A Cut-off Grade Optimization Model in Multi Product Open Pit Mining Considering Reclamation and Valuable Waste Materials

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Abstract. The common problem found in the mining company is how to determine the cut-off grade for the classification of ore and waste. The cut-off grade will greatly affect the revenues and costs of the mining companies. In this study, we develop cut-off grade optimization model by considering multi product and environmental factor such as reclamation and revaluing of waste materials. Multi product was chosen because most of the mining industry not only produce one type of mineral products. The main goal of this study is to develop a cut-off grade model to maximize the net present value (NPV). To illustrate the application of the model, the numerical example is given for mining case using the available data of Golgohar Iron Mine in Iran which produced three types of iron products, such as concentrated, sizing, and pellet.

Keywords: Cut-Off Grade, Open Pit Mining, Single Item-Multi Product, Reclamation

1. Introduction

The growth of population makes the increased demand and extraction activities of natural resources as raw materials for industry and also a source of energy [1,2]. One of them is the needs for the minerals such as nickel, iron, and copper to satisfy the demand of industry as well as infrastructure [3]. The mining process consists of two methods, underground and open pit mining. The open pit mining is the method most widely used by the mining industry [4].

The common problem found in the mining company is how to determine the optimum cut-off grade for the classification of ore and waste. Cut-off grade is the value or minimum grade in the decision-making process of advanced processing related minerals in the mining industry [5]. The minerals mined is classified as ore when have same or higher grade and classified as waste if it had lower grade [6]. The cut-off grade will greatly affect the revenues and costs in the mining companies. The objective function which widely used in the mining operation is to maximize the NPV.

Mining operations are inseparable from the environmental impact, where according to a recent study by [7], the waste generated by the mining activities in 2030 will reach 56 billion tons. Therefore, mining companies are not only responsible in the process of exploitation of the ore and get the revenue, but also to plan the use of best resources and environmental management. One form of responsibility for the environment management is the reclamation or backfilling of a mine site after mining activities ceased. Reclamation is intended to reduce the level of danger from the mine site and also can be reused for other useful functions in the future [8]. The management of mining waste also has economic value for mining companies, where the waste which is usually disposed can be reprocessed into a valuable materials [9].
The research of determination of optimum cut-off grade considering environmental factors has attracted many researchers. Rashidinejad, et al [3] developed model based on an algorithm developed by [10]. The model considered the management of acid waste from the processing of copper. The model was not only maximizing the value of the NPV but also in the same time minimizing the environmental impact. Bascetin, et al [11] had research about the relationship between economic considerations and the environment in the management of sustainable resource with the added cost of reclamation per unit of production using the algorithm of [10] to solve the model. The optimization results showed an increase in the total NPV through mine planning while simultaneously minimize the environmental impact. The model was further developed by [12] considered the revenue from the reclamation. The model focuses on the aspects of the environment in the form of re-use of land in the post-mining reclamation periods.

Narrei and Osanloo [13] develop a model based on the previous model of [12] by adding costs as well as income from the process of pit reclamation and tailings dam. In addition, the model incorporates revenue from re-processing the waste material or tailings from the mining process carried out. In another study, research [14] indicated that the majority of open pit mining not only produces one type of product only, besides that they only mined one type of metal. As an example the Golgohar Iron Mine in the Fars Province, Iran which mined and produced products of iron. The Golgohar Iron Mine have three types of iron products namely ore concentrate, sizing, and pellet. At the previous research for the optimum cut-off grade in multi products open pit mining is not considering the environmental factors. So, this research will develop a mathematical model to calculate the optimum cut-off grade for maximize the NPV in open pit mining which produces multi products by considering the environmental factors in term of reclamation and reprocessing of waste materials. In this model, we assume that the open pit mine produced three types of iron products, so, there are three product prices for each types. The model considers the sales revenue from the products, relamation revenue, valuable waste material revenue, mining cost, processing cost, concentrate cost, sizing cost, pelletizing cost, reclamation and revaluing waste cost.

