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Research paper

Cutoff grade optimization based on maximizing net present value using a computer model



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ABSTRACT

After designing the final range of open pit mines, one of the first essential decisions to be made in the production planning framework is to determine the cutoff grade. The cutoff grade of mines, due to interconnections with technical and economic parameters, is one of the most important parameters for the design of open pit mines. Considering the fundamental role of plant cutoff grade on the economical operation of a mine, the optimal selection of this grade is of great importance. One of the main problems in mining operations is how to determine the optimal cutoff grades of ore deposits at different periods during the life of a mine, it can be considered based on one of the goals of maximizing annual profit or net present value extraction during the mining period. Despite the existence of a range of different techniques for determining the optimal cutoff grade, Lane's algorithm is usually the most widely used cutoff grade optimization technique, which is calculated taking into account the technical and economic factors of production. Cutoff grade optimization with the goal of maximizing the net present value over the years of the mine's life, as well as the correlation with the distribution of the grade and tonnage of the remaining ore, requires a long calculation process, especially for large mines. In this research, optimal cutoff grade programming based on Lane's theory and aimed at maximizing the net present value in MATLAB software (computer model) has been carried out. Mineral operations consist of three phases: mining, processing, and refining. In single-product and single-process mode, the optimum cut-off grade and the net present value of production are calculated for each year of the mine's life. After validating the outputs of the model, the implementation of the computer model based on the data of Gol Gohar iron mine No.1 in a five-year plan was carried out. The changes in optimal cutoff grade and changes in net present value from 48.65% to 18,582 billion rials in the early years of the mine increased to 40.5% and approximately 3000 billion rials at the end of the mine's life.

1. Introduction

The cutoff grade is used to clean the minerals of a deposit from waste materials. The waste material can be left in place or sent to a drainage site, but minerals are sent to the processing plant for processing and eventually a sale. Determining which material in the ore is of value and which material should be waste is one of the most important aspects of mining. This decision is made with the aid of the cutoff grade (the lowest grade minerals are extracted). The cutoff grade is considered to be the main technical and economic factor of the operation of open pit mines and processing plants and it plays a major role in decision making concerning the sustainable development of mining, the volume of extraction operations and the profitability of manufacturing operations. Considering the scope of mining activities, the price changes of minerals, and the presence of valuable metals, the cutoff grade should be determined and optimized. Optimization of the cutoff grade determines the strategies for mixing minerals in different

situations in order to increase revenue and reduce the gravity of the vector, especially at high depths inevitably. Determining the cutoff grade is one of the most indispensable operations in open-pit mining, which determines whether the mine is profitable economically. Determining the cutoff grade, as one of the first decisions in the framework of the final design of an open pit mine, is one of the most important technical and economic parameters of production during the exploitation period (Asad, 2007; Taylor, 1972). The cutoff grade determines the boundary between mineral and waste. The technical and economic scale is determined by parameters such as geological characteristics, technical limitations of operations and various economic parameters (Ataei, 2003; Osanloo & Ataei, 2003). The part of the material within the mineral deposit which is above the cutoff grade is deposited in the ore and the store economic sector and sent to the processing plant. The part of the material, which is inferior to the standard, is sent as waste to the mine waste depository and does not yield a profit for the mine (Osanloo, Gholamnejad, & Karimi, 2008;

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Shishvan & Sattarvand, 2015). A higher cutoff grade increases the average grade of the ore entering the plant and thus results in the higher net value of the ore unit (Dagdelen, 2001). In the calculation of the breakeven cutoff grade, the time value of money, the distribution of ore deposit and the capacity of different operational units are not considered; extraction according to this grade does not lead to optimization of operation (Bascetin & Nieto, 2007). The head to series cutoff grade is also used to determine the final mining range (Hustrulid, Kuchta, & Martin, 2013; Taylor, 1985). The optimization of cutoff grade considers maximizing net present value or net annual profit, and it is strongly influenced by price changes, and one of the most important issues discussed by the management of mining companies is how to change the cutoff grade in response to price changes (Shinkuma & Nishiyama, 2000; Shinkuma, 2000). At present, one of the accepted guidelines in open pit mines planning studies is cutoff grade optimization. In recent years, the majority of efforts made have been devoted to the development of models for the optimization of the cutoff grade with the target of maximizing net present value. In these models, economic factors, such as mining capacity, processing plant capacity, smelter plant capacity, as well as the distribution of deposit and time value of money, are considered (Ahmadi & Shahabi, 2018; Mohammadi, Kakaie, Ataei, & Pourzamani, 2017). These calculations are mainly based on time, which is proportional to the distribution of the grade, and the tonnage of the reserves remaining variables. The main objective of this research is to propose a computer model for determining the optimal cutoff grade using MATLAB software, which is presented taking into consideration the different working conditions in the mine. The cutoff grade strategy for an open pit mine has an impact on annual liquidity flows and the net present value of the project. Determining the optimum cutoff grade that maximizes the net present value of mining operations is influenced by economic parameters such as metal prices, mining costs, processing, as well as mining operations, including mining capacity, the processing plant, and refining and distributing the ore deposit. In this research, the main objectives are to increase the net present value during the production period, in order to comply with technical limitations, to determine the proper lifetime of the mine and to establish the maximum net present value during the life of the mine.

