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CUTOFF GRADES OPTIMIZATION WITH ENVIRONMENTAL MANAGEMENT; A CASE STUDY: SUNGUN COPPER PROJECT

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Abstract: *Cutoff grade is a grade used to assign a destination label to a parcel of material. The optimal cutoff grades depend on all the salient technological features of mining, such as the capacity of extraction and of milling, the geometry and geology of the orebody, and the optimal grade of concentrate to send to the smelter. The main objective of each optimization of mining operation is to maximize the net present value of the whole mining project, but this approach without consideration of environmental issues during planning is not really an optimum design. Lane formulation among the all presented algorithms is the most commonly used method for optimization of cutoff grades. All presented models for optimum cutoff grades are ore-oriented and in none of them the costs related to waste materials which must to be minimized during the mine life are considered. In this paper, after comparison of traditional and modern approaches for cutoff grade optimization in open pit mines, a real case study is presented and discussed to ensure optimality of the cutoff grades optimization process.*

Keywords: *Cutoff grade modeling, Pit optimization, Acid mine drainage, Waste dump; Tailings dam; Environmental management*

1. Introduction

Mining design and planning is a very complex and multi-disciplinary subject that requires a thorough engineering knowledge and a good understanding of the many issues. For projects, the basic principle is that projects with a positive Net Present Value (NPV) should be undertaken. The main objective of each optimization of mining operation is to maximize the NPV of the whole mining project. This objective is subject to many constraints including long term response stewardship of the resource and the environment. Environmental protection has the highest priority in modern mining. Mining environmental management tends to focus on concerns over the impact of waste disposal on the surface, primarily in the form of tailings and waste material structures such as tailings dams and waste dumps [1]. Some of these materials may be acid generating and they have to be managed properly to protect the environment [2].

In surface mining methods, particularly in open pit mining method, there are additional environmental concerns such as land disturbance by the mine pit, noise due to traffic and mining activities in the local community and restoration/reclamation of the disturbed area. For a shallow deposit in a remote area, one the surface mining methods may be the obvious choice. If the deposit is located within or close to a village or town, surface mining may prove difficult. If surface mining is the preferred choice, the associated concerns must be dealt with properly [3]. Environmental concerns from the last two decades have growth increasingly so; the definition of best mining design has been changed [4].

The best environmental controls, and least expensive in the long run, are waste management practices that focus on "prevention" rather than "treatment". It is always easy and less expensive to prevent any pollution then to solve if after being created, researches were concentrated on promising prevention techniques such as layering and blending through strategic mine planning. End-of-pipe treatment technologies and disposal practices not only carry high capital and operating costs, but also they invite future and long-term liabilities. The only true way to eliminate these liabilities is elimination or minimization of the waste and pollution in the first place at the source [5].

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The legacy of past mining practices is large quantities of acid generating waste materials and tailings. Despite undesirable outcomes in the past, the mine design process continues to focus on technical mining and financial considerations with environmental and social objectives considered later in the design sequence, unfortunately more often in the form of impact mitigation [6]. Cutoff grade is the criterion normally used in mining to distinguish between ore and waste materials in the body of a deposit and extensively affects the size and the life of deposits. The optimal cutoff grades in traditional approach depend on all the salient technological features of mining, such as the capacity of extraction and of milling, the geometry and geology of the orebody, and the optimal grade of concentrate to send to the smelter [7]. Fig. 1 shows the sources of increased value in mining operations. As it can be seen, the optimal cutoff grade strategy and tactics is one of these sources. The elements shown in Fig. 1 are mutually dependent, and reinforce and interact positively with each other to generate combined value greater than the sum of their individual contributions.

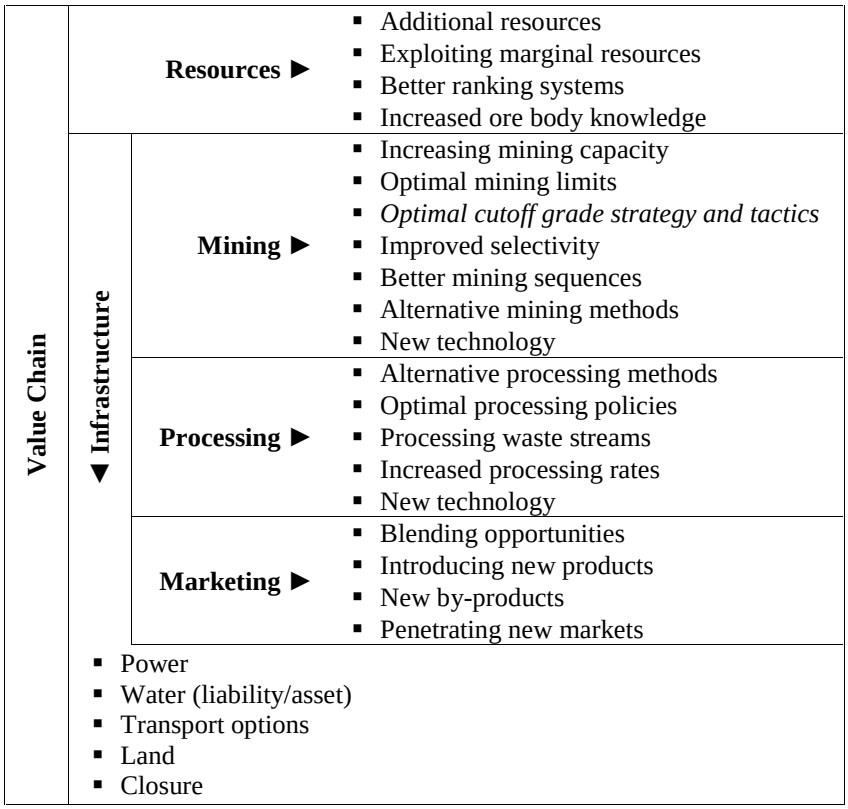


Fig. 1. Sources of increased value in mining operations [8]

Nowadays it is believed that the public expect the mining industry show care of the environment and try to eliminate the adverse environmental impacts or at least minimize the intensity as well as the length of them. Sustainable development requirements finally lead to using improved and environmentally-friendly technologies. Using sustainable development principles must be started at the beginning of the project [9].

The problem discussed in the paper is finding an optimum balance between the cutoff grade and environmental strategy and tactics. In practice, achieving the optimum balance is the real challenge. Calculating the optimum cutoff grades involves a mini-feasibility study in which all the known and potential costs of the project are account for. The fact that the calculation of optimum cutoff grades can neither be determined nor measured precisely with a single parameter further complicates the problem [10].