2. Model Development

These research describes the mathematical model to calculate the optimum cut-off grade in open pit mining which produces multi product by considering the reclamation and reprocessing of waste materials. We used mathematical approach through analytic method to solve the problem by using Lane Algorithm. The main objective of this model is to maximize the NPV. In this research, we assume that the mine is capable to satisfy the market demands of three items of iron products, such as concentrate, sizing, and pellet. The notations used in this paper are shown in Table 1.

| Symbol | Parameter | Unit       |
|--------|-----------|------------|
| $i$    | Year indicator | -          |
| T      | Years of production | Year      |
| $Q_m$  | Material mined    | Ton        |
| $Q_c$  | Ore processed     | Ton        |
| $Q_r$  | Marketable product | Ton       |
| $Q_p$  | Pelletizing throughput | Ton  |
| $Q_{gr}$ | Sizing throughput     | Ton       |
| $Q_{con}$ | Concentrated throughput | Ton   |
| M      | Mining plant capacity | Ton/year |
| C      | Concentrate capacity | Ton/year  |
| P      | Pelletizing plant capacity | Ton/year |
### Mathematical Model

| Symbol | Description                                      | Unit         |
|--------|--------------------------------------------------|--------------|
| $\beta$ | Part of ore sent to pelletizing plant            | -            |
| $\alpha$ | Part of ore sent to concentrate plant           | -            |
| $P_{gr}$ | Sizing price                                    | Rial/ton     |
| $P_c$    | Concentrate price                                | Rial/ton     |
| $P_p$    | Pellet price                                     | Rial/ton     |
| $C_m$    | Mining operating cost                            | Rial/ton     |
| $C_c$    | Processing operating cost                        | Rial/ton     |
| $C_p$    | Pelletizing operating cost                       | Rial/ton     |
| $C_{gr}$ | Ore sizing operating cost                        | Rial/ton     |
| $A$      | NA material mined                                | -            |
| $B$      | AG material mined                                | -            |
| $D$      | Reused waste materials                           | -            |
| $W$      | Reused tailing                                   | -            |
| $V$      | AG tailings                                      | -            |
| $U$      | NA tailings                                      | -            |
| $I_a$    | Income from revaluing the waste rock             | Rial/ton of waste |
| $I_w$    | Income from waste rock reclamation               | Rial/ton of waste |
| $R_p$    | Revenue from pit reclamation                     | Rial/lb of product |
| $R_t$    | Revenue from tailing dams reclamation            | Rial/ton of tailing |
| $R_u$    | Revenue from reused tailing materials            | Rial/ton of product |
| $C_{pr}$ | Cost of pit reclamation                          | Rial/lb of product |
| $a$      | NA waste disposal operating cost                 | Rial/ton of waste |
| $b$      | AG waste disposal operating cost                 | Rial/ton of waste |
| $u$      | NA tailings disposal cost                        | Rial/ton of tailing |
| $v$      | AG tailings disposal cost                        | Rial/ton of tailing |
| $f$      | Fixed cost                                       | Rial/year    |
| $y_c$    | Recovery of processing                           | %            |
| $d$      | Discount rate                                     | %            |

AG: Acid Generating, NA: Non-acid Generating

The assumption used on this model are as follows:

a. Maximum capacity of the concentrate plant is 12 million tons, sizing plant is 1 million tons, and pelletizing plant is 4.2 million tons.
b. The minimum grade for sending material from the concentrated plant to the sizing unit is 57%.
c. All of the final products price is constant at each year.

