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Determination of Optimum Production Capacity and Mine Life Considering Net Present Value in Open Pit Mining at Different Overall Slope Angles

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In modern mining industry, with increasing competitive environment and unit costs, it is necessary to evaluate mineral resources optimally from the aspects of economy, safety and environment. On the other hand, production increase is another reality and obligation for today's mining operations. The activities related to the extraction of ore deposit consist of risky operations, which are a great hazard for capital investments that will take many years. Therefore, in terms of feasibility, it is very important to determine optimum production capacity and a mine life in the mine planning. In open pit mine planning, many factors affect total fixed and operating costs, such as haulage costs, particularly when the mine goes deeper, geomechanical features of the ore body and surrounding rocks, diggability and slope stability related to overall slope angle. In this study, with the help of the developed software, by encompassing all these parameters and considering Net Present Value (NPV), it is targeted to determine optimum open pit production capacity and economic mine life, which are the major parameters in feasibility studies of mining projects.

Key words: *Open pit, mine planning, net present value, optimum capacity, economical mine life*

Introduction

It is necessary to exploit reserves more economically and prudently for optimal evaluation of non-renewable mineral deposits. In addition, increasing competition and challenging market conditions gradually urge profit-maximized production planning. The mining industry is a very risky industry compared to other industries because it depends on ore body estimations and decision makers must consider many uncertain inputs together [1]. The uncertainties have an important impact on project investment decisions. Identifying the potential sources of uncertainties is very important in order to obtain accurate results. Therefore, each uncertainty and its impact on the project should be analysed carefully [2].

At present, the large-scale open pit operations are looking at ways to improve the economics of their operations using Net Present Value (NPV) as a criterion. The mine planners of this new millennium are looking beyond the optimization techniques that traditionally provide the highest undiscounted profits. The available commercial packages are retooling their programs to overcome shortcomings of traditional mine planning techniques and providing NPV maximized mine plans and schedules [3].

Mine planning and design is an area in the mining industry that is given little attention, yet it is the area that influences the Net Present Value (NPV) of the mineral reserve most. In order to maximize the NPV, regular review of the pit design may be required to evaluate an updated geological reserve, or to assess the impact of new metal price forecasts, or new changes in the geotechnical parameters affecting pit slope or access [4]. The objective of the planning process for an open pit mine is usually to find optimal annual schedules that will give the highest Net Present Value (NPV) while meeting various productions, blending, sequencing and pit slope constraints [3].

Evaluation of Mining Investment Projects and NPV

Benefit maximized production capacity is a very important subject to strategic mine planning of ore deposits. Planning series of steps are undertaken in varying amounts of detail, depending on the precision, economic action, or decision being sought. The stages of the mine planning cycle and relevant elements are schematically illustrated in Figure 1. The elements of this planning cycle are creating a new project, a broad-brush mine plan; (depth, stripping ratio, ore grade, selling price, distance, etc.); strategic planning and development; detailed long-term mine plan or feasibility study; machine equipment selection; mine development phase; yearly planning, monthly planning and daily planning schedules [5].

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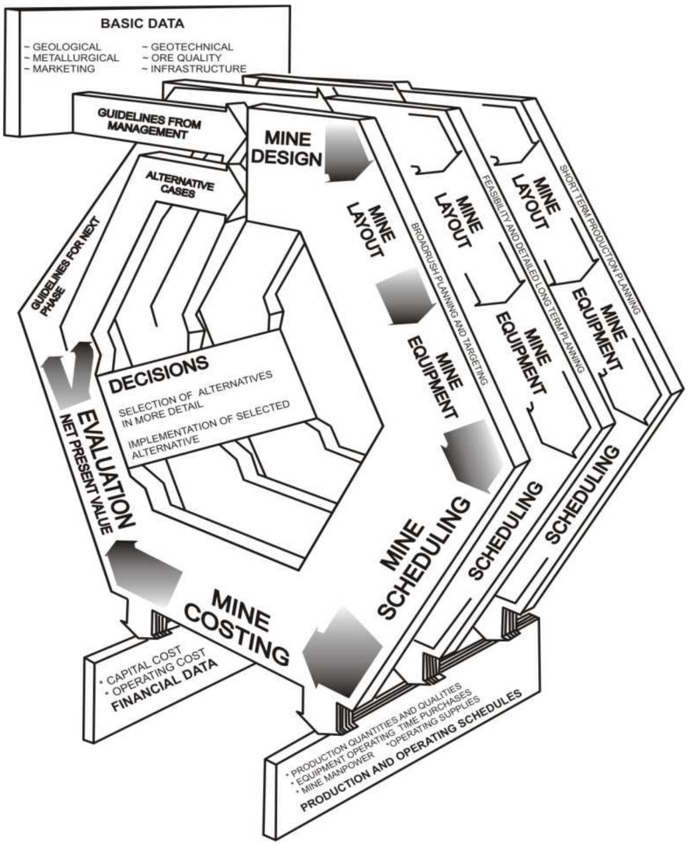


Fig. 1. Phases of mine planning cycle and related elements [5].

