filling}}{\rho_{ore}} \times n_{OC} \times t_{eff,s}}{t_{total} \times Q_{prod}} \right| \tag{5}$$

The haulage system is highly dependent on the production level, crusher stations, and hoisting system and is affected by breakdowns and shutdowns. When these occur, production is increased for a short term to meet periodical production targets. Therefore, an overall efficiency factor for the mining system ($\eta_{\text{system}}$) is used, which is composed of all the efficiency factors from the production, crusher, and hoisting systems. Numbers for equipment in peak production ($n_{\text{Rail,peak prod.}}$) are rounded up to an integer number to guarantee the needed production rate.

$$n_{\text{Rail}},\ \textbf{peak prod}. = \left\lceil \frac{\frac{q_{\text{OC}} \times \eta_{\text{f}}}{\rho_{\text{ore}}} \times n_{\text{OC}} \times t_{\text{eff,s}}}{t_{\text{total}} \times Q_{\text{prod}}} \times \eta_{\text{system}} \right\rceil \tag{6}$$

Additional trains are only used during the short peak production times; therefore, these are factored in the capex but not considered in the opex calculation.

**Evaluation Key Performance Indicators** Capex, opex, and total costs were selected as the relevant key performance indicators (KPIs) of each haulage system. The initial acquisition of the haulage equipment ($C_{\text{total}}$) and the infrastructure are the largest components of the capex ($C_{\text{i}}$) and are calculated in total for every haulage system by:

$$C_{\text{total}} = \sum C_i \tag{7}$$

The equipment costs result from the performance calculation above and include, for rail, the locomotives as well as the number of ore cars. The infrastructure for a rail system consists of track, signaling, communication, and catenary systems. For a conveyor system, the infrastructure also includes transfer stations, the equipment results come from the Mine and Mill Cost Guide. For rail and conveyor haulage, ventilation is not stated as they usually work with battery or electrical power. As diesel trucks are most common for rubber-tired haulage, this will lead to the need of additional ventilation power, which is affecting capex and opex. Drifting, crushing facilities, and loading and unloading stations are needed in every haulage system. Capex are given as cost per unit (equipment), cost per meter (drifting and infrastructure), and individual costs for project management, commissioning, and training.

Reinvestments for haulage equipment ($C_{\text{Reinv}}$) are also considered and are based on the life of mine (LOM), operating hours ($t_{\text{life}}$), percentage of reinvestment ($\varepsilon_H$), and initial capex ($C_{\text{equip}}$). By using the factor $\varepsilon_H$, long life parts of the equipment can be excluded from the reinvestment.

$$C_{\text{Reinv}} = \varepsilon_H \times C_{\text{equip}} \times \frac{\text{LOM}}{t_{\text{life}}} \tag{8}$$

The opex ($O_{\text{total}}$) are standardized per ton of ore moved and includes the running costs of the haulage equipment, crusher facilities, operating labor, and ventilation costs. It is calculated for every haulage system as shown in Fig. 2. $O_{\text{i}}$ stands for individual annually cumulated opex cost together with the yearly production rate ($Q_{\text{prod}}$).

$$O_{\text{total}} = \sum \frac{O_{\text{i}}}{Q_{\text{prod}}} \tag{9}$$

To make an overall comparison, the total costs, resulting from capex and opex are a significant KPI and scaled down per ton. Capex is normalized by the yearly production rate and LOM. A discount rate ($i$) is also added. The calculation of the total costs is as follows:

$$\frac{T_{\text{total}} = O_{\text{total}} + C_{\text{total}} + C_{\text{Reinv}}}{\frac{Q_{\text{prod}} \times \text{LOM} + C_{\text{total}} + C_{\text{Reinv}}}{2 \times \frac{i}{Q_{\text{prod}}}}} \tag{10}$$

Table 1 shows the KPI comparison dashboard:

## 4 Results: A Case Study at the Kiruna Mine

### 4.1 Mine Site Description

The state-owned company, LKAB, operates the world's largest underground iron ore mine in the north of Sweden. Mining at Kiruna originated in the nineteenth century and it has developed into one of the most modern mining sites of the world. The magnetite-apatite orebody in Kiruna is 4 km long and 80 m thick, reaches a known depth of 2 km, and has an average iron content of 65% Fe. The mining method used is sublevel caving. After blasting, the ore is mucked by LHDs to an ore pass system where it reaches the main transportation level. Between 1999 and 2013, the main transportation level was at a depth of 1045 m and was operated by a rail haulage system. During this time, the new main level which is now situated 1365 m underground was planned [3]. Figure 3 illustrates the current track layout.

Even though LKAB always used trains on the haulage level in the past, a LCC prefeasibility study was conducted over several months, to determine the most cost-efficient transportation system. One motivation for the extensive study was the desire to increase the production rate from 27 to 35 Mt. per year on the new level, which would result in an average daily production rate of 100,000 t/day. The study considered rail systems and trucks. In respect of this paper, the study acts as a benchmark to validate the simulation tool.

The LCC study neglected the use of conveyor belts for several reasons. When using conveyor belts, the iron ore must be crushed down to smaller lumps near the tapping galleries.

**Table 1** KPI comparison dashboard

| Haulage System | Capex [$] | Reinvestment [$] | Opex [$/t ROM] | Total Cost [$/t ROM] | Equipment [#] | Equipment peak [#] |
|---|---|---|---|---|---|---|
| Rail | $C_{total,Rail}$ | $C_{Reinv.,Rail}$ | $O_{Rail}$ | $T_{Rail}$ | $n_{Rail}$ | $n_{Rail,peak\ prod}$ |
| Truck | $C_{total,Truck}$ | $C_{Reinv.,Truck}$ | $O_{Truck}$ | $T_{Truck}$ | $n_{Truck}$ | $n_{Truck,peak\ prod}$ |
| Conveyor | $C_{total,Conveyor}$ | $C_{Reinv.,Conveyor}$ | $O_{Conveyor}$ | $T_{Conveyor}$ | | |

With the planned layout, it would have been necessary to build 10 small crushers in the tapping galleries. This would have increased investment costs because of the extra tunneling and equipment needed. A system of conveyor belts would not have been as flexible as trucks or trains. In addition, the needed crushing in the loading areas was assessed as critical due to rock stability problems in the vicinity of the deposit.

The following input parameters and assumptions are used for the simulation (Table 2):

Table 3 highlights the calculation results. For reasons of confidentiality, the numbers are shown on a relative basis with the rail system acting as the reference point. The results show that, in peak production times, 7 rail systems would have to be purchased. In comparison, 22 trucks would have to be purchased. Capex are 12% lower while opex are 66% higher; thus, total costs are 45% higher using trucks instead of rail systems. In theory, conveyor belts would reduce capex by about 70% and opex by 44% and, overall, reduce total costs by 47%.

## 5 Discussion and Conclusion

The developed simulation tool was validated with a previous LCC study of LKAB. The results are very similar and only show small deviations. It can be stated that this tool can be used in early project definition stages within the framework of scoping studies. There, the inaccuracies in the range of ± 25%