The objective function of the model shown in Equation (1).

\[
\text{MaxNPV} = \sum_{i=0}^{N} \frac{NCF_i}{(1+d)^i}
\]  

(1)

From the Table.1, we know the quantity of ore sent to concentrate plant, sizing unit, and pelletizing is define by the value of \( \alpha \) and \( \beta \). The equations for each quantity can be defined as follow:

\[
Q_{\text{gr}} = (1 - \alpha)Q_c
\]  

(2)

\[
Q_{\text{con}} = (1 - \beta)Q_{\text{con}}
\]  

(3)

\[
Q_p = \beta Q_{\text{con}}
\]  

(4)

\[
Q_r = Q_{\text{Salableconcentrate}} + Q_p + Q_{\text{gr}}
\]  

(5)

As describe before, the revenue from selling the products, such as concentrate, sizing, and pellet can be defined as follow:

\[
R_1 = P_p Q_p
\]  

(6)

\[
R_2 = P_{\text{gr}} (1 - \alpha)Q_c
\]  

(7)

\[
R_3 = P_c (1 - \beta)Q_{\text{con}}
\]  

(8)

The revenue from the reclamation and revaluing waste materials can defined as:

\[
R_4 = I_w A(Q_m - Q_c)
\]  

(9)

\[
R_5 = I_w B(Q_m - Q_c)
\]  

(10)

\[
R_6 = I_u D(Q_m - Q_c)
\]  

(11)

\[
R_7 = R_u (Q_c - Q_r)
\]  

(12)

\[
R_8 = R_v (Q_c - Q_r)
\]  

(13)

\[
R_9 = R_{u} W(Q_c - Q_r)
\]  

(14)

\[
R_{10} = R_{p} Q_r
\]  

(15)

On the other hand, the cost function related to mining, concentrating, pelletizing, sizing, fix cost, reclamation, and revaluing waste materials cost are shown as follow:

\[
T_1 = C_m Q_m
\]  

(16)

\[
T_2 = C_c \alpha Q_c
\]  

(17)

\[
T_3 = C_p Q_p
\]  

(18)

\[
T_4 = C_{\text{gr}} (1 - \alpha)Q_c
\]  

(19)
\[ T_s = fT \]  
\[ T_b = aA(Q_m - Q_c) \]  
\[ T_i = bB(Q_m - Q_c) \]  
\[ T_n = uU(Q_c - Q_r) \]  
\[ T_{10} = C_{pr}Q_r \]

By using the revenue and the cost, the operation cash flow (profit) can be defined as:

\[
NCF = \sum_{i=1}^{10} R_i - \sum_{i=1}^{10} T_i
\]

\[
NCF = P_p Q_p + P_{gr}(1-\alpha)Q_c + P_c(1-\beta)Q_{con} + I_w A(Q_m - Q_r) + I_u B(Q_m - Q_c) + I_u D(Q_m - Q_c) + R U(Q_c - Q_r) + R V(Q_c - Q_r) + R Q_r - C_m Q_m \\
- C_c \alpha_Q_c - C_p Q_p - C_{gr}(1-\alpha)Q_c - aA(Q_m - Q_r) - bB(Q_m - Q_r) - uU(Q_c - Q_r) - vV(Q_c - Q_r) - C_{pr}Q_r - (f + dNPV)T
\]

Or

\[
NCF = [P_p Q_p + P_{gr}(1-\alpha)Q_c + P_c(1-\beta)Q_{con}] + [(I_w A + I_w B + I_u D)(Q_m - Q_r)] \\
+ (R U + R V + R Q_r)(Q_c - Q_r) + R P Q_r] - [C_m Q_m + C_c \alpha_Q_c + C_p Q_p + C_{gr}(1-\alpha)Q_c] \\
- [(aA + bB)(Q_m - Q_c) - (uU - vV)(Q_c - Q_r) - C_{pr}Q_r - (f + dNPV)T
\]

The quantity of the concentrate can be defined depends on the quantity of input ore, recovery rate, and average rate, so the equation can be defined as follow:

\[ Q_{con} = g \alpha \gamma Q_c \]

By considering equation (29) the operation cash flow is:

\[
NCF = P_p Q_p + [(P_{gr} - C_{gr})(1-\alpha) + \alpha(P_c(1-\beta) g y_c - C_c)]Q_c] \\
+ [(I_w A + I_w B + I_u D)(Q_m - Q_c)] + (R U + R V + R Q_r)(Q_c - Q_r) + R P Q_r] \\
- [(aA + bB)(Q_m - Q_c) - (uU - vV)(Q_c - Q_r) - C_{pr}Q_r - (f + dNPV)T
\]