The NPV method describes the difference between the present value of all cash flows and investment and gives realistic results. Therefore, when compared to other evaluation methods, NPV is considered and preferred as a more realistic and reliable tool in project evaluation [6] and thus the decision on the mining investment is mostly attributed to the NPV of the project.

Construction of a financial model needs accurate estimations of income and costs. Estimation of the revenues and costs includes many uncertainties [1] because the uncertainties affect the estimated value and they compose the value chain. Therefore, the inputs should be analyzed to optimize the overall mine process. Optimization of the value chain must be done properly starting from the initial phase until the end process to identify high-risk areas and remove their impact on the maximization of the profit. Evaluation of the value chain is an interdisciplinary process and the interdisciplinary components of the value chain are geology, geomechanical, mining and metallurgical engineering. They relate to each stage from exploration through feasibility study, to grade control, mineral processing and marketing [2]. A simplified demonstration of the mine value chain process and the nodes of uncertainty considered for estimation of NPV are presented Figure 2.

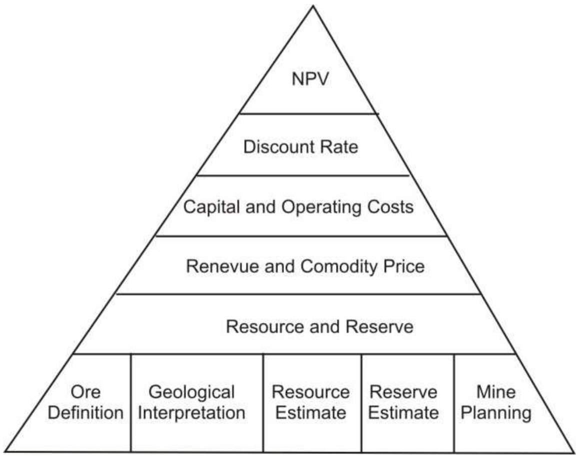


Fig. 2. Mine Value Chain [7].

Life-of-mine instances of the above model contain many blocks and periods. Therefore, researchers often assume a fixed cutoff grade and tend to aggregate entities (strata in earlier work and aggregated blocks later).

Early work consists of aggregating the blocks into strata, or horizontal layers, subject to a simple set of constraints. Solving the problem of production scheduling determines which sublayers to extract at what time and to which extent (referred to as shallow or deep mining). The corresponding model maximizes the NPV (influenced by factors such as sale price, transportation distance, and stripping ratio, while ensuring that each sublayer is removed either via deep or shallow mining, and that only one sublayer is mined within a given period [8]. When the literature work on this topic is investigated, it is seen that Elevli [9] presented a model that maximizes the NPV of extracted blocks subject to hard sequencing constraints and soft constraints on production and processing capacity. Sevim and Lei [10] described open pit ultimate limits, the cut-off grade, the mining sequence, and the production rate interactions. The methodology in their study based on a combination of optimum mining sequence, ore and waste production ultimate pit limits, and mine life. In all possible sequences, pushbacks were formed with generated pits and are evaluated with respect to their NPV. Erarslan and Celebi [11] determined a production schedule to maximize NPV subject to factors such as grade, blending, and production constraints [8]. Probably, the most important role of this approach is that it calculates the optimization factor, σ, in an iterative approach updating the remaining reserves, thus the mine life, for each year, in each iteration, in order to maximize the NPV of the project. This new approach using a variable optimization factor basis resulted in an improved total NPV as shown later in this paper. The program computes the optimization factor, “σ” by maximizing the project NPV, which is based on the ore tonnage–grade distribution and economic parameters of the mine, such as sale price, processing costs, mining costs, capital costs, fixed costs, mining capacity, discount rate and recovery percentage [12].

The algorithms that optimize ultimate pit limits conventionally search for an ultimate contour, which maximizes the total sum of the profits of all the blocks within the contour. The optimal ultimate pit limit is an important key for long term strategic planning. Current algorithms assume that this contour is excavated at once without considering the time aspect of the problem. The planning of an open pit mine considers the temporal nature of the exploitation to determine the sequence of block extraction in order to maximize the generated income throughout the entire planning period. It can be stated that mine planning, as an economic exercise, is constrained by certain geological, operational, technological, and local field circumstances. The mine planning models, which were developed previously by various researchers, usually define a discrete finite planning horizon [13, 11, 14, 15, 16].