2. Previous studies on optimization techniques

There are many theories concerning the determination of optimal cutoff grade, but most of the recent research shows that determining the optimal cutoff grade with the issue of maximizing net present value is a more reliable method than other methods (Minnitt, 2004; Osanloo & Ataei, 2003; Osanloo, Rashidinejad, & Rezaei, 2008). In determining the optimal cutoff grade, minerals must be extracted so that they maximize the net present value of the operation (Tatiya, 1996). Several issues have to be considered when determining the optimal cutoff grade: the cutoff grade varies with time, the distribution of the grade varies in different parts of the mine, and its cutoff grade has a nature of randomness (Rafiee, Ataei, & Azarfar, 2016). One of the most commonly used methods for determining the optimal cutoff grade is to maximize the net profit or net present value of the Lane algorithm (Lane, 1964). This algorithm is now also the most used in determining the optimal cutoff grade of open pit mines. The model used in this algorithm is an operational research model and consists of a target function and three constraints (Dimitrakopoulos, Martinez, & Ramadan, 2007; Hustrulid et al., 2013). Lane divides mine operations into three stages: mining, processing, and refining. According to the capacity of each of these stages, three cutoff grade-limiting economic and three cutoff grade equilibria are calculated, and finally, with a graphical method, one of these cutoff grades will be the optimal cutoff grade (Lane, 1964, 1988; Wang et al., 2010). Therefore, the process of calculating the cutoff grade using this method is very long and the possibility of error in this method is high. Also, the production of functions that cannot be

differentiable and the use of hypotheses to simplify the problem are considered as defects of this method. To optimize the cutoff grade, Lane modeled the operating process of a mine, which only sold its refined product, and defined the target function. After Lane's theory, no other model or method has been presented and the researchers have carried out their studies using other optimization methods based on this theory. Ataei and Osanloo (2003) studied the optimization of the cutoff grade of single metal deposits with the target of maximizing the net present value by using Knockout Techniques and compared its results with the Lane model (Ataei & Osanloo, 2003). In 2005, during the study of Lane's algorithm, various adjustment factors for the product price were combined with constant and operational costs in this algorithm and proved the effectiveness of the adjustment of economic parameters in the target function. In this case, prices are dealt with dynamically (Asad & Dessureault, 2005). The determination and optimization of the optimum cut-off grade was achieved by applying an optimization factor based on the Generalized Reduced Gradient (GRG) algorithm for a metal mine (Bascetin & Nieto, 2007). In order to optimize the cutoff grade by considering environmental issues based on minimizing acid leakage, a model was developed (Rashidinejad, Osanloo, & Rezaei, 2008). The model is based on Lane's theory, but is different in that it takes into account the costs of waste accumulation and reduces incomes, and, based on this model, determines the optimum cutoff grades (Gholamnejad, 2008). With the introduction of artificial intelligence technology in the field of mineral activity, a model for the nonlinear simulation of mineral activities using the artificial neural network and genetic algorithm to optimize cutoff grade was developed (He, Zhu, Gao, Liu, & Li, 2009). A model based on the Lane's algorithm was determined, taking into account the combined aggregate mineral inventory, economic parameters, and modifications to optimize the accuracy of the cutoff grade (Asad & Topal, 2011). A model for determining the optimal cutoff grade of open pit mines by using the strategy of combining the genetic algorithm and nonlinear programming was developed (Azimi & Osanloo, 2011). This model was able to create a number of scheduled plan for the cutoff grades and production rates, and then use dynamic planning to optimize and determine the cutoff grades that maximize the net present value (Barr, 2012). Jafarnejad developed a model for optimization based on Lane's theory that has three stages of extraction, concentration and market operations. In this model, the price of the mineral for the entire life of the mine is not fixed and variable. Using this model, the effect of mineral price changes on the optimum cutoff grade was investigated (Jafarnejad, 2012). In order to optimize the cutoff grade scale based on Lane's theory, with the goal of maximizing the net present value, multi-stage random planning was used for a metal mine (Li & Yang, 2012). To modify the Lane method, a model for optimizing the cutoff grade of a metal mine, taking into account the variable capacities of the units during the life of the mine, was used to improve the results (Abdollahisharif, Bakhtavar, & Anemangely, 2012). The multi-criteria decision scoring method was used to optimize the cutoff grade and set the optimal cutoff grade under uncertain prices and to plan the production of the mine (Azimi, Osanloo, & Esfahanipour, 2012). A model for optimizing the cutoff grade of gold, lead, and zinc was determined using the genetic algorithm and compared the results using web search and dynamic programming (Cetin & Dowd, 2016).