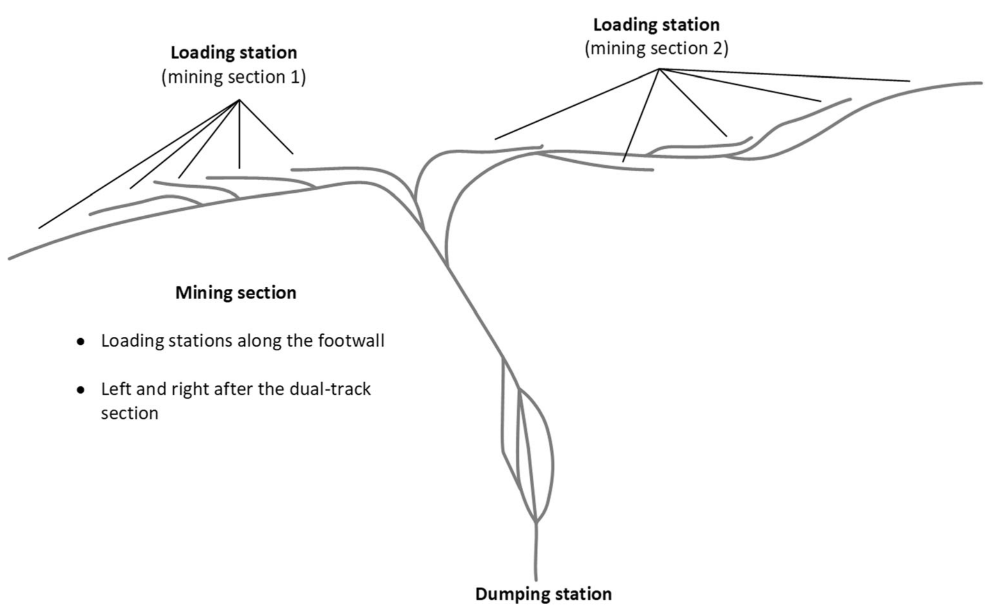


**Fig. 3** Track layout on the Kiruna Mine 1365 level

**Table 2** Input data

| Input | | | Input | | |
|---|---|---|---|---|---|
| **Production Data** | | | **Mine Layout** | | |
| Production per year | 35,000,000 | t/a | Number of mining sections | 2 | # |
| Life of mine | 20 | a | Number of loading points | 18\|19 | # |
| Bulk density | 2.60 | t/m³ | Number of dumping points | 4 | # |
| **Shift System** | | | Distance to mining section | 1.0\|2.0 | km |
| Days per year | 350 | d | Production rate mining section | 47\|53 | % |
| Shifts per day | 3 | # | Slope | 2.5 | ° |
| Shift time | 8.00 | h | | | |
| **Equipment Selection** | | | **Financies** | | |
| Size of Locomotive | 108 | t | Discount rate | 10 | % |
| Size of ore cars | 20 | m³ | Labour cost | 70 | $/h |
| Number of ore cars | 21 | # | Energy cost | 0.04 | $/kWh |
| Truck size | 120 | t | Diesel cost | 0.85 | $/l |

are industry standard [12]. The tool is able to save a lot of time and only needs basic input parameters which make it a very cost-efficient evaluation methodology. Cost results are strongly depending on the hourly costs of the equipment. For this reason, further work in the improvement of the equipment database is recommended by the authors.

Concerning the Kiruna case study and with focus on the actual state of the art in automotive haulage technology, lots of trucks and drivers would be needed to transport a daily production of 100,000 t. Using trucks would also require a substantial logistical input. For example, large amounts of diesel fuel would have to be transported down to the level and the ventilation capacity would need to be increased. The necessity for larger drifts would also result in higher development costs.

Using automatic trains was figured out to be the most cost-efficient way to transport the iron ore from the tapping galleries to the dumping stations. The system consists of loading

**Table 3** Calculation results

| Haulage System | Capex [$] | Reinvestment [$] | Opex [$/t ROM] | Total Cost [$/t ROM] | Equipment [#] | Equipment peak [#] |
|---|---|---|---|---|---|---|
|  | 100% | 100% | 100% | 100% | 5 | 7 |
|  | 88% | 514% | 166% | 145% | 17 | 22 |
|  | 31% | 49% | 66% | 53% | | |

stations, which can load a train with 21 ore cars with a payload of 650 t.

In contrast to other tools and studies (e.g., LCC), initial comparisons of the different haulage systems can be made very quickly and with little efforts.

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## Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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