The decision as to what should be mined within the ultimate pit limits is time-dependent and proper solution needs to take into account the knowledge of when a given block will be mined and how long one will need for stripping the overburden. The analysis of pit limits, which maximize NPV, requires that the time value of money is taken into care in defining which blocks should be mined and which blocks should be left in the ground during the life of the project. The open pit limits that maximize the undiscounted profits for a given project will certainly not maximize the NPV of the project [3].

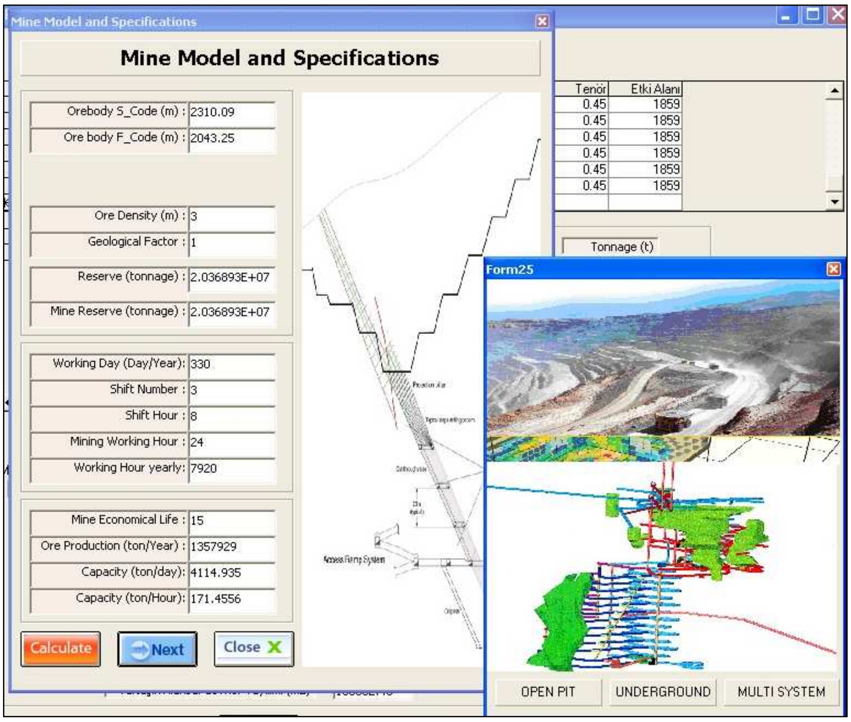
The study reported by Askari et. al. [17] yields the trajectory of the pit geometry over time with the respective volume of materials and net present value (NPV) of the mining operation. Generally, the optimized pit limit has been designed using Lerchs-Grossman algorithm in mining. The best-case annual schedule, generated by NPV over a mine life at a discount rate of per annum, is available in a recent study of [17].

Hypothetical Case Study

In open pit mine planning, many factors affect total fixed and operating costs, such as haulage costs, particularly when the mine goes deeper; geomechanical features of surrounding rocks; diggability and slope stability related to overall slope angle. In this study, by means of the developed software; overall slope angle, machine selection, initial investment and annual operating and fixed costs, operating efficiency, ore-grade value and ore sale prices were taken into consideration as shown in Figure 3.

In addition, required number of machines and their initial investment costs were determined depending on changing production capacity and economical mine life in different production models. For these alternative models, cost analyses were performed and unit costs and NPVs were calculated.

A change in the overall slope angle, which determines the stripping ratio, is one of the main factors affecting the unit cost value. The stripping ratio increases when mine goes deeper while the amount of recovered ore remains constant in inclined deposits. In this instance, the amount of overburden increases as well. Also, as dip of ore increases, both overall and instantaneous slope angle increase (Fig. 4).



Mine Model and Specifications

Orebody S_Code (m) : 2310.09
Ore body F_Code (m) : 2043.25
Ore Density (m) : 3
Geological Factor : 1
Reserve (tonnage) : 2.036893E+07
Mine Reserve (tonnage) : 2.036893E+07
Working Day (Day/Year): 330
Shift Number : 3
Shift Hour : 8
Mining Working Hour : 24
Working Hour yearly: 7920
Mine Economical Life : 15
Ore Production (ton/Year) : 1357929
Capacity (ton/day): 4114.935
Capacity (ton/Hour): 171.4556

Tenör	Etki Alanı
0.45	1859
0.45	1859
0.45	1859
0.45	1859
0.45	1859
0.45	1859

Tonnage (t)

Fig. 3. The software interface of mine planning and technical parameters taken into consideration.