3. The Gol Gohar Sirjan mineral and industrial complex

The Gol Gohar collection of iron ore in Iran, which is one of the great reserves of iron ore in Iran, is located approximately in the center of the triangular between Kerman, Shiraz and Bandar Abbas. Fig. 1 shows Gol Gohar No. 1 mine. This set of mines has six reserves. Mass No. 1 is considered to be the priority for extensive exploration, design, preparation and extraction studies due to more promising exploratory outcomes and mineral deposits on the ground. Based on the results of exploratory work, the overall shape of this mass is a lens stretched



Fig. 1. Iron Gol Gohar No. 1 mine.

along the NW-SE which measures 1700×500 m. The greatest thickness of the mineral mass in the central part is about 230 m. The depth of mass varies from ground level to a depth of 100 m. The operation of this reserve after the preparation and installation of the required equipment and machinery began in March 1994 (Mohammadi et al., 2017).

4. Cutoff grade optimization based on the lane model

In the last few decades, optimization has focused on maximizing net present value. This requires minerals to be mined in the early years of the life of the mine and gradually mined materials with the slightly lower grade. In other words, the optimal cutoff grade will be a function of time and its value will be greater in the earlier years of the mine.

To apply the NPV maximization function, it is assumed that the net present value of all the remaining profits of V , right before mining, is Q_m . After time T , Q_m is mined from the reserve, P is realized as profits, and the rest of the profits will be realized in the future. The net present value of all the remaining profits is comprised of two components:

- 1- PV_p , resulting from the profit P realized at time T after mining Q_m ,
- 2- PV_w , resulting from the profits realized by minerals remaining after the time T .

These benefits are considered to be P_1 of profit at the time T_1 , P_2 of the earnings obtained at time T_2 . The value of all the remaining profits for mines after time $t = T$ and at time T is W . Fig. 2 shows a graph of the net present value.

The present values of P and W are obtained at the time $t = 0$, as follows:

$$PV_w(t = 0) = \frac{W}{(1 + d)^T} \tag{1}$$

$$PV_p(t = 0) = \frac{P}{(1 + d)^T} \tag{2}$$

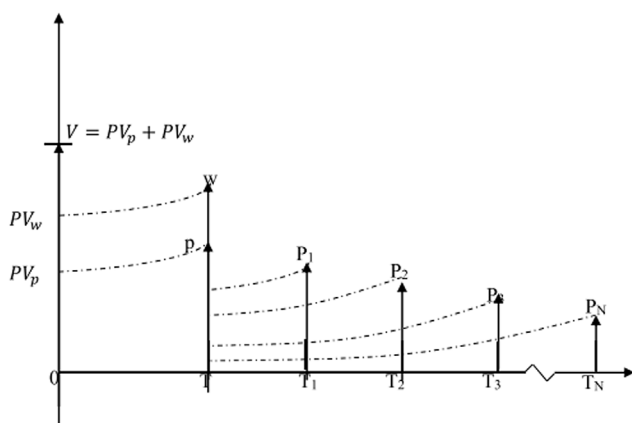


Fig. 2. Graphical representation of the net present value calculation (Hustrulid & Kuchta, 1995).

In these equations, d is the discount rate. Therefore, the present value at time $t = 0$ is equal to:

$$V = PV_p + PV_w = \frac{P}{(1 + d)^T} + \frac{W}{(1 + d)^T} = \frac{P + W}{(1 + d)^T} \tag{3}$$

$$W + P = V(1 + d)^T \tag{4}$$

If the expression $(1 + d)^T$ is expanded, the following occurs:

$$(1 + d)^T = 1 + Td \tag{5}$$

Combining equations (4) and (5) results in the following equation:

$$W + P = V(1 + d)^T = V + VTd \tag{6}$$

Since the net value of the remaining reserves at time $t = T$ is equal to W , the difference between the present value of the remaining reserves at times $t = T$ and $t = 0$ is equal to:

$$v = V - W = V - [V + VTd - P] = P - VTd \tag{7}$$

4.1. Specify the target function

In order to calculate the optimal cutoff grade based on the Lane method, the mineral operation is considered as a process consists of three sections of mining, production of concentrate, smelting, and refining. Each of these sections has costs and limited capacity. Meanwhile, fixed costs are also included. Operating profit (P) is determined by costs and benefits. Also, due to the average grade of minerals sent to the mineralization plant (\bar{g}), the recovery percentage (y), and the operating profit, the net present value of the remaining reserves (v) is calculated, which is presented in equations (8) and (9) (Hustrulid et al., 2013):

$$P = (s - r)Q_r - mQ_m - cQ_c - fT \tag{8}$$

$$v = [(s - r)\bar{g}y - c]Q_c - mQ_m - (f + Vd)T \tag{9}$$

In the above relationships, T is the length of the production period, Q_m the amount of materials to be mined, Q_c the amount of minerals sent to the processing plant, Q_r the amount of final product, f fixed costs per unit time, S the final selling price, m the mining cost per ton of the material, c the cost of the concentrator for each ton of minerals, r the cost of smelting and refining each unit of the final product and d the discount rate. In equation (9), V is the net present value of the residual reserve at the start of operation (time $t = 0$), which is obtained by repeating the above procedure. These parameters are given in Table 1.