The following constrains are:

\[ Q_m \leq M \]  
\[ Q_{con} \leq C \]  
\[ Q_p \leq P \]  
\[ A + B + D = 1 \]  
\[ U + V + W = 1 \]
Equations (31), (32), and (33) show the constraint in mining for concentrating, and pelletizing capacity. Equations (34) and (35) shows constraint in quantity of acid, non-acid, and valuable materials.

Limitating Economic Cut-off Grades

For determine the cut-off grade, we have to derivative the function of NCF for each process. The cut-off grade when limitation is in the the mining capacity can be defined as follows:

$$g_m = \frac{(1-\alpha)(P_g - C_g) + \alpha C_c + uU + vV + I_u A + I_u B + I_u D - R_U - R_V - R_W - aA - bB}{(\alpha(1-\beta)y_c P_c - \alpha p_c (P_p - C_p) + uU + vV - R_U - R_V - R_W - C_{pr} + R_p} \tag{36}$$

The cut-off grade when limitation is in the the concentrate capacity can be defined as follows:

$$g_{con} = \frac{(1-\alpha)(P_g - C_g) + \alpha C_c + uU + vV + I_u A + I_u B + I_u D - R_U - R_V - R_W - aA - bB + \frac{f + dNPV}{C}}{(\alpha(1-\beta)y_c P_c - \alpha p_c (P_p - C_p) + uU + vV - R_U - R_V - R_W - C_{pr} + R_p} \tag{37}$$

The cut-off grade when limitation is in the the pelletizing capacity can be defined as follows:

$$g_p = \frac{(1-\alpha)(P_g - C_g) + \alpha C_c + uU + vV + I_u A + I_u B + I_u D - R_U - R_V - R_W - aA - bB + \frac{f + dNPV}{P}}{(\alpha(1-\beta)y_c P_c - \alpha p_c (P_p - C_p) + uU + vV - R_U - R_V - R_W - C_{pr} + R_p} \tag{38}$$

In the mining industry, the optimum cut-off grade must not smaller than $g_m$ and also higher than $g_c$. The value of $g_c$ is indicate the minimum cut-off grade of ore that will process, so if the optimum cut-off grade is higher, it will make some valuable ore thrown. The relationship of the $g_m$, $g_c$, and $g_p$ is:

$$g_m \leq g_p \leq g_{con} \tag{39}$$

$$g_m \leq G_{opt} \leq g_{con} \tag{40}$$

Balancing Cut-off Grades

The next step is determine the average grade between two related process such as mining-concentrating, mining-pelletizing, and contentrate-pelletizing. This average grade is determined by adjusting the capacity of each pair process. So, the cut-off grade for each pair are choosen by the selected rules as follows:

$$G_{mcon} = g_m \text{ if } g_{mcon} \leq g_m \tag{41}$$

$$G_{mcon} = g_c \text{ if } g_{mcon} \geq g_c \tag{42}$$

$$G_{mcon} = g_{mcon} \text{ otherwise} \tag{43}$$

Or $G_{mcon} = \text{ middle value of } g_m, g_c \text{ and } g_{mcon}$.

$$G_{pcon} = g_p \text{ if } g_{pcon} \leq g_p \tag{44}$$

$$G_{pcon} = g_c \text{ if } g_{pcon} \geq g_c \tag{45}$$
\[ G_{pcon} = g_{pcon} \text{ otherwise} \quad (46) \]

Or \( G_{pcon} = \text{middle value of } g_p, g_{con} \) and \( g_{pcon} \).

\[ G_{mp} = g_m \text{ if } g_{mp} \leq g_m \quad (47) \]
\[ G_{mp} = g_p \text{ if } g_{mp} \geq g_p \quad (48) \]
\[ G_{mp} = g_{mp} \text{ otherwise} \quad (49) \]

Or \( G_{mp} = \text{middle value of } g_m, g_p \) and \( g_{mp} \).