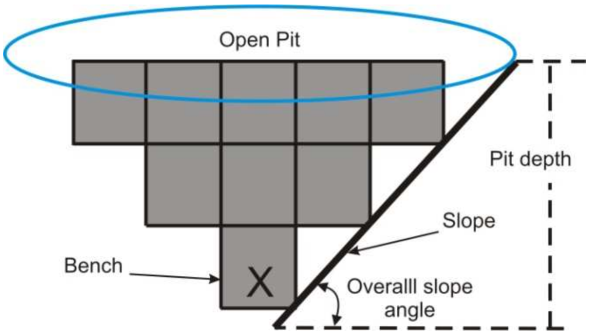


Fig. 4. Overall slope angle and mine depth for an open pit [18].

In the computation of required number of machinery-equipment and economic analysis, the flowchart of mine-costing procedure shown in Figure 5 was employed as a guideline. Economic evaluation was made in the form of cash flow diagrams with the presence of financial data (discount rate) relying upon total operating cost and total capital cost. Here, total operating cost consists of equipment operating cost and workforce cost and etc., whereas the total capital cost consists of purchase and replacement cost associated with interest and depreciation [5].

In the model study, ore reserve was estimated at 20 million tons, diggability class of overburden was accepted as “medium”, transport distance was taken as 2000 meters, the discount rate was selected as 10 % and maximum economical life was assumed to be 25 years. For any given constant production capacity, number of required trucks and shovels and also their initial investment costs were determined for various production alternatives. Total capital and operating costs were computed and eventually, taking into account the NPV, economic evaluation was carried out.

In our day, shovel+truck method is the most popular overburden removal and ore excavation technique because of its low investment cost, flexibility and easy use. Also, it is preferred due to its ability to adapt to the increases in production capacity and to hard topographic and deep mine conditions. For these reasons, shovel+truck was handled and preferred in the current study to conform to the general structure. As a result of computations, the required number of shovels and trucks was determined both for overburden and ore excavation (Fig. 6). In addition, the total initial investment cost was found related to the number of machines and their purchase prices.

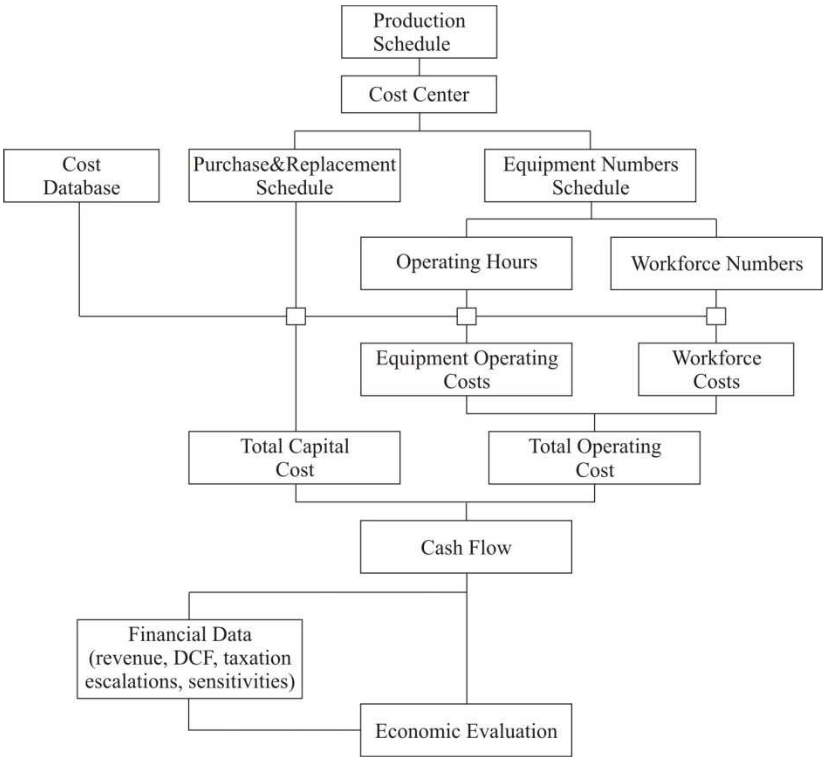
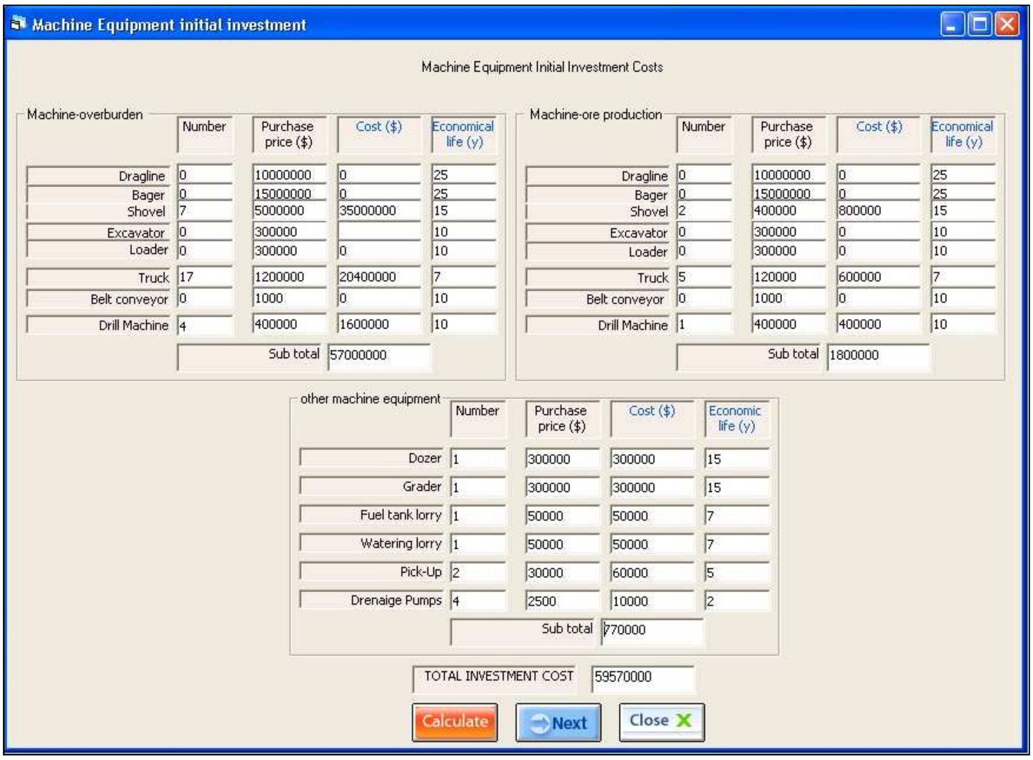