To maximize NPV, the value of v should be maximized. When maximizing operations, the capacity of each mining unit, processing plant, and refining plant may be a limiting factor. With respect to each limiting factor, the value of T varies in equation (9), as shown in Table 2.

Table 1
Effective parameters in cut-off grade optimization.

Symbol	Definition	Unit
Q_m	Material mined	Ton
Q_c	Ore Processed	Ton
Q_r	Ore produced	Ton
M	Mining capacity	ton/year
C	Processing plant capacity	ton/year
R	Unit refining capacity	ton/year
S	Final selling price	Rial/ton
m	Mining cost	Rial/ton
c	Processing cost	Rial/ton
r	refining cost	Rial/ton
F	Fixed cost	Rial/year
T	Years of production	Year
y	Recovery	%
D	Discount rate	%

Table 2
Objective function and duration of production for each limiting factor.

Limiting Capacity	Years of production	Function
Mining	$T = \frac{Q_m}{M}$	$v_m = [(s - r)\bar{g}y - c]Q_c - \left[m + \frac{f + Vd}{M}\right]$
Concentrating	$T = \frac{Q_c}{C}$	$v_c = \left[(s - r)\bar{g}y - \left(c + \frac{f + Vd}{C}\right)\right]Q_c - mQ_m$
Refining	$T = \frac{Q_r}{R}$	$v_r = \left[\left(s - r - \frac{f + Vd}{R}\right)\bar{g}y - c\right]Q_c - mQ_m$

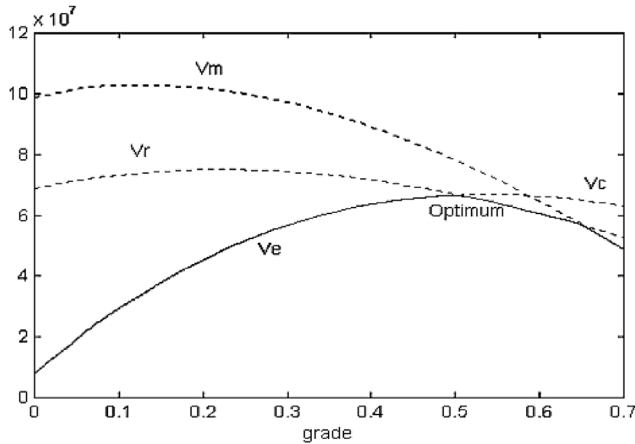


Fig. 3. Curve V_m, V_c, V_r, V_e (Rafiee et al., 2016).

According to Table 2, v_m, v_c, v_r can be plotted as a function of grade, as shown in Fig. 3. The value at which v is maximum, is the goal for optimizing the cutoff grade. On the other hand, there are three functions v , one has to try to optimize the three objective functions as much as possible. Therefore, the common part of the three functions and the maximum value of the shared part of these functions must be determined. So, the goal is to achieve a grade that will satisfy the following function.

$$\max v_e = \max[\min(v_m, v_c, v_r)] \tag{10}$$

4.2. Optimization of the target function

According to Lane's theory, the optimal cutoff grade will match on the optimal point of one of the curves v_m, v_c, v_r , or on one of the equilibrium cutoff grades that are independent of the economic factors (Lane, 1988). The Lane's algorithm contains the following steps:

4.2.1. Determining the optimal point for each of the three curves V_m, V_c, V_r

To do this, the values V_m, V_c, V_r relative to g should be derived, as should the zero equivalent of the contract, as shown in Table 3.

4.2.2. Determining the limits of operation balancing

Table 3 shows how the cutoff grade is calculated for a limiting factor

Table 3
The optimal amount of each limiting factor.

Limiting capacities	Equation of optimum cut off grade
Mining	$g_m = \frac{c}{y(s - r)}$
Concentrating	$g_c = \frac{c + \frac{f + dV}{C}}{y(s - R)}$
Refining	$g_r = \frac{c}{y\left(s - r - \frac{f + dV}{R}\right)}$

Table 4
Optimal cutoff grade for balancing operations.

Limiting capacities	Equation of optimum cut off grade
Mining- Concentrating	$g_{mc} = 1 - \frac{C}{M}$
Concentrating- Refining	$g_{cr} = \frac{2R}{C} - 1$
Refining – Mining	$g_{rm} = \left(1 - \frac{2R}{M}\right)^{0.5}$

(mining or processing plant or refining unit), when the optimal cutoff grade is calculated using economic factors. However, in general, the optimal cutoff grade is not necessarily the cutoff of economic limitation, and if there is more than one limiting capacity, the equilibrium point in which each part works with full capacity should be taken into consideration. So there are three points of equilibrium, these being: 1) The cutoff grade balance between mining and the processing plant (g_{mc}), which is the ratio of the amount of ore obtained to the amount of mined materials equal to C/M . 2) The cutoff grade balance between the processing plant and the refining unit (g_{cr}), which could be recovered metal from every ton of ore equal to R/C . 3) The cutoff grade balance between the mining and the refining unit (g_{mr}), which could be recovered metal for each ton of material equal to R/M . Table 4 presents the results of these calculations.