The \( G_{opt} \) is the middle value of \( G_{mcon}, G_{pcon} \) and \( G_{mp} \). After that the quantity of \( Q_m, Q_c, Q_{con}, Q_p \) and NPV can be computed.

### 3. Numerical Example

This section presents a numerical example of the model to determining cut-off grade to maximized NPV in open pit mining with multi products. The parameters used to illustrate the numerical example in this study are taken from [12]. The parameters describe in Table 2 and Table 3.

| Grade (%) | Tonnage (ton) |
|-----------|---------------|
| Waste     | 109305000     |
| 40.5-45   | 6137335       |
| 45-49.5   | 27346643      |
| 49.5-54   | 33254956      |
| 54-58.5   | 11258398      |
| 58.5-63   | 438098        |
| Total ore (ton) | 78435430 |
| Total waste (ton) | 109305000 |
| Total material (ton) | 187740430 |

| Symbols | Value            |
|---------|------------------|
| M       | 40000000         |
| C       | 12000000         |
| P       | 42000000         |
| Cm      | 32000            |
| Cc      | 212000           |
| Cp      | 400000           |
| Cgr     | 50000            |
| f       | 4000000000000    |
| Pp      | 2600000          |
The first step is to calculate the optimal cut-off grade is determine the time period of the mining project by divide the total material with the capacity of mining ($M$). For the project, the total material is 5 years. After that, by substituting the parameter data in Table 3 into equation (36), (37), and (38), we can calculated the limiting cut-off grade for mining, concentrate and pelletizing process. Then we can get the optimum cut-off grade by using the balancing cut-off grade rules.

**Table 4. Optimum cut-off grade without reclamation and revaluing waste**

| Cut-off Grade | i=1, V=0 | i=2, V=NPVnew | i=3, V=NPVnew | i=4, V=NPVnew | i=5, V=NPVnew |
|---------------|----------|---------------|---------------|---------------|---------------|
| $gm$          | 31.00%   | 31.00%        | 31.00%        | 31.00%        | 31.00%        |
| $gcon$        | 48.99%   | 47.85%        | 46.03%        | 43.09%        | 38.36%        |
| $gp$          | 45.97%   | 44.61%        | 42.58%        | 39.69%        | 35.78%        |
| $gmcon$       | 51.47%   | 51.47%        | 51.47%        | 51.47%        | 51.47%        |
| $gmp$         | 80.50%   | 80.50%        | 80.50%        | 80.50%        | 80.50%        |
| $gpcon$       | 10.00%   | 10.00%        | 10.00%        | 10.00%        | 10.00%        |
| $Gmcon$       | 48.99%   | 47.85%        | 46.03%        | 43.09%        | 38.36%        |
| $Gmp$         | 45.97%   | 44.61%        | 42.58%        | 39.69%        | 35.78%        |
| $Gcnon$       | 45.97%   | 44.61%        | 46.03%        | 39.69%        | 35.78%        |
| $Goptimal$    | 45.97%   | 44.61%        | 46.03%        | 39.69%        | 35.78%        |
After determine the optimum cut-off grade, the next step is determine the tonnage of $Q_m, Q_c, Q_p, Q_{con}, Q_{gr}$, and saleable concentrate for calculated the NCF by using equation (30) and NPV by using equation (1).