Fig. 5. Flowchart of mine-costing procedure [5].



Machine Equipment Initial Investment Costs

Machine-overburden

	Number	Purchase price ($)	Cost ($)	Economical life (y)
Dragline	0	10000000	0	25
Bager	0	15000000	0	25
Shovel	7	5000000	35000000	15
Excavator	0	300000		10
Loader	0	300000	0	10
Truck	17	1200000	20400000	7
Belt conveyor	0	1000	0	10
Drill Machine	4	400000	1600000	10

Sub total 57000000

Machine-ore production

	Number	Purchase price ($)	Cost ($)	Economical life (y)
Dragline	0	10000000	0	25
Bager	0	15000000	0	25
Shovel	2	400000	800000	15
Excavator	0	300000	0	10
Loader	0	300000	0	10
Truck	5	120000	600000	7
Belt conveyor	0	1000	0	10
Drill Machine	1	400000	400000	10

Sub total 1800000

other machine equipment

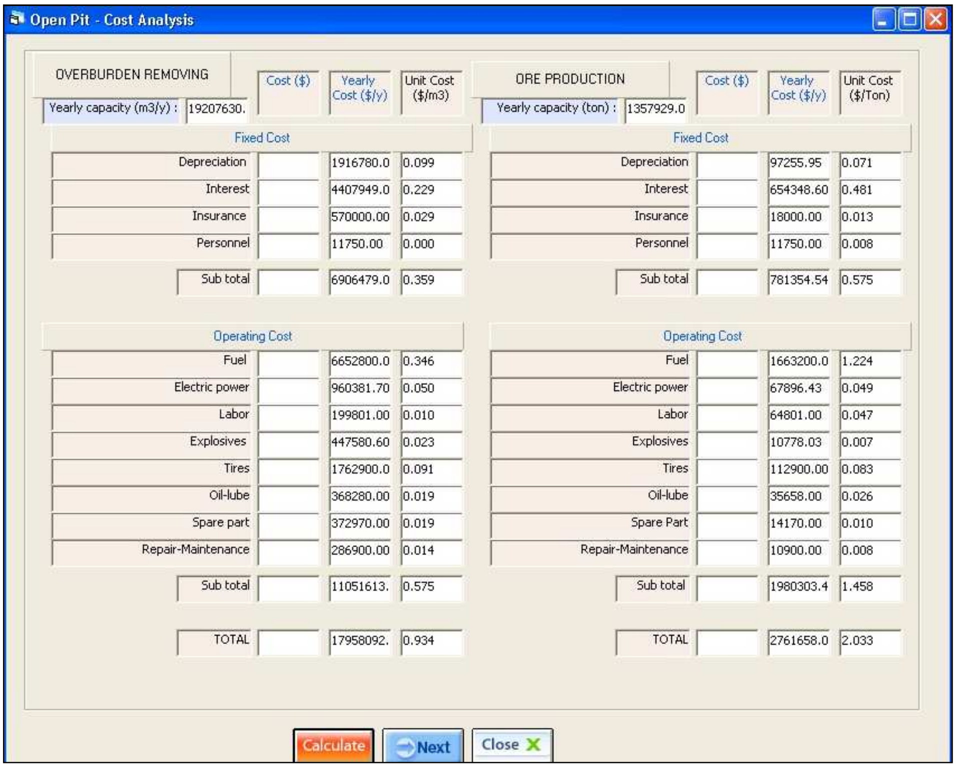
	Number	Purchase price ($)	Cost ($)	Economic life (y)
Dozer	1	300000	300000	15
Grader	1	300000	300000	15
Fuel tank lorry	1	50000	50000	7
Watering lorry	1	50000	50000	7
Pick-Up	2	30000	60000	5
Drenaige Pumps	4	2500	10000	2

Sub total 770000

TOTAL INVESTMENT COST 59570000

Fig. 6. List of machinery-equipment used and machinery initial investment on the interface.

Total yearly costs and unit costs were divided into two groups as overburden removal and ore production in the form of fixed and operating cost items for constant annual capacities. Fixed costs consist of depreciation, interest, insurance and personnel costs while operating costs are comprised of fuel, electric power, labour, explosives, tires, oil, spare parts and maintenance costs (Fig. 7).



OVERBURDEN REMOVING	Cost ($)	Yearly Cost ($/y)	Unit Cost ($/m3)
Yearly capacity (m3/y) : 19207630.			
Fixed Cost			
Depreciation		1916780.0	0.099
Interest		4407949.0	0.229
Insurance		570000.00	0.029
Personnel		11750.00	0.000
Sub total		6906479.0	0.359
Operating Cost			
Fuel		6652800.0	0.346
Electric power		960381.70	0.050
Labor		199801.00	0.010
Explosives		447580.60	0.023
Tires		1762900.0	0.091
Oil-lube		368280.00	0.019
Spare part		372970.00	0.019
Repair-Maintenance		286900.00	0.014