4.2.3. Determining the optimal cutoff grade percentage of the six previous cutoff grades

In the previous stages, six cutoff grades were calculated, of which three are based on capacities, cost or price (g_r, g_c and g_m), and the other three are based solely on the distribution of the grade of minerals and capacities (g_{mr}, g_{cr} and g_{mc}). At this stage of the operation, the goal is to determine the optimal cutoff grade of these six grades. With respect to the following relationships, these six grades are reduced to three grade, and in the end the middle value of these three levels is chosen as the optimal cutoff grade for the purpose of maximizing the net present value.

$$G_{mc} = \begin{cases} g_m & (g_{mc} \leq g_m) \\ g_c & (g_{mc} \geq g_c) \\ g_{mc} & \text{otherwise} \end{cases} \tag{11}$$

$$G_{cr} = \begin{cases} g_r & (g_{cr} \leq g_r) \\ g_c & (g_{cr} \geq g_c) \\ g_{cr} & \text{otherwise} \end{cases} \tag{12}$$

$$G_{mr} = \begin{cases} g_m & (g_{mr} \leq g_m) \\ g_r & (g_{mr} \geq g_r) \\ g_{mr} & \text{otherwise} \end{cases} \tag{13}$$

$$G_{opt} = \text{Middel}(G_{mc}, G_{rc}, G_{mr}) \tag{14}$$

5. Maximize the target function

As stated above, the problem with determining the optimal cutoff grade of an ore deposit is finding a method that optimizes the three objective functions. Various types of optimization methods can be used for this purpose. These methods are divided into three groups: analytical methods, numerical methods, and intelligent optimization methods.

Analytic methods or differential and accounting methods can be used for continuous and derivative functions. In these methods, the derivative of the function is used and the optimal point is obtained. The calculation of the numerical value of the objective function is the last step of the process. The optimal value of the objective function is calculated after determining the optimal value of the decision variables.

