Sensitivity Analysis to Evaluate Haulage Systems Selection for Underground Mines Using Discrete Event Simulation and Mixed Integer Programming*

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Salama, A. and Nehring, M. (2024), "Sensitivity analysis to evaluate haulage systems selection for underground mines using discrete event simulation and mixed integer programming", *Ghana Mining Journal*, Vol. 24, No. 1, pp. 121-132.

Abstract

As deposits located in near surface continue to be mined out, the mines will focus on deeper operations whereby the haulage distance to the mine surface is going to be one of the main challenges. Several haulage systems such as diesel and electric-powered trucks, shaft, and conveyors can be utilized for hauling operations at shallow or great mine depth. When they are to be used for longer haul distances to the mine surface, the haulage methods with less operating costs will be beneficial towards cost reduction. To improve the decision making, the haulage selection processes require knowledge of the mine planning, scheduling under variable parameters. Therefore, this paper presents a sensitivity analysis to analyse the effects of changes on selected parameters on the net present value (NPV) of the mine plans generated for an orebody at 1000- and 3000-meters levels for diesel and electric-powered trucks, shaft, and belt conveyor haulage methods using discrete event simulation and Mixed Integer Programming to evaluate the most sensitive parameters on the selection of haulage operations as mine depth increases. The simulation analysis aimed to assess the performance of these haulage options in achieving the production target of 100,000 tonnes of ore per month for each option at each depth. The simulation results were used to determine the energy cost per tonne of each haulage scenario for each depth and then exported to the mixed integer programming to calculate the operating cash flows to generate an operating NPV. The results show that, in hauling of material from underground to mine surface, diesel trucks are only feasible at shallow depth, while electric trucks, shaft, and conveyor belt systems can be used for longer haul distance. It also indicated that, diesel-powered trucks are observed to have low NPVs compared to other haulage options, while shaft and belt conveyor generated high NPVs with increasing mine depth. It is therefore concluded that, mine planners can minimize risks when evaluating haul methods, and use sensitivity to guide a suitable choice and flexibility on the hauling operations.

Keywords: Mine planning, Discrete event simulation, Mixed integer programming, Sensitivity analysis

1 Introduction

The selection of haulage systems is a common challenge in underground mine planning when making decisions with goals such as expansion of production capacity, vertical and horizontal integration, adoption of a new technology, or reduction of haulage costs (Alpay and Yavuz, 2009; Salama *et al*., 2014). These goals have a role in the processes of planning and consequence in the economic evaluation of the investment project (Dimitrakopoulos and Sabry, 2007; Abdel Sabour and Poulin, 2006). In underground mining operations, several haulage systems such as diesel and electric trucks, shaft, and conveyors can be utilized for ore and waste transportation to the mine surface. These systems usually contain other supplementary ore handling components such as loaders, ore passes, and underground crushing systems. The haulage systems can be used at shallow or great mine depth depending on several factors such as the overburden size, orebody geometry, rock conditions, and level of production (De la Vergne, 2003). When they are to be used for longer haul distances to the mine surface, the haulage methods with less operating costs, will be beneficial towards cost reduction.

Diesel-powered truck haulage is among the popular means of transportation which has been used to haul the mined-out materials for both open pit and underground mines (Elevi *et al.*, 2002; Salama *et al.*, 2014; Chaowasakoo *et al.*, 2017). Despite of being flexible and less investment cost, the disadvantages of using this system are difficultness in reaching the production target especially when the haulage distance is long, and high operating costs. The increase in costs of operations may force mine planners to continue analysing the feasible mode of transportation such as shaft system, electric-powered trucks, and belt conveyor. Electric-powered trucks consist of trolley-electric lines which are mounted at the back of the drift and require a special infrastructure which makes to have high initial costs. It uses electricity as a source of energy during transportation (Paraszczak *et al.*, 2013; Skawina and Salama, 2021). During operation, it needs less amount of diesel during loading and unloading period which led into low operating costs.

**Manuscript received October 03, 2023*
Revised version accepted April 27, 2024
https://doi.org/10.4314/gm.v22i1.3

Shaft systems incur a large initial fixed cost investment and rely on the subsequent low operating cost of material movement to the surface. Shafts are also used to provide various services such as ventilation, water supply and moving of spare parts to an underground mine (Beerkircher, 1989; Salama *et al.*, 2014). Belt conveyors are cost effective hauling method as the hauling distance from the draw points to dumping point is further increases (Krol *et al.*, 2017). Belt conveyors had advantages of high, continuous output, ability to operate over a range of grades and low operating costs. Their disadvantages are inflexible, high initial investment cost, and it has limitations in terms of size of the material to be conveyed (Krol *et al*., 2017).