Work undertaken in the field of cut-off grade optimization has not advanced much beyond the work undertaken by Lane in 1988 [11]. Lane formulation among the all presented algorithms is the most commonly used method for optimization of cutoff grades. Dagdelen [12] and [13], Whittle and Wharton [14], Sinding and Larsen [15], Dagdelen and Mohammad [16], King [17], Ataei and Osanloo [18], and Ramirez-Rodriguez and Rozgonyi [19] have presented algorithms for determining the optimum cutoff grades for single or multiple metal deposits. Among the aforesaid researches, only King and Ramirez-Rodriguez and Rozgonyi tried to incorporate an environmental strategy into the process of cutoff grade optimization. In this paper, after comparison of traditional and modern approaches for cutoff grade optimization in open pit mines, a real case study is presented and discussed.

2. Optimal Cutoff Grades for Open Pit Mines

2.1. Traditional Approach

To maximize the NPV of a project, it is widely accepted to use the dynamic cutoff grades, rather than using the constant, breakeven cutoff grade. Lane proposed a manual (heuristic) approach to determine the optimum cutoff grade policy that maximizes the NPV of a project under three constraints: mining, milling (processing) and marketing (refining) [20]. This is not unusual but there are many operations which may be comprised of just the first or the first two stages of operation. These stages either individually limit the mining operation or in pair. The limitation of capacity of an individual stage leads to the determination of mine, mill, and market limiting economic cutoff grades. However, if stages are limiting the throughput in pairs, the capacities of these stages are balanced to use the maximum capacity of each stage by considering grade tonnage distribution of the deposit. This leads to the determination of mine-mill, mill-market and mine-market balancing cutoff grades.

The concept is to use a cutoff grade higher than breakeven cutoff grades during the early years of the project to have higher cash flows to improve NPV, by taking the time value of money into account. To maximize the NPV of the project, cutoff grade calculations have to include the fixed costs associated with not receiving the future cash flows quicker due to the cutoff grade decision taken now. Since these fixed costs are always positive, cutoff grades are calculated to be higher than the breakeven cutoff grade. Consequently, higher cutoff grades are used during the earlier years of the project.

The objective function of the problem is to maximize the NPV of operation which can be represented mathematically as following:

$$\text{Max NPV} = \left(\sum_{i=0}^{N} \frac{CF_i}{(1+d)^i} \right) \quad (1)$$

Where the cash flow arising from one unit of mineralized material is:

$$CF_i = (S_i - r_i) \times Qr_i - c_i \times Qc_i - m_i \times Qm_i - (f + d \times NPV_i) \times T \quad (2)$$

Subject to:

$$Qm_i \leq M \quad for\ i = 1, \ldots, N \quad (3)$$

$$Qc_i \leq C \quad for\ i = 1, \ldots, N \quad (4)$$

$$Qr_i \leq R \quad for\ i = 1, \ldots, N \quad (5)$$

$$Qr_i = g \times y \times Qc_i \quad (6)$$

Notations of the above equations are defined in Table 1. It must be notified that the capacities of the equipment and the installations do not often permit much flexibility and therefore cutoff grades can only be varied within narrow limits. In contrast, when expansion schemes are being designed, and even more so when totally new mines are being developed, the theory can indicate cutoff grades quite different from conventional policies with very substantial corresponding improvements in the overall returns [21].

There are many shortcomings to the Lane's cutoff grade optimization approach among them unsound assumption of the known mine life during implementation of the algorithm and lacking for blending requirements, stockpiling lower grade ore materials and environmental issues. There have been many heuristic modifications to Lane's algorithm to overcome some of the aforesaid shortcomings but none of them incorporates environmental issues. Regardless of these shortcomings, the Lane's algorithm will be applicable in management of mineral resources insofar the concept of maximization of NPV of a project would be valid.

2.2. Modern Approach

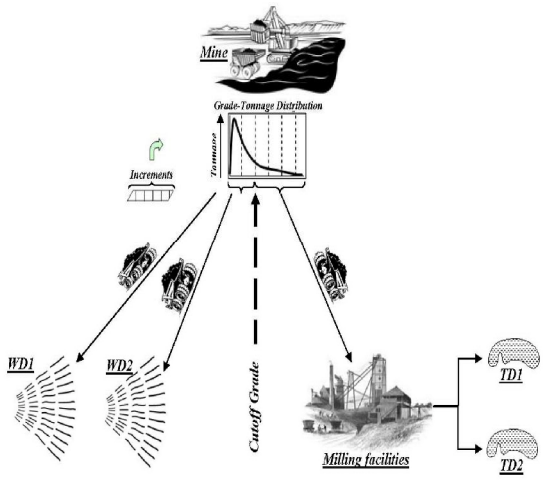
To produce sustainable results of mining operations, holistic design criteria must be integrated in the design process. The best practice is consideration of environmental mine-waste management requirements with special reference to eliminate or minimize the waste and pollution in the first place at the source.

Open pit mining, froth flotation and smelting are the most commonly practice in metal production. This process associated with land disturbance and causes pollution on the mine site and groundwater contamination in the vicinity by the waste materials and tailings.

Economic evaluation of open pit mines at the planning stage are typically used to develop a cutoff grade, which is the minimum grade of ore that can be mined profitably or, in some cases, to breakeven. The cutoff grade is different for each open pit mine and is a function of the anticipated revenues and costs. The cutoff grade and the physical limits of an open pit mine are, therefore, sensitive to changes in revenue (e.g. metal price fluctuations) and costs (i.e. mining, milling, taxes, mine decommissioning, mine closure, etc.) [22].

In modern approach, the potential for acidic drainage is determined early in the planning process. A decision can be made at the planning stage to segregate reactive wastes and relocate the wastes to the open pit mine or locate properly according to layering or blending technique once it is mined out.

In such a case, the economic evaluation of the open pit mine and the pit design would take into consideration all anticipated costs to implement an in-pit disposal or layering/blending program. Fig. 2 shows the schematic representation of mined material destinations from an open pit mine to milling facilities and to two waste dumps. The produced tailings send to two tailings dams.



WD: Waste Dump; TD: Tailings Dam

Fig. 2. Schematic representation of mined material destinations

In the modern approach WD1 and WD2 are designated for dumping of non-acid generating and acid generating materials respectively. Some mitigation is required for WD2 and the related capital and operating costs must be determined based upon the detail design. In some special cases to prevent Acid Mine Drainage (AMD), it may be feasible to mix acid generating and acid buffering materials with together in specific proportion. In similar logic, TD1 and TD2 are designated for disposing of non-acid generating and acid generating tailings respectively. Separation of tailings in the standpoint of acid generation characteristics is not well established in the mining industry, but it is along the sustainable mining practice and is a cost-effective and reasonable solution for reduction of acid generation tailings.