Table 5. Net present value without reclamation and revaluing waste

| Year | $Q_m$ | $Q_c$ | $Q_p$ | $Q_{con}$ | Saleable Concentrate | $Q_{gr}$ | NCF | NPV       |
|------|-------|-------|-------|-----------|----------------------|---------|-----|----------|
| 1    | 39944772 | 14460465 | 2518177 | 6528566 | 1379973 | 424804 | 8.530E+12 | 2.402E+13 |
| 2    | 39944772 | 14824290 | 2532263 | 6628647 | 1401127 | 435492 | 8.290E+12 | 1.995E+13 |
| 3    | 39944772 | 15366026 | 2552695 | 6775850 | 1432242 | 451407 | 8.128E+12 | 1.554E+13 |
| 4    | 39944772 | 16140754 | 2573445 | 6972731 | 1473858 | 474166 | 8.052E+12 | 1.058E+13 |
| 5    | 27795658 | 11959629 | 1801837 | 5022271 | 1061580 | 351337 | 5.005E+12 | 2.951E+12 |

As shown in Table 4 and 5, the cut-off grade reduced from 45.97% to 35.78% in 5 year. The total NPV with a discount rate 21% is obtained to be Million Rial 73401,87.

Table 6. Optimum cut-off grade new model with reclamation and revaluing waste

| Cut-off grade | $i=1, V=0$ | $i=2, V=NPV_{new}$ | $i=3, V=NPV_{new}$ | $i=4, V=NPV_{new}$ | $i=5, V=NPV_{new}$ |
|---------------|-------------|---------------------|---------------------|---------------------|---------------------|
| gm            | 31.00%      | 31.00%              | 31.00%              | 31.00%              | 31.00%              |
| gcon          | 60.66%      | 58.81%              | 55.84%              | 51.06%              | 43.38%              |
| gp            | 58.76%      | 55.45%              | 50.85%              | 44.85%              | 37.71%              |
| gmcon         | 51.47%      | 51.47%              | 51.47%              | 51.47%              | 51.47%              |
| gpcon         | 80.50%      | 80.50%              | 80.50%              | 80.50%              | 80.50%              |
| Gmcon         | 10.00%      | 10.00%              | 10.00%              | 10.00%              | 10.00%              |
| Gmp           | 60.66%      | 58.81%              | 55.84%              | 51.06%              | 43.38%              |
| Gconp         | 58.76%      | 55.45%              | 50.85%              | 44.85%              | 37.71%              |
| Goptimal      | 58.76%      | 55.45%              | 50.85%              | 44.85%              | 37.71%              |

Table 7. Net present value new model with reclamation and revaluing waste

| Year | $Q_m$ | $Q_c$ | $Q_p$ | $Q_{con}$ | Saleable concentrate | $Q_{gr}$ | NCF | NPV       |
|------|-------|-------|-------|-----------|----------------------|---------|-----|----------|
| 1    | 39944772 | 11152729 | 1962200 | 5059341 | 1066626 | 327633 | 9.030E+12 | 2.543E+13 |
| 2    | 39944772 | 11933288 | 2059649 | 5361773 | 1130386 | 350563 | 9.113E+12 | 2.193E+13 |
| 3    | 39944772 | 12967899 | 2170955 | 5738415 | 1209791 | 380957 | 9.311E+12 | 1.780E+13 |
| 4    | 39944772 | 14243455 | 2285564 | 6170725 | 1300932 | 418429 | 9.598E+12 | 1.261E+13 |
| 5    | 27961341 | 10932513 | 1653102 | 4597710 | 969304 | 321164 | 6.281E+12 | 3.704E+12 |

In the second scenario with new model development, the cut-off grade reduced from 58.76% to 37.71% at the fifth year. The total NPV with a discount rate 21% is obtained to be Million Rial 81474,88. Its means, there are 12% improvement of NPV using the new model for multi-product with considering reclamation and revaluing waste materials.

4. Conclusion

In this study, we demonstrated the relationship between economic and environmental factors such as reclamation and revaluing of waste materials. We also considered the industry with a multi
products to calculate the optimum cut-off grade. In this model, we consider the reclamation cost because mining industries have responsibilities to maintain the environmental effect from their mining activities. By using the developed model in this paper, the mining industry can get maximum NPV while in the same time maintain the environmental sustainability. This model is also simple and easy to be applied. For the future research, this cut-off grade model can be developed further by adding the price uncertainty for the selling products to get a closer real value of the profit and NPV.

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