The decision to the selection of the most appropriate mode of transportations is an important factor in underground mine planning. To improve the decision making, the selection process requires knowledge of the mine planning, scheduling under financial variable parameters. Therefore, this paper presents a sensitivity analysis to analyse the effects of likely changes on selected parameters on the Net Present Value (NPV) of the mine plans generated for an orebody at different depth levels for diesel and electric powered trucks, shaft, and belt conveyor haulage systems. The aim is to evaluate the most sensitive parameters of the haulage operations as mine depth increases. The quantifiable parameters considered in this analysis are commodity price, mining rate, fixed cost, operating costs, and ore grade. The values of these parameters are estimated based on the most probable forecasts, which cover a long period of time, and are influenced by a great number of variables such as mining and milling costs, metal recovery, discount rate, government or resource owner taxes, and depreciation. The actual values of these parameters may differ considerably from the forecasted values, depending on future developments and implementation of the project.

Copious authors have advanced the state of the art in the broad topic of mine planning, scheduling and equipment selection under variable parameters in solving various mining problems in both open-pit and underground mining operations. Dimitrakopoulos and Ramazan (2004) demonstrated the orebody variability in terms of ore grade, tonnes and quality to optimize the long-term production scheduling. Their finding reveals that the approaches of including variability in mine operations improve the results rather than rely on traditional approach. Dimitrakopoulos and Sabry (2007) evaluated mine plans under uncertainty by comparing the value using net present value (NPV) and real option valuation, and concluded that both methods can be used in economic valuation with the higher value being observed in real option. Boland *et al.* (2008) uses mixed integer multistage stochastic programming to estimate mine production scheduling with multiple geological properties with the aim of maximizing NPV. They concluded that the approach demonstrates the improvements that can be made to mine schedules rather than rely on single geological property estimate. Nehring *et al.* (2010) described the production schedule optimization in underground mine operation using mixed integer programming. Their analysis allows in solving much larger underground scheduling problems within a reasonable time with potential to improve the NPV. Dehghani and Ataee-pour (2012) uses binomial tree technique to determine the NPV of the copper mine by assuming the uncertainty of the metal price and operating costs. They found that the method is suitable and applicable in forecasting the economic uncertainty of mining projects.

Ramazan and Dimitrakopoulos (2013) described the production scheduling with uncertainty supply. They developed a multiple conditionally orebody models for optimizing annual production schedule in open pit mines unlike the traditional scheduling that are based on a single orebody model. They found that the approach manages the risk of not meeting the production targets by controlling the magnitude and the probability of the risk within individual production periods with increased value of NPV. Salama *et al.* (2015) presented the optimization of the value of the mine plan under metal price uncertainty without considering a fluctuation mining rate. The authors suggest that, when mining operations look to gain as much value as possible, it is not appropriate to keep operating under the same mine plan if commodity prices have altered during the course of operation. In addition to this, the authors suggest that a mining rate which can be altered throughout mine life, due to a reconfiguration in the number of equipment, even if production costs increase, should be explored as a means for further maximizing the value of the mine plan. Ramazan and Dimitrakopoulos (2018) analysed the long-term production scheduling with multiple simulated orebody models using integer programming formulation with the aim of maximizing NPV. They concluded that using a set of multiple orebody models allows for the integration of deposit variability to the optimization process. Upadhyay and Askari-Nasab (2018) uses a discrete event simulation combined with goal programming to develop uncertainty scheduling to allow mine planners to achieve mine’s operational and short-term objectives.

Much of the literature evaluates mine operations with variability in the broad topic of mine planning, optimization, scheduling and equipment selection using various methods such as Genetic algorithms, Mixed integer programming, and Discrete event simulation. To the author’s knowledge, no noticeable research evaluates the haulage system selection under variable parameters for underground mine operations proceeds at great depth. Therefore, this paper develops the work conducted by (Salama *et al.,* 2014; Salama *et al.,* 2015; Salama *et al.,* 2017) to carryout sensitivity analysis to evaluate the effects of likely changes on quantifiable parameters to the net present value (NPV) of the mine plans generated for an orebody at depth levels of 1000 and 3000 meters respectively. During the analysis, discrete event simulation was used to determine the performance of these haulage options in achieving the desired production target of 100,000 tonnes of ore per month for each option at each depth. The simulation results obtained were used to determine the energy cost per tonne of each haulage scenario for each depth and then exported to the mixed integer programming. Once costs have been established, Mixed Integer Programming (MIP) was used to calculate operating cash flows associated with each mined stope in order to generate an operating NPV for each haulage option.

2 Materials and methods

Sensitivity analysis was carried out to analyse the effects of likely changes on parameters on NPV of the mine plans generated for an orebody at depth levels of 1000 and 3000 meters, using diesel and electric-powered trucks, shaft, and belt conveyor haulage systems. The quantifiable parameters used were commodity price, mining rate, fixed cost, operating costs, and ore grade. The aim was to evaluate the most sensitive parameters of the haulage operations as mine depth increases. Sensitivity analyses are usually prepared from a base case discounted cash flow model, with changes to the input data translating into changes in the payback period, internal rate of return, or net present value. Among these methods of investment appraisal, the most widely used is the sensitivity analysis on discounted cash flow NPV. NPV considers the time value of money, cash flows, and the full life of the project. The problem with this technique is the determination of cost of capital which is not always constant over the life of project which results in to the stressing of profit maximization (Moyen *et al.,* 1996; Dimitrakopoulos and Sabry, 2007; Ramazan and Dimitrakopoulos, 2018). Sensitivity analyses look at varying one or more of the input parameters to determine how much the return-on-investment changes. Within acceptable ranges, sensitivity analysis provides significant insight into the project risk by determine which parameter the project is more sensitive. It can be depicted how the mine project is typically highly sensitive to variation in parameters affecting its revenue. A sensitivity analysis, once performed, may influence the decision about the financial project, or at least show the decision maker which parameter is the most critical to the financial success of the project. During the analysis, one parameter at a time can be varied in steps while other parameters are held constant to see how much effect this variance has on NPV (Torries, 1998). Sensitivity analysis can be greatly facilitated by construction of interactive models on computer spreadsheets or using specialized risk analysis software (Lawrence, 2001).