Tab. 1. The notations of the problem

Notation	Explanation	Unit	Remarks
i	Year indicator	-	
N	Mine life	Year	
T	Time taken to work through one unit of mineralized material	Year	
M	Mining throughput	Tons/year	
C	Milling throughput	Tons/year	
R	Marketing throughput	Tons/year	
Qm	Material mined	Tons/year	
Qc	Material milled	Tons/year	
Qr	Marketable product	Tons/year	
S	Metal/commodity price	$/ton of product	
m	Mining operating costs	$/ton of material	Ore + Waste
a	NA waste disposal operating costs	$/ton of waste	WD1
b	AG waste disposal operating costs	$/ton of waste	WD2
c	Milling operating costs	$/ton of ore	
u	NA tailings disposal costs	$/ton of tailings	TD1
v	AG tailings disposal costs	$/ton of tailings	TD2
r	Marketing costs	$/ton of product	
f	Fixed or Time costs	$/year	
CF	Cash flow per unit of mineralized material	$/year	
g	Average head grade	%	
y	Metallurgical recovery	%	
d	Discount rate	%	
A	NA material mined and send to WD1	-	
B	AG material mined and send to WD2	-	
U	NA tailings send to TD1	-	
V	AG tailings send to TD2	-	

AG: Acid generating, NA: Non-acid generating;

The objective function of the problem in modern approach is same as Eq. (1) in the traditional approach.

$$Max\ NPV = \left(\sum_{i=0}^{N} \frac{CF_i^*}{(1+d)^i} \right) \quad (7)$$

But definition of the cash flow arising from one unit of mineralized material is not the same and can be represented as following:

$$CF_i^* = (S_i - r_i + u_i U_i + v_i V_i) \times Qr_i - (c_i + u_i U_i + v_i V_i - a_i A_i - b_i B_i) \times Qc_i - (m_i + a_i A_i + b_i B_i) \times Qm_i - (f + d \times NPV_i) \times T \quad (8)$$

The following constraint is evident:

$$A_i + B_i = 1 \text{ and } U_i + V_i = 1 \quad (9)$$

Eq. (8) consist of all costs, but the allocation of certain costs needs close attention, particularly in relation to

capital costs, working costs and development costs. A capital cost is an expenditure related to establishing or increasing the capacity of a component of the mining system. Other capital costs are either related to replacement and maintenance of equipment. A capital investment for the purpose of expanding capacity affects the calculation of the present value stream, (i.e. the capital injection immediately increase the subsequent present values), but it has no direct effect on the calculation of the optimum cutoff grades. Similarly, capital expenditures (CAPEX) affect the cash flow, and hence the present value stream, but it has no direct effect on the calculation of the optimum cutoff grades. On the other hand, all replacement and maintenance expenditure which is judged as necessary for the continuation of the operation at current levels is effectively a fixed or time cost. As such, whether it is capital expenditure or not, it can be counted as part of the term "f".

2.2.1. Limiting Economic Cutoff Grades:

Limiting economic cutoff grades may be limited individually by mining, milling facilities (crushing and concentrator plants, etc.) or marketing throughputs.

If mining throughput is the governing limitation, the optimum cutoff grade is given by Eq. (10):

$$g_m = \frac{c_i + u_i U_i + v_i V_i - a_i A_i - b_i B_i}{\left(S_i - r_i + u_i U_i + v_i V_i\right) \times y} \quad (10)$$

If milling throughput is the governing limitation, the optimum cutoff grade is given by Eq. (11):

$$g_c = \frac{c_i + u_i U_i + v_i V_i - a_i A_i - b_i B_i + \frac{f + d \times NPV_i}{C}}{\left(S_i - r_i + u_i U_i + v_i V_i\right) \times y} \quad (11)$$

If marketing throughput is the governing limitation, the optimum cutoff grade is given by Eq. (12):

$$g_r = \frac{c_i + u_i U_i + v_i V_i - a_i A_i - b_i B_i}{\left(S_i - r_i + u_i U_i + v_i V_i - \frac{f + d \times NPV_i}{R}\right) \times y} \quad (12)$$

Where the overall net present value (i.e., NPV_i) is obtained from the following equation:

$$NPV_i = \frac{CF_i^* \times \left(\left(1+d\right)^N - 1\right)}{d \times \left(1+d\right)^N} \quad (13)$$

It can be seen that two of the limiting economic cutoff grades are unknown initially since they depend upon knowing the overall net present value. This in turn depends upon the cutoff grade. The effect of changing economic conditions has been ignored in the economic model and the term "d × NPV_i" considered as an opportunity cost. Since the unknown NPV_i appears in the equations, an iterative process must be used. In practice, initial levels are assumed, a policy calculated, and the present values on termination compared with the specified terminal value. Depending upon the difference, the initial levels are modified and a new policy is calculated. This iterative process is repeated until only minor improvements can be achieved; i.e. the mathematical gunnery practice is utilized.

The optimum cutoff grade will never be less than g_m, since it is the breakeven cutoff grade. Also, the optimum cutoff grade will never be higher than g_c, since this will lead to throwing some of the valuable ore in waste dumps. Hence, the following relationship holds:

$$g_m \leq g_r \leq g_c \quad (14)$$

Therefore, the optimum cutoff grade that maximizes the objective function is the any value between g_m and g_c. This can be presented as:

$$g_m \leq G_{opt} \leq g_c \quad (15)$$

2.2.2. Balancing Cutoff Grades:

If two components simultaneously to be in balance i.e. operating at full capacity, three cases are raised. To be able to calculate this, one needs to know the distribution of grades of the mined material.

The first balancing cutoff grade (g_{mc}) is the cutoff grade that becomes from Eq. (16):

$$\frac{Qm_i}{M} = \frac{Qc_i}{C} \quad (16)$$

The effective optimum cutoff grade satisfying mining and milling (G_{mc}) is:

$$\begin{aligned} &G_{mc} = g_m \quad if \quad g_{mc} \leq g_m \\ &G_{mc} = g_c \quad if \quad g_{mc} \geq g_c \\ &G_{mc} = g_{mc} \quad otherwise \end{aligned} \quad (17)$$

Or G_{mc} = Middle value among g_m, g_c & g_{mc}

The second balancing cutoff grade (g_{cr}) is the cutoff grade that becomes from Eq. (18):

$$\frac{Qc_i}{C} = \frac{Qr_i}{R} \quad (18)$$

The effective optimum cutoff grade satisfying milling and marketing (G_{cr}) is:

$$\begin{aligned} &G_{cr} = g_r \quad if \quad g_{cr} \leq g_r \\ &G_{cr} = g_c \quad if \quad g_{cr} \geq g_c \\ &G_{cr} = g_{cr} \quad otherwise \end{aligned} \quad (19)$$

Or G_{cr} = Middle value among g_c, g_r & g_{cr}

The third balancing cutoff grade (g_{mr}) is the cutoff grade that becomes from Eq. (20):

$$\frac{Qm_i}{M} = \frac{Qr_i}{R} \quad (20)$$

The effective optimum cutoff grade satisfying mining and marketing (G_{mr}) is:

$$\begin{aligned} G_{mr} &= g_m \quad if \quad g_{mr} \pounds g_m \\ G_{mr} &= g_r \quad if \quad g_{mr} \, ^3 \, g_r \\ G_{mr} &= g_{mr} \quad otherwise \end{aligned} \quad (21)$$

Or G_{mr} = Middle value among g_m, g_r & g_{mr}
The overall effective optimum cutoff grade (G_{opt}) is middle value among G_{mc}, G_{cr} and G_{mr} and subsequently Qm, Qc, Qr and NPV can be computed.