Sub total		11051613.	0.575
TOTAL		17958092.	0.934

ORE PRODUCTION	Cost ($)	Yearly Cost ($/y)	Unit Cost ($/Ton)
Yearly capacity (ton) : 1357929.0			
Fixed Cost			
Depreciation		97255.95	0.071
Interest		654348.60	0.481
Insurance		18000.00	0.013
Personnel		11750.00	0.008
Sub total		781354.54	0.575
Operating Cost			
Fuel		1663200.0	1.224
Electric power		67896.43	0.049
Labor		64801.00	0.047
Explosives		10778.03	0.007
Tires		112900.00	0.083
Oil-lube		35658.00	0.026
Spare Part		14170.00	0.010
Repair-Maintenance		10900.00	0.008
Sub total		1980303.4	1.458
TOTAL		2761658.0	2.033

Fig. 7. Software interface of cost analysis and economic evaluation.

Results and Discussions

In this study, the effects of production capacity changes in machine investment, operating and fixed cost and NPV values were examined. With rising overall slope angle and stripping ratio, the number of required trucks, shovels and drilling machines and also their initial investment cost increased as depicted in Table 1.

Tab. 1. Relationship between required number of machines and initial investment costs due to variable operating parameters.

Overall slope angle	**Economic mine life**	**Ore production capacity**	**Stripping ratio**	**Required Number of Machines**						**Machinery initial investment cost**
				Overburden removal			**Ore production**			
[degree]	[years]	[ton/day]	[m^3/ton]	Shovel	Truck	Dril.	Shovel	Truck	Dril.	[$]
30 °	5	12345	14.36	42	103	26	7	16	1	349,890,000
	10	6172	14.36	21	52	13	3	8	1	175,930,000
	15	4115	14.36	14	34	9	2	5	1	116,970,000
	20	3086	14.36	10	26	6	2	4	1	86,050,000
	25	2469	14.36	8	21	5	1	3	1	69,130,000
45 °	5	12345	7.32	21	52	13	7	16	1	178,490,000
	10	6172	7.32	11	26	7	3	8	1	92,330,000
	15	4115	7.32	7	17	4	2	5	1	59,570,000
	20	3086	7.32	5	13	3	2	4	1	44,250,000
	25	2469	7.32	4	10	3	1	3	1	35,130,000
60 °	5	12345	4.36	12	31	8	7	16	1	106,290,000
	10	6172	4.36	6	15	4	3	8	1	52,930,000
	15	4115	4.36	4	2	3	2	5	1	35,770,000
	20	3086	4.36	3	8	2	2	4	1	27,850,000
	25	2469	4.36	2	6	2	1	3	1	19,930,000