An operating cost per tonne was first estimated for each analysed haulage option. The production estimations were carried out using AutoMod discrete event simulation software, and the cost was estimated by analysing the results and adjusting and extrapolating a set of actual operating costs.

2.1 simulation model

The model formulation consists of ore-body mined at two underground depth levels of 1,000 metres, and 3,000 metres using four haulage options which are diesel and electric-powered trucks, vertical shaft, and decline conveyor. The simulation analysis aimed to assess the performance of these haulage options in achieving the desired production target of 100,000 tonnes of ore per month for each option at each depth. LHDs were used to load and haul ore from the working faces to the diesel or electric trucks. The electric trucks leave the trolley electricity line during loading and dumping and use a small diesel motor. For shaft and conveyor systems, LHDs were used to load and haul ore and dump to the ore passes. The ore pass drop material to the chute located at lower level where materials are conveyed to the shaft point or three equal roll idlers at 35° troughing angle conveyor system. Times to load a bucket, travelling to ore pass, dumping and return to loading point are all used as input variables. Only a single LHD can load at a loading point and other LHDs arrives will wait until the loading point is free. On dumping, only a single LHD is allowed to dump and that there is no interaction during dumping for LHDs from both side of the orebodies. Models were developed using AutoMod^{TM} simulation software. The software has the advantages of modelling the mass movement with high level of details, and they are also commonly used simulation language environments capable of satisfying the characteristics necessary for the study. The AutoMod^{TM} software consists of a built-in material movement system and simulation environment, with static and dynamic graphics where the moving objects can be observed during the simulation run. The software has high flexibility which allows the modification of syntax and built-in environments for various parameters such as speed, turning speed, acceleration, or deceleration.

Complete programming codes were created and the simulation output was generated. The system was simulated for a month which consists of 7 working days for two shifts of 10 hours in each day. During the breaks, the machine was sent to the closest parking space.

2.2 Mixed Integer Programming models

The simulation results were then used to calculate operating cash flows associated with each stope using MIP. The MIP model was created using a Mathematical Programming Language and then solved using IBM ILOG CPLEX 10.3 version optimization tool. The solution process for each of the analysed scenarios were left to run for approximately 8 hours and was cut short even if convergence to the optimal solution had not yet been achieved. During analysis, the operating costs are subtracted from the operating revenues to calculate the undiscounted cash flows associated with the extraction phase of each stope which in turn forms the basis for the production scheduling optimisation process. NPVs were calculated based on the operating cash flows generated by each haulage option. The results were then used to calculate the undiscounted cash flows associated with the extraction phase of each stope which in turn forms the basis for the production scheduling optimisation process. The results are then used to carry out optimised production scheduling in order to generate an operating NPV for each quantifiable parameter. The MIP model comprises of an objective function and several constraints. The objective function was to maximize the NPV of all activities under consideration by determining the optimal schedule within which to progress each stope through production (Equation 2.1).

$$Max\colon \sum_{s,t} n_t \times cf_s \times w_{st} \qquad (2.1)$$

Where n_t represent value of the discount factor for time period t, cf_s is the undiscounted cashflow ($) from each stope, and w_{st} stands for binary variable required to reflect stope operating conditions. The MIP model also comprises numerous constraints (shown as 2.2 to 2.6) which reflect the practical limitations imposed by the sublevel stoping method over the long-term scheduling horizon. These constraints can be classified according to the limitations they impose on resources, sequencing and timing.

$$\sum_{s\in\beta_t} r_s \times w_{st} \leq sc_t \; \forall t \qquad (2.2)$$

$$\sum_{t\in\beta_s} w_{st} \geq w_{s't} \qquad \forall\, s,\, t \mid s' \in mbm_s \qquad (2.3)$$

$$w_{st} + w_{s't} \leq 1 \qquad \forall\, s, t \mid s' \in mbm_s \qquad (2.4)$$

$$\sum_{t\in\beta_s} w_{st} \leq 1 \qquad \forall s \mid l_s > T \qquad (2.5)$$

$$\sum_{t\in\beta_s} w_{st} = 1 \qquad \forall s \mid l_s \leq T \qquad (2.6)$$

Where sc_t is the truck/shaft/conveyor fleet movement capacity (t) for each time period t, r_s stands for extraction reserve (t) for each stope, l_s is the latest start time for stope. Constraint (2.2) limits production of all development and stope extraction ore from exceeding the truck/shaft/conveyor fleet capacity in any long-term time period. All proceeding production sequencing between stopes also enforced by constraints (2.3) and (2.4). Constraint (2.5) ensures that commencement of stope production is initiated no more than once during the long-term scheduling horizon if their late start date occurs beyond the scheduling horizon. Constraint (2.6) requires stope production commences at some point during the long-term scheduling horizon if their late start date falls within the long-term scheduling horizon. These modelled equations were used to generate optimal production schedule and mine plan at variable commodity price, mining rate, fixed cost, operating costs, and ore grade from each haulage option.