3. Algorithm of the Modern Approach

The steps of the algorithm developed for calculating the optimum cutoff grades in accordance with the modern approach are as following:

1. Enter all data as per the Table 1, except "i", "N", "T", "Qm", "Qc", "Qr" and "CF". Grade-tonnage distribution in the optimum Ultimate Pit Limits (UPL) and mining planning increments (pushbacks) as well as development milestones are ranked as input data;
2. Set the pushback indicator "p" to 1;
3. Set the year indicator "i" to 1;
4. Set the iteration indicator "j" to 1;
5. Compute the reserve available in the optimum UPL "$(T_{dep})_i$" and current pushback "$(T_{pb})_i$", if "$(T_{dep})_i$" is equal to zero, then check if the "j" is not equal to 1, STOP; and if "j" is equal to 1 then go to step 16, otherwise go to the next step;
6. Set V = NPV_i , the initial NPV_i = 0;
7. Determine the overall effective optimum cutoff grade "$(G_{opt})_i$" and "$(g)_i$", then compute the annual tonnage of waste "$(T_W)_i$", ore "$(T_O)_i$" and product "$(T_p)_i$", as well as the Overall Stripping Ratio (OSR);
8. Compute material mined, milled, and marketable product;
9. Compute the life of mining operation;
10. Compute the discrete "CF_i" and "NPV_i";
11. Compare the "NPV_i" computed in step 10 with the previous "V" (step 6). If the computed "NPV_i" is not converged, then go to step 16, otherwise, go to the next step;
12. Set i = i + 1;
13. Grade-tonnage distribution adjustments by subtracting "Qc_i" from the grade intervals above the "$(G_{opt})_i$" and "(Qm_i-Qc_i)" from the grade intervals below the "$(G_{opt})_i$" in proportionate amount such that the distribution is not changed;
14. Checking depletion of the current pushback;
15. Checking development milestones, if "i" is equal to the next development milestones, then set new developed capacities for M, C, R and add the related CAPEX to f; otherwise go to step 4;
16. Set j = j + 1, then go to step 6;

The steps of the algorithm are also illustrated in Fig. 3.

4. Case Study, Sungun Copper Project

The Sungun Copper Project (SCP) is situated in the East Azarbaijan Province (Azarbaijan-e Sharqi) in the north-west part of Iran. The grid reference for the project area is 46º 43' east, 38º 42' north. The border with Turkey lies some 200 km to the west. The Aras River that also forms the border of Iran with Armenia and Azerbaijan lies approximately 40 km to the north of the mine. The mine lies, by road, approximately 130 km north east of the city of Tabriz and about 75 km north-west of the provincial capital Ahar. The nearest sizeable town to the mine is Varzaghan which lies some 32 km to the south. An important nature reserve, the Arasbaran lies immediately adjacent to the project area, to the east of the Miankafeh and Illgineh Rivers. The mine is bounded to the east by the Sungun River. The general region around and to the north of the project area is mountainous known as the Gharadagh mountain range and is characterized by rounded peaks and ridges separated by steep sided valleys. It is part of an extensive chain that stretches from the Alps in the west to the Himalayas in the east and the highest mountains in the vicinity of the mine have elevations in excess of 2700 m. Sungun copper mine is the second largest porphyry copper deposit of Iran. The largest copper deposit of Iran is Sarcheshmeh. Porphyry copper deposits, due to the nature of their relatively low grade world-wide, are developed at as high a plant throughput as possible consistent with a minimum mine life of approximately 20 years. This format is adopted in order to take advantage of the "economy of scale" where the mine's fixed costs are borne by a large production of copper. The concentrator plant has been commissioned in mid 2006.

4.1. Geology, Exploration and Block Modeling

The mineralization is largely hosted by a hydrothermally altered quartz-monzonite porphyry intrusion, which forms part of the Sungun Stock. Exploration activities in Sungun copper mine is comprised of 240 cored, mostly vertical (83%), drillholes with the length of more than 80,000 m. A synopsis of the exploration drillholes is given in Table 2.

Tab. 2. Exploration drillholes of Sungun copper mine

Stage	Years	No. of DHs	Length (m)	Ave. Depth (m)
1	1989-1992	47	15,544	338
2	1992-1993	98	40,888	430
3	1993-1995	11	6,956	632
4	2003-2004	84	16,806	200
Total		**240**	**80,194**	

Four lithological zones have been recognized as being significant in regard to grade: Leached, Supergene, Hypogene and Skarn. Two additional zones are also recognized both of which are considered waste: Dyke and Soil. The Leached Zone sometimes includes "oxide" copper mineralization (with >50% copper as

oxide), principally as malachite and azurite, at its base. When developed, the Supergene Zone, mineralization comprises veins and dissemination of covellite and lesser chalcocite in solid solution or exsolved with digenite, and with native copper and cuprite developed close to its top. Mineralization in the Hypogene Zone comprises pyrite, chalcopyrite, bornite and molybdenite. The average thickness of this zone is based on the depth of the drillholes, which often stopped in mineralized rock.