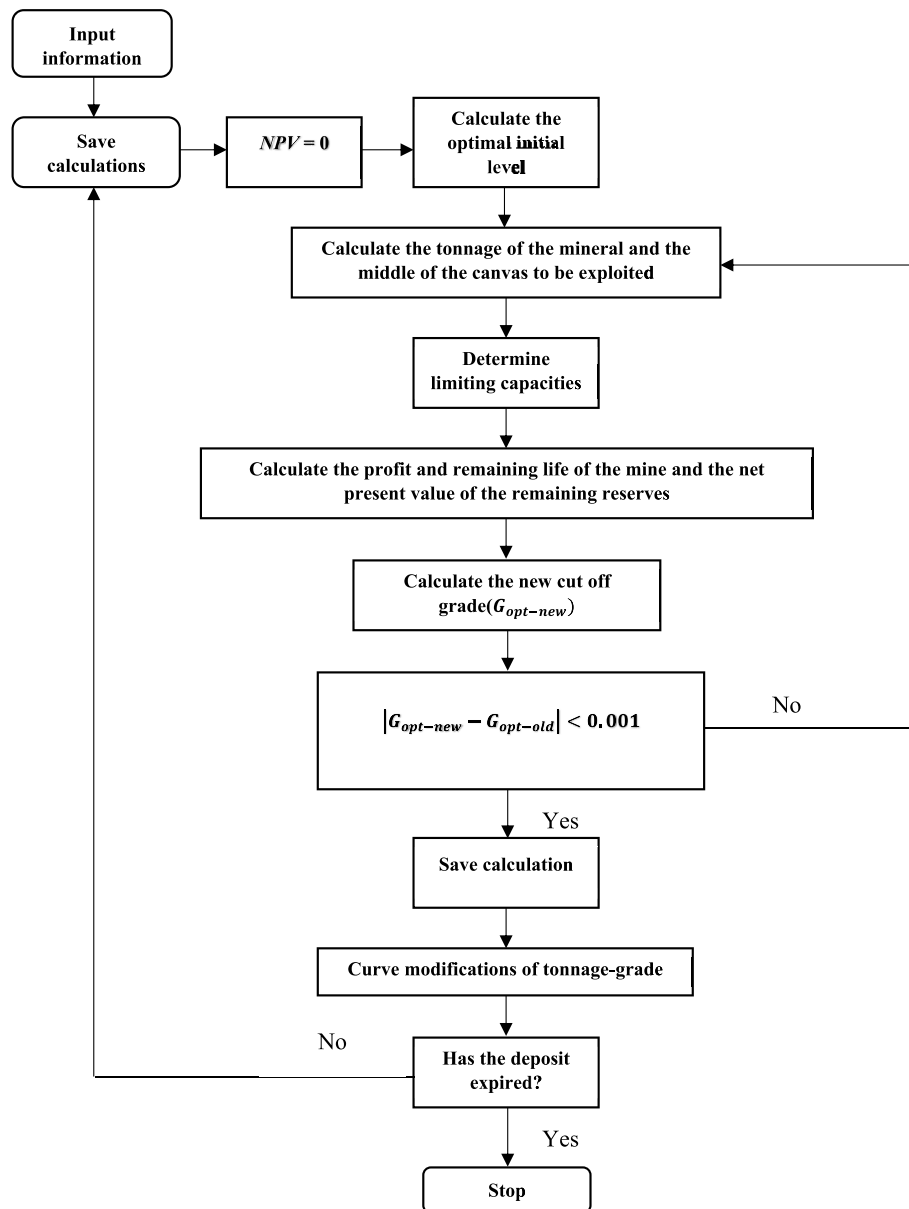


Fig. 4. Flowchart of the computer model for determining the optimal cutoff grade with the goal of maximizing the net present value.

These methods may be appropriate for certain problems, including simple deposits with low reserves. However, if the optimization problem includes target functions or ranges that are not directly dependent on variables or these complex functions, these problems cannot be solved with the use analytical methods. In numerical methods, contrary to analytical methods, the values of the objective function are calculated for different values of the variables and then the results are determined according to the optimal answer. The basis of most numerical optimization methods is the production of a sequence of approximate values. Numerical methods, in turn, are divided into two types of elimination and interpolation methods, and in intelligent methods, the search is performed for a number of points, and the value of the objective function in these points of evaluation and the more desirable point is created.

6. Implementing the computer model

As described in Section 5, a computer model is written using Matlab software. As shown in Fig. 4, this model first introduces data on the distribution of ore deposits and economic and operational information,

and then performs a calculation of available reserves using in the pit. It is assumed that in the first stage, for the current year, the net present value is equal to zero, then the optimum cutoff grade is calculated. Then, based on existing inequalities, the six-point optimum is determined, the three-tier optimum is determined, and the mid-range is determined as the optimal first-order criterion. In the next step, based on the optimum cutoff grade, the tonnage of the mineral input to the condensing plant and the average grade of exploited ore can be calculated based on the full range. Following this, the amount of minerals, the amount of mineral sent to the processing plant and the quantity of the final product are controlled, and, according to the capacity of the constraints, other capacities are calculated. The remaining life of the mine and the annual profit are then calculated and the net present value of the remaining reserves is determined. At this stage, the optimum cutoff grades, which are six cutoff grades, are calculated. According to the six optimum cutoff grade graphical method, the three cutoff grade of the optimal and the mean are considered as the new optimum cutoff grade and are compared with the value of the past optimum cutoff grade. If the ratio of two grades is less than 0.001, the new optimum cutoff grade is determined as the grade of the optimum for that year.

Otherwise, by deducting the tonnage of the ore mined from the higher-grade fine ranges, the optimum cut-off grade and the fractionation of the waste ore from the sub-optimum, the amount of tonnage of the mineral input to the processing plant is calculated. For each year, the tonnage must be recalculated for each of the brightness ranges. All of these steps must be performed by deducting the tonnage of the ore mined from the total tonnage of the mine after each year, and all of these steps must be carried out to the extent that the entire ore mineral is extracted. With these steps, an optimal cutoff grade and a maximization net present value is achieved every year.

7. Validation of the model

In order to evaluate the computer model, the optimum cutoff grade of an example is with following parameters is considered. In this example, the final range of 1000 tons of mineral matter with a distribution of 0–1 in the range of 0.1, with the tonnage of each group of 100 tons, Mining capacity of 100 tons per year, processing capacity of 50 tons per year, unit refining capacity of 40 lb/year, mining cost of \$1 per ton, processing cost \$2 per ton, refining cost \$5 per lb, fixed cost of \$300 per year, final selling price of the product being \$25 per lb and 100% recovery, and a discount rate of 15% (Hustrulid & Kuchta, 1995) are considered in order to validate the model.

The optimal cutoff grade value was calculated using the Lane method, which means that the optimal cutoff grade at the beginning of the life of the project is 0.5% and at the end of its life it reaches 0.4%. Also, the optimal cutoff grade was obtained using a computer model, which means that the optimal cutoff grade during the life of the project is 0.5% and at the end of its life reaches 0.405%. Figs. 5 and 6 show the change in the net present value and variations in the cutoff grade for different years of the project life. As can be seen, the results of the proposed computer model are in close agreement with the Lane method.

8. Case study

Cutoff grade optimization in Gol Gohar iron mine No. 1 using the provided computer model is discussed. Input data is the same as mine data, as shown in Tables 5 and 6. Mining capacity indicates the maximum annual extraction rate, which is 40 million tons per year. The concentrate plant capacity indicates the maximum amount sent to the processing plant per year, which is 12 million tons per year. The refining capacity indicates the maximum amount of final product produced in the year, which is 4,200,000 tons in the mineral complex. *f* indicates fixed costs per unit time, *S* indicates the final selling price of the product, *m* indicates the cost of mining for each material, *c* indicates the cost of concentrate for each of the minerals, *r* indicates the cost of smelting and refining for each unit of the final product and *d* indicates the discount rate.