3 The case study

The ore-body amenable to sublevel stopping was used for the purpose of investigating the impact of various operational scenarios on operating value. The scenarios being investigated include mining of the ore-body at various depths using a number of haulage options across various commodity price, mining rate, fixed cost, operating costs, and ore grade. The operation under investigation extracts copper bearing ore from an ore-body striking east-west and dipping at 70 to 75 degrees in the southerly direction. For the purposes of this investigation, the exact same ore-body will be mined at two underground depth levels of 1,000 metres, and 3,000 metres. The four haulage options under consideration are: diesel and electric-powered trucks both operating on decline (inclined at 10%), vertical shaft, and decline conveyor (inclined at 20%). It was assumed that, the ore-body at these depth levels is at the same stage of production with 3.4 Mt already having been mined from a total initial reserve of 20 Mt grading 2.19% Cu for 438,375 tonnes of Cu metal. The remaining reserve in each case is 16.2 Mt, which will vary slightly in grade between each depth levels depending on which stopes have been removed. The targeted total production rate for this operation is 100,000 tonne per month, which is 1.2 Mtpa. At these production rates, this operation is therefore expected to have a remaining mine life of 13.5 years. The differing operating conditions that are required as a result of increased rock stress due to increased depth is reflected in altered stope size and sequencing. Optimised production scheduling in each case will therefore incorporate and continue from the existing schedule by including stopes that are already in production and by continuing to adhere to particular rock stress management constraints. At a 1000 m depth, a total of 100 equally sized stopes using the maximum allowable size of 25 m x 25 m x 100 m with a capacity of 200,000 tonnes for each stope were investigated. Of the initial 100 stopes, 17 have already completed the entire production process to become a fully consolidated fillmass. A total of 5 stopes are currently in some phase of production. This therefore leaves the remaining 78 stopes available for the commencement of production with the internal development phase.

At 3000 m depth, a total of 200 equally sized stopes using the maximum allowable size of 25 m x 12.5 m x 100 m (half the size of stopes at the 1000 m) with a capacity of 100,000 tonnes for each stope were analysed. Of the initial 200 stopes, 34 have already completed the entire production process to become a fully consolidated fillmass. A total of 10 stopes are currently in some phase of production. This therefore leaves the remaining 78 stopes available for the commencement of production with the internal development phase. Therefore, the operating cost per tonne for these stopes was calculated across each analysed haulage option and the results were used to calculate operating cash flows.

3.1 Input data

Long term production scheduling was carried out at monthly intervals over the life of the operation. Some of the data for operating costs on each haulage option was taken from papers published by (Salama *et al.*, 2014; Salama *et al.*, 2015, Salama *et al.*, 2017). The aim was to evaluate the effects of likely changes on parameters to the NPV of the mine plans generated for the orebody at depth levels of 1000 and 3000 meters for diesel and electric powered trucks, shaft, and belt conveyor haulage systems. Table 1 shows data obtained from the mine and which used to create the base case model.

Table 1 Input data for base case model

Item	Value	Unit
Income Tax	30	%
Depreciation	8	%
metal price	5000	$
loan interest	15	%
loan Duration	7	Years
Copper grade	2.19	%
Monthly Production	100,000	Tonnes
Mine life	13.5	Years
Discount rate	10	%
Fixed costs	80	M$

The base case model was created at copper price of $5,000. The price of $5,000 was used since most feasibility studies on copper projects conducted over recent years generally use a price between $5,000/t and $5,500/t over the long term even though the copper price at the time that this study is being performed is about $7,930/t Cu. These data were used to obtain NPVs for each hauling option. Capital costs required to implement each haulage option for all cases are outside the scope of this investigation and are therefore not included. The NPVs calculated based on the operating cash flows for each haulage option at depth levels of 1000 m and 3000 m (Tables 2 and 3) were used as input in carryout the sensitivity analysis. During sensitivity analysis, the base case model was calculated when the factor is 1, while other parameters were adjusted by the risk-free rate for the entire life of mine by factors ranging 0.6 to 1.5. The ore grade was varied between 0.9 to 1.2. This is because when there is for example a rise of the selling price, lower-grade ores will be incorporated into the mine plan, while when there is a fall in selling price, high grade can be blended with low grade to reflect the changes. Table 3 shows the negative NPVs for diesel-powered trucks mainly due to high costs of operation.

Table 2 NPVs across all quantifiable parameters for each haulage options at 1000 m depth.