In our model study, the economic mine lives range from 5 to 25 years. When an open pit is designed with an overall slope angle of 45^0 providing a stripping ratio of 7.32 m^3/ton; as the production capacity is increased, the number of required shovels, trucks and drilling machines that would compose the machinery park also increases. Hence, the initial investment costs of machinery and also NPV increase.

The case, in which overall slope angle is chosen as 30^0, safer operating conditions are reached, but this situation offers a less economy in terms of NPV (Tab. 2). In case of 60^0 overall slope angle, although NPV provides very high profitability, less safety operations occur (Table 2).

Tab. 2. Economic evaluation for different overall slope angles (30^0, 45^0 and 60^0).

Overall slope angle [degree]	**Economic mine life** [year]	**Ore production capacity** [ton/day]	**Ore production capacity** [ton/year]	**Machinery initial investment cost** [$]	**NPV** [$]
30	5 years	12345	4,073,786	349,890,000	287,137,345
	10 years	6172	2,036,893	175,930,000	287,517,088
	15 years	4115	1,357,929	116,970,000	230,540,096
	20 years	3086	1,018,447	86,050,000	199,107,254
	25 years	2469	814,757	69,130,000	160,856,798
45	5 years	12345	4,073,786	178,490,000	596,922,138
	10 years	6172	2,036,893	92,330,000	500,064,883
	15 years	4115	1,357,929	59,570,000	407,884,800
	20 years	3086	1,018,447	44,250,000	338,148,726
	25 years	2469	814,757	35,130,000	280,732,994
60	5 years	12345	4,073,786	106,290,000	726,334,083
	10 years	6172	2,036,893	52 ,930,000	596,588,548
	15 years	4115	1,357,929	35,770,000	479,249,590
	20 years	3086	1,018,447	27,850,000	392,193,270
	25 years	2469	814,757	19,930,000	330,877,867

The case, in which overall slope angle is taken 45^0, seems to be the optimal choice both in terms of safety operation and highly-achieved NPV. For all overall slope angle conditions; as production capacity increases, unit production cost decreases inversely proportional. NPV also shows analogy to production capacity, but produces the highest values in the case of mine life of 5 years. Figure 8 shows the relationships cumulatively between NPV, unit cost and machinery initial investment cost at various production capacities. It is obvious that higher NPV values can be obtained by designing the open pit mines at higher production capacities and increasing slope angles. The amount of the initial investments for machine-equipment becomes higher when short term-large capacity operations are at stake. However, this may lead to some disadvantages such as shortages in financing, marketing difficulties, and complexity in operations at large investments.

The change of the obtained NPV versus machine depreciation was defined as "R" and investigated in the study. As the "R" value becomes minimum for short mine lives, it increases with longer mine lives due to the fact of low machinery initial investment. At the same time, depreciation of machinery decreases and on the other hand, NPVs, which would be gained out of the project, also decrease. This situation causes a handicap for the investors and mining operations. Since the investment costs of large-scale mines cause financial hardships for entrepreneurs, the optimization issue of machinery-equipment suitable for ideal production capacity is one of the most crucial decisions to be made in the planning and operational stages of an open pit mine. The ratio of estimated NPV to machinery initial investment cost and also machinery depreciation are the two key factors which determine accurately the optimal production capacity in an open pit mine (Tab. 3).

According to the obtained data; while mine life is 5 years and in case production capacity is 4,073,786 tons per year, the peak NPV is attained as 596,922,000 $ and on the other side, machinery depreciation is maximum with 8.76 $/ton and R value is minimum with 3.34. As the mine life increases associated with a decrease in production capacity, NPV and machinery depreciation values drop to minimum with 280,732,994 $ and 1.72 $/ton, respectively. At the longest mine life, R value reaches maximum with 7.99. When these complicated values are plotted as in Figure 8, the optimal conditions for mine planning could be foreseen.