As can be seen in Table 7, the results of the computer model show that, at the beginning of the life of the mine in this five-year plan, the mine is not balanced and does not work at full capacity, but the

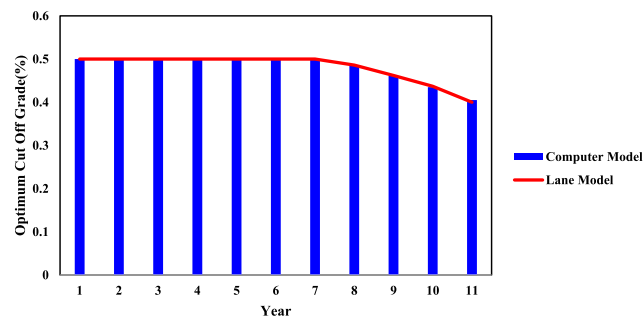


Fig. 6. Optimal cutoff grade changes.

Table 5

Annual capacity of different parts of the operation and economic parameters used in the model.

Parameter	Unit	Value
Mining capacity	ton/year	40,000,000
Concentrate plant capacity	ton/year	12,000,000
Refining capacity	ton/year	4,200,000
Mining cost	rial/ton	32,000
Processing cost	rial/ton	212,000
Refining cost	rial/ton	450,000
Fixed cost	rial	400,000,000,000
The price of the final product	rial/ton	6049,000,000
Recovery	%	67
Discount rate	%	21

Table 6

Grade distribution of Gol Gohar mineral deposits in the 5-year plan.

Grade (%)	Tonnage (ton)
Waste	109,305,000
40.5–45	6,137,335
45–49.5	27,346,643
49.5–54	33,254,956
54–58.5	11,258,398
58.5–63	438,098
Total ore (ton)	78,435,430
Total waste (ton)	109,305,000
Total material (ton)	187,740,430

concentration plant and the refinery plant are balanced. The optimal cutoff grade at the beginning of the mine is 48.65%, and at the end of the life of the mine, it reaches 40.5%. Also, changes in the net present value and optimal cutoff grade changes in the years of the mine life are shown in Figs. 7 and 8, respectively.

Every year, after determining the optimum cutoff grade, the grade distribution tonnage table was also corrected. By deducting this adjusted table at the end of each year from its values at the beginning of the same year, the amount of mining from different grade intervals can be calculated. Accordingly, for this period of 5 years, mining is determined by the interval of the grade and the amount of annual waste of the Gol Gohar mine and this is shown in Table 8.

Additionally, by determining the amount of annual waste and the amount of mineral extraction (total extraction amounts from different grade intervals), the amount of the annual trashing ratio is determined. Table 9 shows the amount of total extraction, mineral, waste and the trashing ratio.

Due to the amount of minerals extracted each year as well as the maximum capacity of the processing plant, some minerals are accumulated annually. Table 10 shows the amounts of accumulated minerals for each year.

The provided computer model has limitations and assumptions that include:

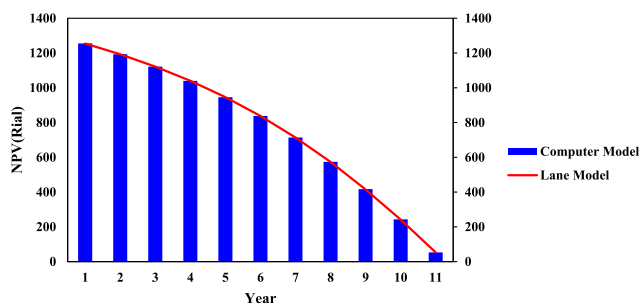


Fig. 5. Net present value changes.

Table 7
Optimum cutoff grade and production of different units in different years of mine life by computer model.

Year	OCOg (%)	Material mined (ton)	Ore sent to concentrator (ton)	Pellet produced (ton)	Cash Flow (billion rial)	NPV (billion rial)
1	48.65	39,989,125	12,000,000	4,200,000	7859	18,582
2	47.83	39,980,577	12,000,000	4,200,000	6963	14,957
3	46.19	39,995,258	12,000,000	4,200,000	6217	10,568
4	45.58	39,991,643	12,000,000	4,200,000	5428	6751
5	40.5	28,869,081	10,264,389	3,473,251	3460	2856

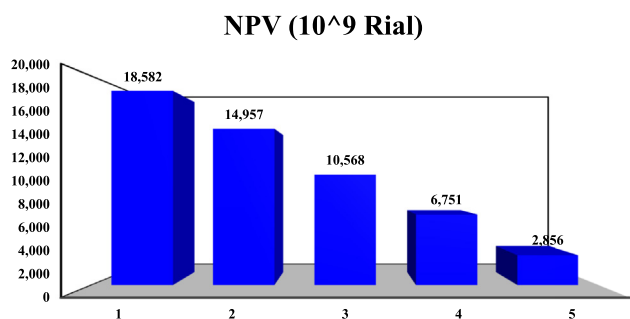


Fig. 7. Net present value changes.