		NPV (M$)				
DIESEL TRUCK	**Factor**	**Commodity price**	**Mining rate**	**Fixed costs**	**Operating cost**	**Ore grade**
	0.6	63.58	63.88	463.56	547.90	
	0.7	137.27	136.27	457.01	524.48	
	0.8	285.45	284.05	443.92	477.66	
	0.9	356.45	357.44	437.37	454.24	367.16
	Base case	430.83	431.13	430.83	430.83	430.83

	1.2	577.61	581.07	417.74	387.46	434.18
	1.4	724.38	727.85	404.64	340.63	
	1.5	797.77	801.24	398.10	317.22	
ELECTRIC TRUCK	0.6	131.20	216.35	530.88	583.29	
	0.7	204.59	272.71	524.33	566.26	
	0.8	351.37	385.43	511.24	532.21	
	0.9	424.76	441.79	504.69	515.18	434.48
	Base case	498.15	498.15	498.15	498.15	498.15
	1.2	644.93	610.87	485.06	464.09	501.50
	1.4	791.71	723.59	471.97	430.03	
	1.5	865.10	779.95	465.42	413.01	
SHAFT SYSTEM	0.6	178.50	240.00	578.18	606.94	
	0.7	251.89	301.09	571.63	594.64	
	0.8	398.67	423.27	558.54	570.05	
	0.9	472.06	484.36	552.00	557.75	481.78
	Base case	545.45	545.45	545.45	545.45	545.45
	1.2	692.23	667.63	532.36	520.85	548.80
	1.4	839.01	789.81	519.27	496.26	
	1.5	912.40	850.90	512.72	483.96	
CONVEYOR BELT	0.6	174.72	238.10	574.40	605.05	
	0.7	248.11	298.82	567.85	592.37	
	0.8	394.89	420.24	554.76	567.02	
	0.9	468.28	480.95	548.21	554.34	478.00
	Base case	541.67	541.67	541.67	541.67	541.67
	1.2	688.45	663.09	528.58	516.31	545.02
	1.4	835.22	784.52	515.48	490.96	
	1.5	908.61	845.23	508.94	478.28	

Table 3 NPV across all quantifiable parameters for each haulage options at 3000 m depth.

		NPV (M$)				
	Factor	**Commodity price**	**Mining rate**	**Fixed cost**	**Operating cost**	**Ore grade**
DIESEL TRUCK	0.6					
	0.7					
	0.8					
	0.9					
	Base case	-166.12	-166.12	-166.12)	-166.12	-166.12
	1.2					
	1.4					
ELECTRIC TRUCK	0.6		14.13	126.45	381.08	
	0.7		30.05	119.90	323.61	
	0.8	-53.06	61.88	106.81	208.66	
	0.9	20.33	77.80	100.27	151.19	30.05
	Base case	93.72	93.72	93.72	93.72	93.72
	1.2	240.50	125.56	80.63	-21.22	97.07
	1.4	387.28	157.39	67.54		

	1.5	460.67	173.31	60.99		
SHAFT SYSTEM	0.6	38.02	169.75	437.69	536.70	
	0.7	111.41	216.80	431.15	510.35	
	0.8	258.19	310.88	418.06	457.66	
	0.9	331.58	357.92	411.51	431.31	341.29
	Base case	404.96	404.96	404.96	404.96	404.96
	1.2	551.74	499.05	391.87	352.27	408.32
	1.4	698.52	593.13	378.78	299.58	
	1.5	771.91	640.18	372.24	273.23	
CONVEYOR BELT	0.6	-70.78	115.36	328.90	482.30	
	0.7	2.61	151.52	322.35	445.08	
	0.8	149.39	223.85	309.26	370.62	
	0.9	222.78	260.01	302.72	333.40	232.50
	Base case	296.17	296.17	296.17	296.17	296.17
	1.2	442.95	368.50	283.08	221.72	299.52
	1.4	589.73	440.82	269.99	147.27	
	1.5	663.12	476.99	263.44	110.04	

3.2 Verification and validation of simulation model

The verification and validation processes to ensure that the simulation model is accurately represent the system being modelled and that the simulation results are reliable was conducted. The aim of verifying and validating the model is to increase the confidence level and credibility of the correctness of the model (Skawina et al, 2018). The model verification was done using debugging, and extreme condition tests, while the model validation was conducted using face validity and comparison with the real system. The debugging was done by correcting all errors observed during the simulation runs. This was achieved by correcting the syntax and coding of the simulated program. Comparison with the real system (Table 4) was done by comparing the production data from the operating mine with the results from the simulation. In addition, extreme condition tests and internal validity were used to test the accurate of the simulation model. Internal validity was tested by having a five replications for each set of different runs in each haulage area by ensuring that, after changing the stream random numbers in the model, the model's results did not significantly differ from each other. In most of the cases, the results of running the model with different stream random numbers have deviated from each other by no more than 3.5%.