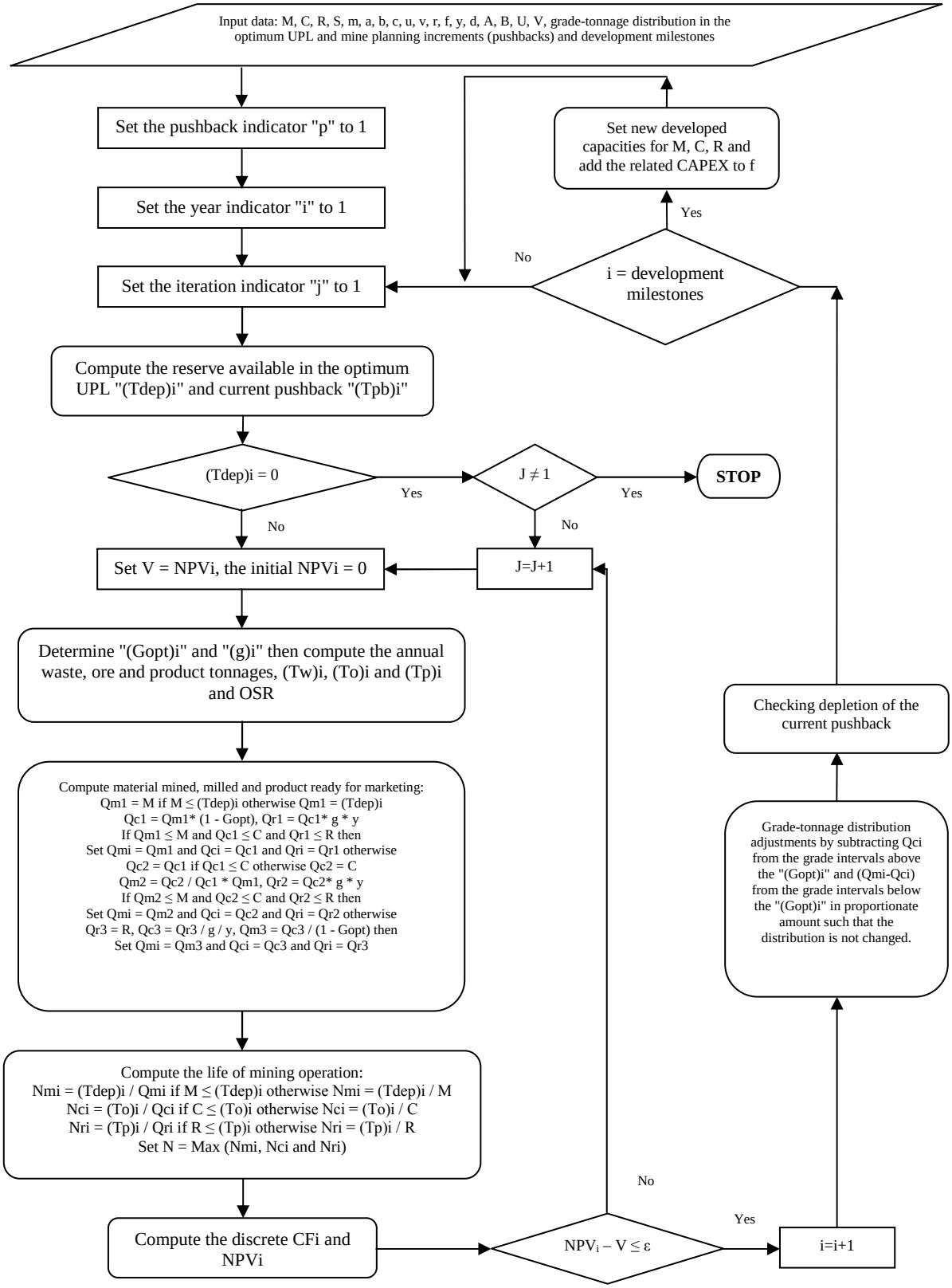


Fig. 3. Flowchart of the modern approach for cutoff grade optimization

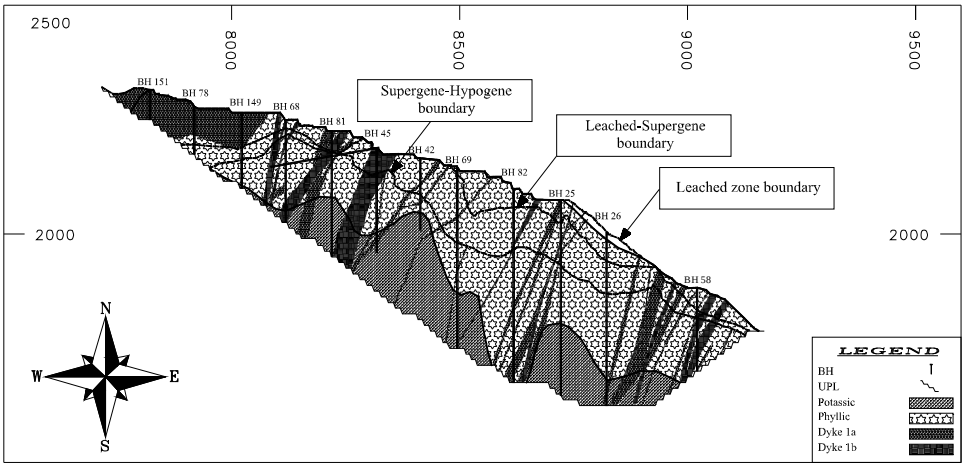


Fig. 4. Lithological cross section of Sungun deposit at 4800 N

The Hypogene Zone often contains considerable thickness of unmineralized porphyry. The dykes (1a, 1b) strike NNW-SSE, dip steeply to the west and have thickness from a few centimeters to several tens of meters. They appear to have acted as a barrier to hydrothermal and Supergenes processes and consequently sometimes mark the boundary between Leached and Supergene material. They also frequently act as a focus for high-grade copper-molybdenum mineralization in the adjacent monzonite porphyry host rock. A few dyke intersections in the Leached and Supergene zones show high copper values, but this may be the result of secondary deposition into a mechanically weakened and pervious rock. Mineralized dyke in the Hypogene Zone is very rare and, when recorded, may be largely derived from the adjacent host rock. The alteration zones of Sungun deposit consist of Potassic, Phyllic, Propylitic, and Argillic of which the first two zones are recognized to be ore. Pyrite content in each zone is also controlled by alteration. The pyrite content in different sulfidic zonation at the deposit changes from 1% in Potassic Zone to 10% in Phyllic Zone and to 2% in Argillic and Propylitic Zones. The lithological cross section of Sungun deposit at 4800 N is illustrated in Fig. 4.

The dimensions of block model considered for the deposit are 25 m x 25 m x 12.5 m. This corresponds to one quarter the average drillhole spacing and the planned bench height. Sub-blocking also allows adequate definition of lithological boundaries, which will minimize volumetric errors. The blocks are encoded with a coding system to enable lithological constraints to be applied in the interpolation of grades.

4.2. Resource Estimation

The resource statement as used for pit design and mine planning purposes is the Measured and Indicated resources of 807 Mt with 0.62% average grade at the cutoff grade of 0.25%. This is based upon interpolation into a block model using lithological and zone criteria based upon the parameters derived from statistical analysis. Ordinary Kriging has been used for the Supergene and Hypogene Zones and inverse distance method used for the Leached and Skarn Zones where the variograms were considered to be more robust and the sample data less erratic. This estimation has been classified based on JORC standard (AusIMM). Fig. 5 shows grade-tonnage relationships of the resource estimated.