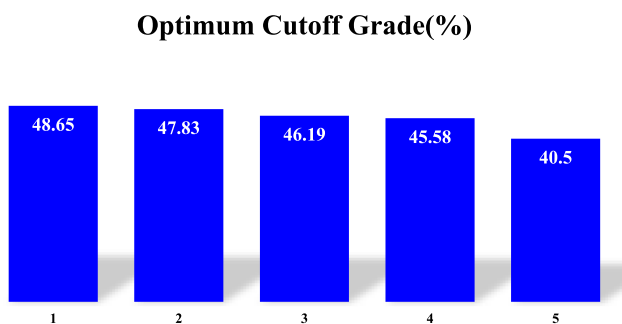


Fig. 8. Optimal cutoff grade changes.

Table 8
Extraction tonnage annually from grade intervals.

Year	Waste	40.5–45%	45–49.5%	49.5–54%	54–58.5%	58.5–63%
1	22,669,086	1,283,674	5,889,932	7,711,643	2,335,340	99,630
2	22,897,041	1,289,528	5,871,112	7,524,185	2,300,625	98,086
3	23,173,417	1,298,028	5,865,008	7,313,086	2,249,990	95,729
4	23,556,063	1,310,833	5,789,244	6,727,139	2,522,128	86,236
5	17,009,392	955,272	3,931,347	3,979,083	1,850,315	58,417

Table 9
Extraction amounts of waste and minerals and the trashing ratio.

Year	Total material (ton)	Waste (ton)	Ore (ton)	Trashing ratio
1	39,989,125	22,669,086	17,320,039	1.30
2	39,980,577	22,897,041	17,083,536	1.34
3	39,995,258	23,173,417	16,821,841	1.38
4	39,991,643	23,556,063	16,435,580	1.43
5	27,783,826	17,009,392	10,774,434	1.57
Total	187,740,429	109,304,999	78,435,430	1.41

- the model is based on basic metal ore, such as copper, in which the constraints are divided into three stages: extraction, processing, and refining unit (market),
- the deposit is assumed to be monolithic, and its linear distribution is considered.

Table 10
The amount of accumulated minerals for each year.

Year	Stockpile (ton)
1	5,320,039
2	5,083,536
3	4,821,841
4	4,435,580
5	510,045
Total	20,171,041

The main advantages of this model can be summarized as follows:

- it considers the various stages of the entire production process, and the optimal combination is selected according to the entire operation,
- capacity limiting the processes of extraction, treatment, and purification is effective,
- the tonnage-grade distribution of the deposit is effective in determining the cutoff grade,
- the time value of money is considered,
- it leads to maximizing profit or maximizing net present value.

The disadvantages of this computer model include the following:

- its dependence on the head-to-head grade to determine the tonnage-grade distribution of ore,
- linear assumptions about the distribution of the grade between categories,
- fixed price assumptions.

9. Conclusions

One of the most important technical and economic parameters for designing and planning for various years of mineral projects is cutoff grades that maximize the net present value, resulting in the optimization of the operation. The main problem in mining operations is how to determine the optimal cutoff grades of ore deposits during different periods of the life of the mine, with the goal of increasing the net present value of extraction. Considering the importance of determining and optimizing the cutoff grade of limitation in mineral activity, this paper presents a new approach to solving the Lane model, a classical method for determining the optimal cutoff grade with the goal of maximizing the present net value. To this end, the data and problem variables and the objective function of the problem were determined, and the coding of the computer model and the target function was selected using MATLAB software. Additionally, on the basis of the calculations, the cutoff grade was calculated. To do this, the problem was formulated according to the Lane model as a three-stage process including mining capacity limitations, processing plant, and market. Then, by analyzing the relationships between the parameters and the decision model variables, a computer model was developed for its solution. Finally, a numerical example was solved once using the Lane method and once using the method presented in this paper. The results

of these methods were compared and their validity was evaluated using the analytical method. Comparison of the economic results obtained from the two methods shows that the net present value obtained from the optimal cutoff grade obtained in the net present value computing model is convergent. Then, using the computer model, the cutoff grade optimization amount of Gol Gohar iron mine No. 1 was estimated. Its economic results show that its optimum cutoff grade at the beginning of this five-year plan is 48.65% and in the final years reaches 40.5%. The net present value in the first year of the life of the mine is 18,582 billion rials, and as the life of the mine passes, the net present value decreases. Also, this model can be used to optimize the final range of open pit mines in the form of a production planning cycle as an offer for further research and to complete this research.

Conflict of interest

Author states that there is not any conflict of interest.

Ethical statement

Author states that the research was conducted according to ethical standards.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jsm.2018.04.002>.

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