Table 4 Comparison of the real and simulated systems

	Belt width (mm)	Production (t)	Skip weight (t)	Skip speed (km/h)	Production (t)
Real system	900	105,000	15	30	103,000
Simulated system	900	100,700	15	30	106,065
Discrepancy (%)		4.1			-3.0

4 Results and Discussion

This study presents a sensitivity analysis to analyse the effects of likely changes on selected parameters on the NPV of the mine plans generated for an orebody at depth levels of 1000 m and 3000 m for diesel and electric-powered trucks, shaft, and belt conveyor haulage systems. The aim is to evaluate the most sensitive parameters of the haulage operations as mine depth increases. During the analysis, AutoMod software was used to determine the expected operating costs associated with each haulage options at each depth level. The simulation analysis aimed to assess the performance of all four haulage options in achieving the desired production target of 100,000 tonnes of ore per month for each haulage option. The number of trucks, skip sizes, or belt sizes were analysed to determine the optimal capacity in achieving the production target. The results show that, the number of trucks required to achieve the production target at 1,000 m depth were 7 and 5 for diesel and electrical respectively. This is because the complete cycle time of the electric truck is shorter than the diesel truck which allowing more cycles to be done within the same period of time. The simulation was repeated for the depth of 3,000 m and the results shows that more diesel trucks than electric truck are required to achieve the same output.

For the shaft system, the results indicated that when the depth is at 1000 m, a shaft system of two skips in balance each of 15 tonnes can haul 100,000 tonnes of ore at a speed of 8.5m/s. The simulation was repeatedly run with the same skip size and variable rope speeds. The results show that rope speeds were increased to 14m/s to haul same material from 3000 m to the surface. The conveyor belt hauls the ore from the storage bin located under the underground crusher to a stockpile on the surface. The belt width of 900 mm and speed of 1.6m/s can haul 100,000 tonnes of ore per month at a rate of 80 tonnes/hour. The simulation results obtained from all haulage options were used in the determination of the energy cost per tonne of ore for each haulage scenario and then exported to the mixed integer programming model for optimization purposes.

Once costs have been established, the IBM ILOG CPLEX 10.3 version was used for optimization, whereby the operating cash flows to generate an operating NPV was determined. A sensitivity analysis was then carried out to show how the mine project is typically highly sensitive to variation in parameters affecting the revenue. During sensitivity analysis, the commodity price, mining rate, fixed cost, operating costs, and ore grade were considered. One of these parameters were varied while others were kept constant. The results for diesel-powered trucks when operated to haul materials from a depth of 1000 m to the mine surface shows that the NPV is 430 M$ for the base case scenario (Fig 1). As parameters start to be changed, it shows that commodity price and mining rate play a significant role in mine profitability. The NPV is observed to increase to 800 M$ and decreased to 100 M$ for high and low commodity price and mining rate, respectively. This shows that, while diesel truck haulage generally offers greater operational flexibility, its high operating costs results in a rapid reduction in its financial viability.

Fig. 1 Sensitivity analysis for Diesel-powered trucks for operations at 1000 m depth

The sensitivity analysis for the electric-powered trucks when operated to haul materials from a depth of 1000 m to the mine surface was then analysed and the results shows that, the NPV is 498 M$ for the base case and increased to 895 M$ when commodity price and mining rate increased (Fig 2). This haulage method is observed to be more financially viable compared to diesel-powered trucks due to low operating cost.

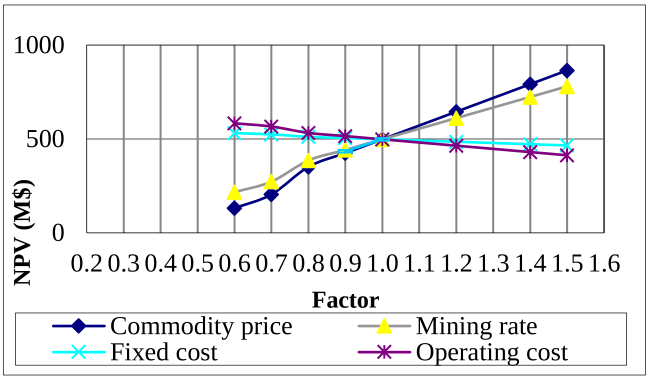
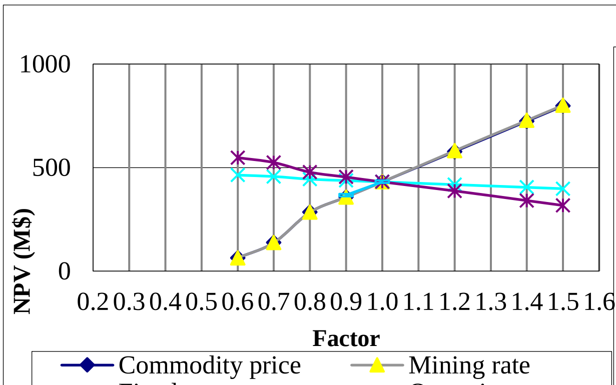


Fig. 2 Sensitivity analysis for Electric-powered trucks for operations at 1000 m depth

Further, the sensitivity analysis for the shaft and belt conveyor haulage systems when operated to haul materials from a depth of 1000 m to the mine surface was analysed (Figs 3 and 4). It can be depicted that; shaft and belt conveyor produce higher NPV compared to diesel and electric-powered trucks. It can further be seen that, when high level of investment in haulage methods is considered, commodity price and mining rate observed to have high impact on NPV. For example, if the commodity price is 20% more than the planned price and nothing else changes, the NPV will increase by approximately 150 M$ (Fig 3). If the commodity price turns out to be 20% less than the planned value and nothing else changes, then the NPV rapidly declined. Fixed costs and ore grade were observed to have low impact to the choice of haulage systems.