Tab. 3. Production capacity, machinery depreciation, NPV and "R" value for 450 overall slope angle.

Mine Life [years]	**Production Capacity** [tons/year]	**Machinery Initial Investment Cost** [$]	**NPV** [$]	**Machinery Depreciation** [$/ton]	**NPV/Machinery Initial Investment Cost** [R Value]
5	4,073,786	178,490,000	596,922,000	8.76	3.34
10	2,036,893	92,330,000	500,064 883	4.53	5.41
15	1,357,929	59,570,000	407,884 800	2.92	6.84
20	1,018,447	44,250,000	338,148 726	2.17	7.64
25	814,757	35,130,000	280,732 994	1.72	7.99

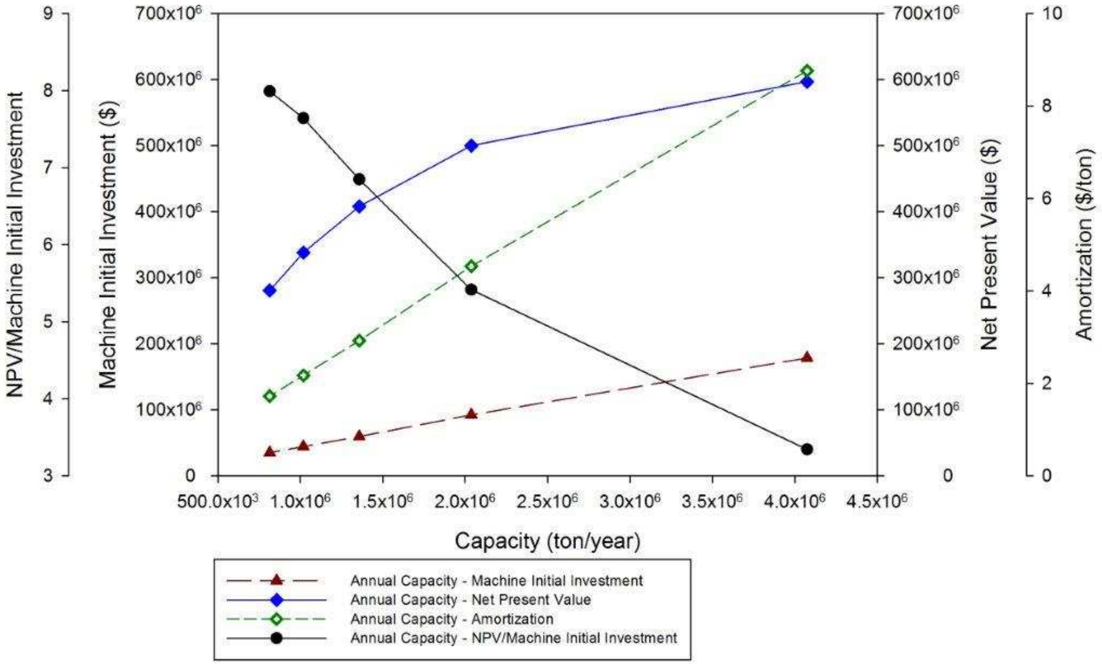


Fig. 8. Correlations between NPV, machinery investment initial cost and unit cost at various production capacities.

In an optimization attempt achieved by taking into account the R value and NPV, machinery initial investment cost and amounts of depreciation (amortization); the optimal production capacity was found as 2 million tons per annum and it would be more reasonable to operate the mine for a lifetime of 8-10 years in this specific model study.

Conclusions

Today, rising costs and competitive environment conditions of mining industry require utilization of mineral resources with the highest possible efficiency. On the other hand, these conditions also lead to the expansion of higher production capacities and necessitate larger capital investments. Therefore, mining plans should consider the parameters of maximum exploitable ore production capacity and optimal operating life in feasibility assessments. This NPV may not be the value which satisfies the highest attainable profit. Therefore, considering the economic lifetime of the machinery involved in such short term operations as well, it would be more rational to plan the optimum annual production capacity within an economical mine life.

Increase in production capacity naturally increases the initial investment cost, but at the same time leads to a decrease in unit cost of production. Shorter operation life, higher capacity and higher overall slope angle provide higher NPV in open pit mine planning. But in this instance, the initial investment cost and depreciation get quite intense depending on the increasing production capacity in short-term planning. Moreover, since high investments arise financial difficulties (high capital and excess interest charge, etc.), machine-equipment optimization convenient for optimum operational capacity becomes a crucial decision in the planning of mine sites. In this context, it is also considered that the optimization of depreciation and the ratio of NPV to total machine initial investment cost (R value) could be used as ancillary factors in the determination of optimum production capacity.

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