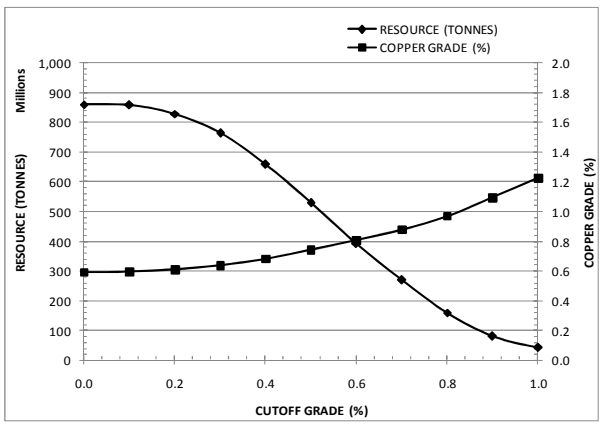


Fig. 5. Grade-tonnage relationships of the resource estimated

An exercise in cross validation has been conducted, comparing block grades with composited and raw data. Given that the general effect of linear geostatistical interpolation techniques is to smooth the data, the results of the cross validation have a good correlation.

4.3. Pit Optimization

The ore production profile is 7 million tons per year for the first six years (Phase 1) of operation and subsequently 14 million tons per year (Phase 2) for the rest of mine life. Concentrator plant produces 150,000 tons concentrate with 30% copper content in Phase 1 that will be duplicated after commissioning of Phase 2.

Datamine® has used to model the geology and the mine planning has been based on this geological block model. The block model is converted into a financial block model by converting the geological information into revenue and cost. Datamine is recognized throughout the world as a suitable geological and mining package for this type of deposit. Whittle® 4X and NPV Scheduler® has been used to evaluate the financial block model in parallel. Open pit mining optimization process and these software require mine design parameter inputs which are then applied to the financial block model both in terms of the financial data and the spatial position of a particular block. Boundary restrictions for pit optimization are limited up to the semi industrial area, crushing plant and the Sungun River. Cash flow pit limit analysis is done by different revenue factors and 70 pit shells have been produced. The UPL has been based on a shell with revenue factor equal to 1. This is the "Best Economic Scenario" and is selected on the maximum financial return.

Final pit analysis for pit expansion with 4 practical pushbacks has been done from the present topography up to the UPL. Results of calculations are shown in Table 3.

Tab. 3. Rock tonnage calculations inside pit shells

Pit shell	Tonnage of mineralized material (ton)	Copper content (ton)
Inside 1	119,176,710	545,802
Between 1 & 2	192,002,345	680,896
Between 2 & 3	234,128,991	731,966
Between 3 & 4	324,182,120	793,217
Total	**869,490,166**	**2,751,881**

4.4. AMD

Generally, for dealing with AMD, two major issues must be considered. One is prediction of AMD generation and the other is investigation about insitu and migrated AMD.

There are one waste dump and one tailings dam in the project area. These two sites and the mine itself are three locations that potentially can generate AMD. Preliminary investigations of the samples from the geological exploratory cores and the waters of the mine and waste dump in 2003 indicated that there is no acidity in the waters [23]. These results are not valid because the sampling procedure was not systematic and most of the samples had been taken from the barren dykes. However, further geochemical testing (pH and heavy metals) demonstrate that AMD generation at downstream of the waste dump in Pakhir valley has been commenced [24].

For tailings dam no laboratory test has been carried out. So, it is assumed that the tailings are potentially acid forming. This assumption is based on the fact that ore produced from copper mines generally contains pyrite that is rejected during flotation and discharged with the tailings. The pyrite has the ability to oxidize in the presence of free oxygen, producing acid conditions [25]. For better understanding the topography and basin hydrogeology of the SCP, more description is presented below:

The mine itself lies just to the north of the watershed and comprises the major part of a single mountain with a maximum elevation of about 2335 m. On the east, west and north faces of the mountain, the mountain drop away sharply into the deeply incised valleys of the Sungun and Pakhir Rivers. A ridge continues from the mountain for about 3 km to the south west where it climbs up to intersect with the north/south dividing watershed. The crushing plant lies on the eastern flank of the ridge.

The Sungun and Pakhir Rivers originate in the elevated areas to the east and west respectively, of the mine to flow north, dropping rapidly to reach the confluence with each other at a level of about 1650 m. The Sungun River then continues to flow north-eastwards down a deeply incised valley to join with the Miankafeh River at an elevation of about 1500 m where the combined rivers become the Illgineh River. The Illgineh River continues to flow in a generally northerly direction through the largely unspoiled area of Arasbaran until it reaches and flows into the Aras River which forms the border with Armenia. Fig. 6 shows a bird's eye view of the SCP.

The Tailings Storage Facility (TSF) lies on the south side of the dividing watershed within a wide saucer shaped valley at the upper reaches of the Zarnekab River. From the tailings impoundment, the Ahar River flows in a southerly then generally easterly direction to flow into the Sattarkhan water reservoir dam which supplies the required potable and sanitary water of Ahar County. Ahar is one of the counties which lie at the north of East Azarbaijan Province and its capital is Ahar city. Ahar county population in 1996 was 198,028 including 37,966 families.

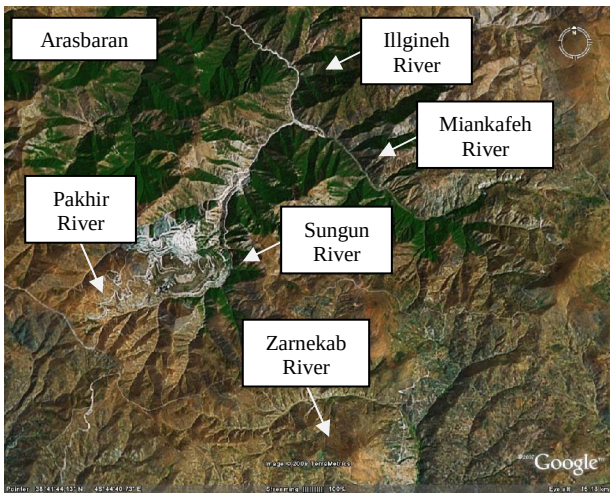


Fig. 6. The SCP bird's eye view

In accordance with the aforesaid paragraphs, any AMD from the mine or waste dump can pollute the Arasbaran nature reserve and Aras River and any AMD from the TSF can pollute the Sattarkhan water reservoir dam.

4.5. Application of the Modern Optimal Cutoff Grades to the SCP

For showing the effect of the modern optimal cutoff grades model in profitability of the SCP, three scenarios are considered. It is assumed that 50% of the waste rock and tailings are acid generating. In the first scenario all estimated costs are considered during the mining operation. In the second scenario the environmental costs ignored and postponed to the end of the mine life. The third scenario is not based on the modern model and a fixed breakeven cutoff grade considered during the mining operation. In the last scenario, the environmental costs ignored and postponed to the end of the mine life as well as the second scenario. The input data for these scenarios are given in Table 4.

Since the iterative steps of optimization are boring and time consuming, an Excel spreadsheet was developed to facilitate doing the calculations.