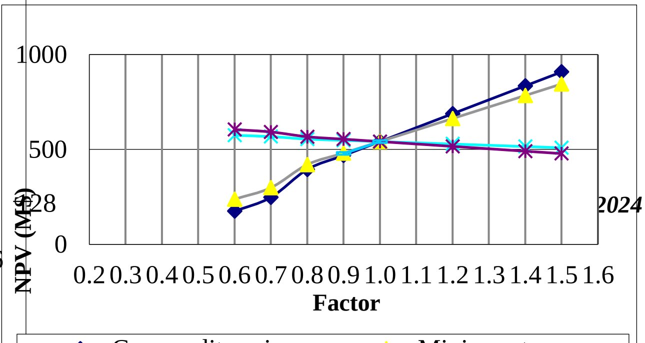


Fig.3 Sensitivity analysis for Shaft system for operations at 1000 m depth

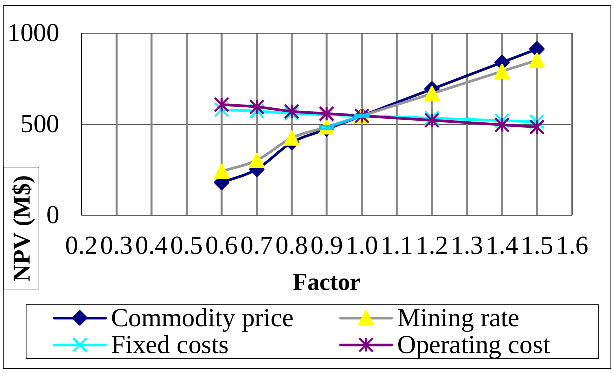


Fig 4 Sensitivity analysis for Belt conveyor for operations at 1000 m depth

Since it is recognized that the ore haulage from deeper levels to the mine surface is one of the most energy intensive activities in a mining operation and is thus one of main contributors to operating cost, it is therefore appropriate to analyse the systems for higher depth (for this case 3000 m). At this depth, only energy and labour costs were included in operating costs estimation and assumed to be three times higher than the current values. The results for this analysis show that at the base case, the NPVs are 100 M$, 400 M$, and 300 M$ for electric-powered truck, shaft, and belt conveyor haulage systems respectively, while diesel-powered truck produces negative NPV (Figs 5, 6, and 7). It also shows that, the commodity price, mining rate, and operating costs play a significant role in mine profitability across all haulage options. In the case of elevated commodity price, while other parameters remain constant, shaft generate higher profit compared to belt conveyor and electric-powered trucks. This depict that, diesel-powered truck haulage is not the favoured option when distance increases, but can be used in conjunction with other haulage options to transport material from lower levels to mine surface. The rapid change in commodity price and continuing increase of the operating costs in diesel-powered truck due to higher energy price will favour electric-powered, shaft, or belt conveyor haulage systems. The use of these haulage systems will require additional infrastructure for full utilization. However, the infrastructure costs are outside the scope of this study.

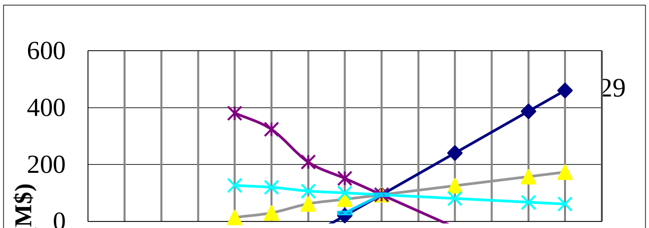


Fig. 5 Sensitivity analysis for Electric-powered trucks for operations at 3000 m depth