Tab. 4. Input data for three scenarios

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3
Cutoff	%	Variable	Variable	0.20
S	$/t	4500.00	4500.00	4500.00
M1	Mt/y	25.00	25.00	25.00
M2	Mt/y	40.00	40.00	40.00
C1	Mt/y	7.00	7.00	7.00
C2	Mt/y	14.00	14.00	14.00
R1	kt/y	80000.00	80000.00	80000.00
R2	kt/y	95000.00	95000.00	95000.00
m	$/t	1.60	1.60	1.60
a	$/t	0.15	0.00	0.00
b	$/t	0.54	0.00	0.00
c	$/t	2.50	2.50	2.50
u	$/t	0.25	0.00	0.00
v	$/t	0.81	0.00	0.00
r	$/t	315.00	315.00	315.00
f	M$/y	10.20	10.20	10.20
y	%	90.00	90.00	90.00
d	%	15.00	15.00	15.00
A	-	0.50	0.50	0.50
B	-	0.50	0.50	0.50
U	-	0.50	0.50	0.50
V	-	0.50	0.50	0.50

Table 5, Table 6 and Table 7 show the results of the aforesaid scenarios respectively.

Tab. 5. Optimal cutoff grades policy for Scenario 1

Year	Pushback	G_{opt}	Cutoff origin	g	OSR	Material mined	Material milled	Marketable product	CF	Cumulative discounted CF
1	1	0.77	g_{mc}	1.16	1.98	20.83	7	73,053	236,261,881	205,445,114
2	1	0.74	g_{mc}	1.13	1.91	20.34	7	71,280	229,798,064	379,205,465
3	1	0.72	g_{mc}	1.11	1.85	19.96	7	69,857	224,572,663	526,865,636
4	1	0.67	g_{mc}	1.06	1.76	19.29	7	67,089	214,288,464	649,385,761
5	1	0.57	g_{mc}	0.97	1.60	18.18	7	60,852	190,346,749	744,021,736
6	2	0.34	g_{mc}	0.73	1.34	16.35	7	45,857	131,133,216	800,714,244
7	2	0.32	g_{cr}	0.64	0.94	27.18	14	80,985	238,307,990	890,303,044
8	2	0.32	g_{cr}	0.64	0.96	27.41	14	80,774	236,970,616	967,769,159
9	2	0.32	g_{cr}	0.64	0.98	27.73	14	80,493	235,174,821	1,034,620,521
10	2	0.32	g_{cr}	0.64	1.01	28.20	14	80,085	232,551,734	1,092,103,753
11	2	0.32	g_{cr}	0.63	1.07	29.00	14	79,408	228,166,278	1,141,146,548
12	3	0.30	g_{mc}	0.60	1.16	30.25	14	75,818	210,715,586	1,180,530,798
13	3	0.35	g_{c}	0.60	1.31	32.41	14	76,198	208,104,941	1,214,353,669
14	3	0.38	g_{mc}	0.68	1.30	32.18	14	85,431	247,199,368	1,249,290,023
15	3	0.35	g_{mc}	0.64	1.28	31.94	14	81,226	230,067,555	1,277,564,057
16	3	0.33	g_{mc}	0.62	1.27	31.80	14	78,484	218,854,703	1,300,951,915
17	3	0.29	g_{mc}	0.58	1.25	31.48	14	73,037	196,688,603	1,319,229,378
18	4	0.20	g_{mc}	0.48	1.22	31.14	14	61,069	147,249,506	1,331,127,891
19	4	0.28	g_{mc}	0.50	1.36	33.09	14	62,832	150,843,776	1,341,726,978
20	4	0.27	g_{mc}	0.54	1.35	32.93	14	68,104	173,214,264	1,352,310,418
21	4	0.25	g_{mc}	0.52	1.34	32.77	14	65,115	161,016,808	1,360,865,350
22	4	0.23	g_{mc}	0.50	1.32	32.68	14	63,354	153,825,975	1,376,972,200
23	4	0.22	g_{mc}	0.48	1.32	32.53	14	63,805	143,436,122	1,373,734,664
24	4	0.19	g_{mc}	0.45	1.31	32.37	14	57,130	128,379,091	1,378,219,496
25	4	0.15	g_{mc}	0.41	1.31	32.33	14	52,044	107,165,051	1,381,474,917
26	4	0.10	g_{mc}	0.35	1.33	32.58	14	43,835	72,323,622	1,383,385,369
27	4	0.09	g_{mc}	0.33	1.45	34.25	14	41,427	58,981,835	1,384,740,174
28	4	0.07	g_{m}	0.28	2.14	20.57	6.55	16,696	2,085,795	1,384,781,835
Total						**791.75**	**342.55**	**1,852,339**		

5. Results and Discussion

As it can be seen, the optimal cutoff grades in the first and the second scenarios are variable and of course in compliance with the Eq. (15). The descending order of the optimal cutoff grades causes higher average head grade of run-of-mine ore and subsequently higher marketable product. Rehabilitation costs in the second scenario are estimated to be $ -335 M that has an extreme negative impact on the cumulative discounted cash flow. It is also note worthily that all optimal cutoff grades instead of the year 13 and the last year, has been chosen from the balancing cutoff grades. This is because of the specific interrelationship between the grade-tonnage distributions in the pushbacks and mining, milling and marketing throughputs. In such cases, profitability of the projects is less sensitive to the economical parameters such as metal price and operating costs. As the second phase of the SCP is envisaged to be commissioned on 2013, it is highly recommended that the throughput of the components optimized with consideration of the grade-tonnage distributions in the pushbacks. This optimization causes the optimal cutoff grades to be chosen mostly from the limiting economic cutoff grades which yields more flexibility.

The profitability of the third scenario is 80% and 44% lower than the profitability of the first and the second scenarios respectively. On the other hand the marketable product also is decreased. It must be notified that the CAPEX has not been considered in the

calculations, because no valid data was accessible and also scenarios are comparative, i.e. not considering the CAPEX does not impact on the results.

6. Conclusion

Environmental protection has the highest priority in modern mining and the optimum mine designs excluding environmental criteria are actually pseudo-optimum designs. The literature review confirmed that integration of mining design concepts and planning with consideration of environmental management has not advanced well in the mining industry. The modern approach for cutoff grades optimization is an effort to increase the sustainability of mining design and planning. The most significant aspect of mining activities particularly porphyry copper mines is producing a large amount and variety of waste materials and tailings that claims attention and must be properly managed to minimize the adverse environmental impacts. The acid generating potential of waste materials and tailings in each alteration zone can be estimated by laboratory and insitu tests. Four coefficients that discriminate between acid generating and non-acid generating waste materials and tailings incorporated into the Lane's algorithm to ensure optimality of optimum cutoff grades. To do this a heuristic modern approach for cutoff grade optimization presented in this paper which not only maximizes the profitability of projects, but also minimizes the adverse environmental impacts of the project simultaneously.

Tab. 6. Optimal cutoff grades policy for Scenario 2

Year	Pushback	G_{opt}	Cutoff origin	g	OSR	Material mined	Material milled	Marketable product	CF	Cumulative discounted CF
1	1	0.77	g_{mc}	1.16	1.98	20.83	7	73,053	244,703,789	212,785,903
2	1	0.74	g_{mc}	1.13	1.91	20.34	7	71,280	238,071,171	392,801,912
3	1	0.72	g_{mc}	1.11	1.85	19.96	7	69,857	232,716,636	545,816,877
4	1	0.67	g_{mc}	1.06	1.76	19.29	7	67,089	222,202,865	672,862,087
5	1	0.57	g_{mc}	0.97	1.60	18.18	7	60,852	197,880,943	771,243,888
6	2	0.34	g_{mc}	0.73	1.34	16.35	7	45,857	138,045,844	830,924,916
7	2	0.32	g_{cr}	0.64	0.94	27.18	14	80,985	250,232,592	924,996,616
8	2	0.32	g_{cr}	0.64	0.96	27.41	14	80,774	248,975,840	1,006,387,260
9	2	0.32	g_{cr}	0.64	0.98	27.73	14	80,493	247,289,987	1,076,682,508
10	2	0.32	g_{cr}	0.64	1.01	28.20	14	80,085	244,829,272	1,137,200,560
11	2	0.32	g_{cr}	0.63	1.07	29.00	14	79,408	240,719,854	1,188,941,661
12	3	0.30	g_{mc}	0.60	1.16	30.25	14	75,818	223,700,769	1,230,752,934
13	3	0.37	g_{c}	0.60	1.31	32.41	14	76,198	221,835,472	1,266,807,400
14	3	0.38	g_{mc}	0.68	1.30	32.18	14	85,431	260,845,417	1,303,672,333
15	3	0.35	g_{mc}	0.64	1.28	31.94	14	81,226	243,632,869	1,333,613,469
16	3	0.33	g_{mc}	0.62	1.27	31.80	14	78,484	232,374,641	1,358,446,131
17	3	0.29	g_{mc}	0.58	1.25	31.48	14	73,037	210,098,895	1,377,969,758
18	4	0.20	g_{mc}	0.48	1.22	31.14	14	61,069	160,550,106	1,390,943,028
19	4	0.28	g_{mc}	0.50	1.36	33.09	14	62,832	164,815,145	1,402,523,817
20	4	0.27	g_{mc}	0.54	1.35	32.93	14	68,104	187,128,536	1,413,957,423
21	4	0.25	g_{mc}	0.52	1.34	32.77	14	65,115	174,876,979	1,423,248,755
22	4	0.23	g_{mc}	0.50	1.32	32.68	14	63,354	167,655,274	1,430,994,528
23	4	0.22	g_{mc}	0.48	1.32	32.53	14	63,805	157,217,567	1,437,310,653
24	4	0.19	g_{mc}	0.45	1.31	32.37	14	57,130	142,104,864	1,442,274,984
25	4	0.15	g_{mc}	0.41	1.31	32.33	14	52,044	120,880,692	1,445,947,054
26	4	0.10	g_{mc}	0.35	1.33	32.58	14	43,835	86,129,062	1,448,222,182
27	4	0.09	g_{mc}	0.33	1.45	34.25	14	41,427	73,367,393	1,449,907,421
28	4	0.07	g_{m}	0.28	2.13	20.57	6.58	16,459	9,323,142	1,450,093,640
29	-	-	-	-	-	-	-	-	-335,548,949	1,114,544,691
Total						**791.75**	**342.58**	**1,852,102**		

Tab. 7. Optimal cutoff grades policy for Scenario 3

Year	Pushback	Breakeven cutoff	g	OSR	Material mined	Material milled	Marketable product	CF	Cumulative discounted CF
1	1	0.20	0.74	0.62	11.33	7	46,671	149,490,215	129,991,491
2	1	0.20	0.74	0.64	11.47	7	46,460	148,378,647	242,187,066
3	1	0.20	0.73	0.66	11.65	7	46,210	147,054,896	338,878,047
4	1	0.20	0.73	0.69	11.86	7	45,906	145,436,160	422,031,644
5	1	0.20	0.72	0.73	12.14	7	45,522	143,384,112	493,318,888
6	1	0.20	0.71	0.79	12.53	7	45,014	140,644,193	554,123,354
7	2	0.20	0.70	0.87	26.21	14	88,576	283,551,054	660,720,598
8	2	0.20	0.55	0.78	24.94	14	69,150	204,285,164	727,501,780
9	2	0.20	0.55	0.81	25.27	14	68,810	202,337,491	785,018,724
10	2	0.20	0.54	0.84	25.71	14	68,390	199,882,909	834,426,722
11	2	0.20	0.54	0.88	26.22	14	67,816	196,498,877	876,662,824
12	2	0.20	0.53	0.95	27.28	14	66,953	191,359,665	912429,313
13	3	0.20	0.52	1.08	29.10	14	65,412	181,987,127	942,007,309
14	3	0.20	0.52	0.91	26.74	14	65,066	184,319,775	968,056,976
15	3	0.20	0.51	0.93	26.98	14	64,868	183,106,337	990,559,735
16	3	0.20	0.51	0.95	27.28	14	64,632	181,641,504	1,009,970,812
17	3	0.20	0.51	0.98	27.67	14	64,330	179,753,825	1,026,674,596
18	3	0.20	0.51	1.01	28.20	14	63,921	177,183,000	1,040,991,889
19	3	0.20	0.50	1.07	29.02	14	63,321	173,365,342	1,053,173,460
20	3	0.20	0.49	1.18	30.48	14	62,297	166,741,014	1,063,361,383
21	4	0.20	0.47	1.46	34.39	14	59,800	150,033,044	1,071,332,740
22	4	0.20	0.47	1.19	30.65	14	59,510	154,805,615	1,078,484,851
23	4	0.20	0.47	1.21	30.92	14	59,363	153,760,057	1,084,662,073
24	4	0.20	0.47	1.23	31.25	14	59,176	152,444,978	1,089,987,629
25	4	0.20	0.47	1.26	31.67	14	58,941	150,790,077	1,094,568,275
26	4	0.20	0.47	1.30	32.23	14	58,634	148,613,698	1,098,493,956
27	4	0.20	0.46	1.36	33.03	14	58,208	145,558,734	1,101,837,419
28	4	0.20	0.46	1.45	34.29	14	57,552	140,788,557	1,104,649,500
29	4	0.20	0.45	1.63	36.79	14	56,318	131,623,623	1,106,935,607
30	4	0.20	0.41	2.30	32.38	9.8	36,455	66,051,137	1,107,933,181
31	4	0.20	-	-	-	-	-	-337,223,999	770,699,182
Total					**756.98**	**373.80**	**1,783,281**		

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