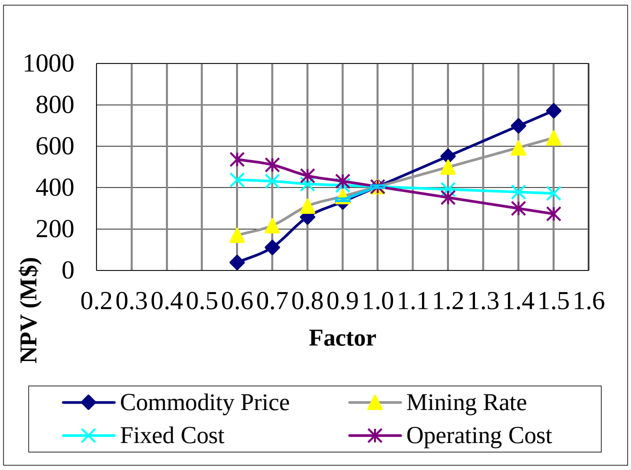


Fig. 6 Sensitivity analysis for Shaft system for operations at 3000 m depth

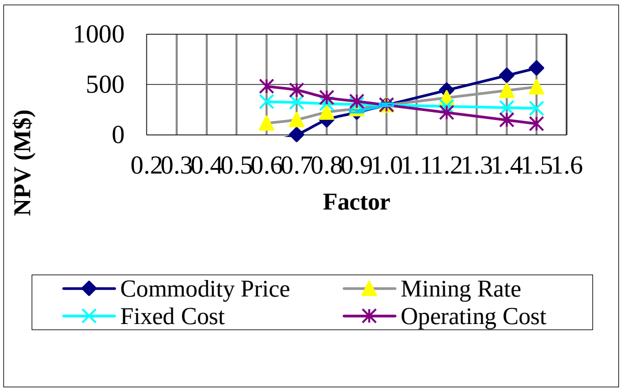


Fig. 7 Sensitivity analysis for Belt Conveyor for operations at 3000 m depth

The method developed in this paper allows the decision makers to define the risk profile associated to the evaluated parameters. The choice of a feasible hauling method for mine operation proceeding at great depth requires knowledge of the mine planning and scheduling and parameters affecting the decision. The outcome of the sensitivity analysis is the information on the extent to which changes on the controlling parameters become significant and thus influence the optimal decision. The decision makers will have the options of minimizing the risk when evaluating haulage systems by using sensitivity analysis to guide a suitable choice and evaluating the flexibility of the parameters during selection processes. Sensitivity analysis provides a useful starting point when considering variations in multiple parameters. For example, if the price of the fuel rises, the mine will preferentially use more electrically-powered equipment compared to diesel. If the selling price rises, lower-grade ores will be incorporated into the mine plan which may then be changed dramatically. As ore deposits near the surface continue to be depleted and mined out, the mines will focus on deeper operations whereby the haulage distance to the mine surface is going to be one of the main challenge. The use of the haulage methods with less operating costs will be beneficial towards cost reduction. The hauling methods selected must be flexible enough to accommodate limitations imposed by existing mine facilities, such as compatibility with production schedule, existing mine development, coping with different geological conditions, and adopting technological changes. If the existing hauling method is based on the electric-powered trucks, the expansion can be achieved incrementally by adding trucks as required until capacity of the planned design is reached which may led to additional requirement of the infrastructure.

Generally, the results obtained in the cases analysed in this paper shows that, diesel-powered trucks are feasible up to 1000 m mine depth. Below this depth, the financial evaluations do not favour the usage of diesel-powered trucks. Electric powered trucks, shaft and conveyor were observed to be the feasible haulage systems for s mine depth below 1000 m depth. Shaft and conveyor systems can be inflexible because of the limited number of fixed feed points, while trucking system is flexible because can travel to most locations in the underground mine. In the situation where the underground mine needs to modify its production capacity, the potential is often related to the configuration and current utilization of the ore handling system. Increasing throughput in fixed systems is relative cheap up to a point where the system utilization is at the optimal design. Beyond this point, higher utilization will probably require duplication of the existing system at significant cost.

5 Conclusions

This paper presents a sensitivity analysis to analyse the effects of likely changes on selected parameters on the NPV of the mine plans generated for an orebody at depth levels of 1000 m and 3000 m for diesel and electric-powered trucks, shaft, and belt conveyor haulage systems using discrete event simulation and Mixed Integer Programming to evaluate the most sensitive parameters on the selection of haulage operations as mine depth increases. The simulation analysis aimed to assess the performance of these haulage options in achieving the desired production target of 100,000 tonnes of ore per month for each option at each depth. The simulation results obtained were used to determine the energy cost per tonne of each haulage scenario for each depth and then exported to the mixed integer programming to calculate the operating cash flows to generate an operating NPV. The results show that:

i. Diesel trucks system required to achieve the production target of 100,000 tonnes per month is only feasible at 1000 m depth. Beyond this depth, diesel trucks were observed to be not practical to haul material directly to the mine surface.
ii. Electric trucks, shaft, and conveyor belt haulage systems were observed to be feasible in hauling material from great depths to the mine surface.
iii. The commodity price, mining rate and operating costs have great impact on NPV compared to fixed costs and ore grade. For example, if the commodity price rise by 20%, the NPV increases by 37% from the base case, while if the fixed costs rise by 20%, the NPV increases by 19%.
iv. At both analysed mine depths, diesel-powered trucks are observed to have low NPVs compared to other haulage options. Diesel-powered truck offers greater operational flexibility, but is not the feasible options regardless of any parameter change when the distance is further increased.
v. Electric-powered trucks are observed to have higher NPVs compared to diesel-powered trucks. The system emits minimal heat and emissions which leads to lower operating costs. Electric-powered trucks can be deployed but a detailed evaluation of the capital required for the additional infrastructure is of necessary.
vi. Shaft and belt conveyor system generated high NPVs compared to diesel or electric-powered trucks. Despite being high capital-intensive, their low operating costs favours the systems to be better haulage options for deeper mines.

Sensitivity analysis provides a useful starting point in haulage systems selection as mine depth increase when considering variations in multiple parameters.

The decision makers will have the options to minimize risks and evaluating the flexibility of the parameters during selection processes.

Acknowledgement

This research work is part of the I^{2}Mine project conducted at Lulea University of Technology, Sweden. The authors would like to acknowledge the EU 7th framework programme for funding this research as in great extent helped towards completion of this work.

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