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A Linear Model for Determination of Block Economic Values

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ABSTRACT: Most algorithms developed for optimisation of the mine layout and production scheduling, for both open pit and underground mines, are implemented on an economic block model of the ore-body. There are various formulae for calculating the economic value of a block. This paper introduces an approach employed to define a linear function for determination of block values in underground metalliferous mines. The proposed value function uses terms BMC, the block mining cost, and BRR, the block revenue ratio, as the constant and the multiplier, respectively. BMC may be fixed for a range of depth or a specific mining method. Costs are categorised into two classes, the ore-based costs and the metal-based costs. Rules of thumb in block valuation and the difference between open pit and underground cases are also discussed. In multi-metal deposits, the main product is set as the base and an equivalent grade is defined and calculated, which substitutes grades of all existing products. The "main product equivalent grade" *(MPEG)* is then used in the mentioned formula. The approach is found to be simple and fast. It is suitable for feasibility studies and preliminary resource appraisal.

1 INTRODUCTION

Determination of block economic values in a block model of the ore-body is the base for constructing an economic model. This is a vital task for most optimisation methods, used in mining industry. Optimisation of the ultimate mine layout and production scheduling are two well known examples, which are fundamentally based on the economic model of the ore-body. This is regardless of the mining method, ie surface or underground mining, and considering or ignoring the time value of money, ie the objective function is maximising the profit or the net present value.

What is normally available in a block model is a set of blocks in three dimensions each containing estimates of a set of data, most importantly assay values. Assay values are useful in discriminating between blocks of ore and waste based on a given cutoff grade. However, for production scheduling purposes and mine layout optimisation, it is necessary to express blocks in economic terms to indicate their net worth, ie their dollar values. The reason is that blocks with the same grade value may have different net worth that affects their mineablity, the optimum mine layout and when they should be mined. Some factors that influence the net value of blocks are the location of blocks, when they will be mined and the mining method applied.

The relative location of a block may affect its net value due to the fact that haulage distance is influenced by the block location. The effect is not considerable for small differences in block locations. However, for blocks that are located far from the dump site or the crusher, it may be significant. In particular, depth of the mine can be divided into different categories each specifying a separate cost for haulage.

The block net value is also affected by when the block will be mined. The revenue obtained from a block depends on the price of the recovered (metal) product contained in the block. However, the product price is usually considered as the main economic uncertainty over time. In addition, the amount spent for the associated cost of blocks, including the payment for equipment, materials and wages vary with time. Moreover, and most significantly, taking into account the inflation rate and the time value of money, the revenue and costs must be discounted by a factor that increase over time.

Various mining methods may also influence the economic value of a block. The value of a block, when excavated using open pit mining methods, is not necessarily the same as when it is mined using underground methods. In addition, the block values may vary with different underground methods. For example, mining costs for a block in a selective mining method, such as cut-and-fill, may be different from those for the block mined in the block-caving or sub-level stoping methods. In the block-caving method, there is no cost for ore extraction (except occasional drilling for initiating the caving process) nor ore handling cost (since the ore falls down due to its gravity). However, the development in the block-caving method is complicated and time consuming, so that it may take years to complete the development (Hamrin, 1982). On the other hand, in the cut-and-fill method, there is no cost for development and the selectivity of the method provides good recovery. However, the method entails drilling and blasting costs and the cost for handling ore to the orepass within the stope as well as the filling cost.

In mine layout optimisation, it is usually practised to use the *Block Economic Values (BEV)* as attributes of blocks. The corresponding model is called the economic block model. An economic block model is a block model, which has each block assigned an estimate of its net economic (dollar) value. The typical element of the economic block model is denoted by *BEV,]/,,* which is a real scalar number and represents the economic value of the block, $B_{,Jt}$.

2 RULES OF THUMB IN CALCULATING BLOCK VALUES

When calculating block values for optimisation purposes, basic rules must be followed. Whittle (1989) has suggested three rules of thumb, in this regard, as presented below.

1. The value must be calculated based on the assumption that the block has *already* been uncovered. That is, the cost required to access the block must not be included to the block costs.
2. The value must be calculated based on the assumption that the block *will* be mined. A block, which contains more waste than ore is not going to be, primarily, chosen for the optimal layout. However, if it has to be mined to satisfy the mining constraints, the ore content will pay for some of the included waste.
3. When considering the cost of mining or the cost of processing for blocks, only those costs must be included that would stop if mining stopped. For example, fuel costs and wages would stop if mining stopped and therefore, must be included in the corresponding cost of mining, processing or refining. The reason is that addition of each extra block to the mine layout extends the life of the mine. Therefore, that extra block should pay for the extra cost during the extra life of the mine (Whittle, 1990).

The assumption, made in the first rule, is true for open pit mining since the cost of accessing a block has, in fact, been paid already when calculating values of preceding blocks. In other words, uncovering a block is equivalent to mining its preceding blocks; the block cannot be mined directly without mining its preceding blocks; so, when a block is going to be mined, it is already uncovered and no extra cost is required. However, in underground mines, accessing a block does not need uncovering that block. That is, each block must contribute in the accessing cost, including required costs for shafts, inclines, underground roadways and so on.

3 BLOCK VALUATION

Various formulae have been suggested to calculate the economic value of a block (Camus, 1992: Whittle, 1993). The approach used in this study is based on the fact that the economic value of a block *(BEV)* is equal to the revenue earned from selling the recovered metal (product) content of the block less all costs encountered for mining that block, processing the metal (product) from the ore and refining it to be prepared for sale. The basic relation may be expressed as below:

$$BEV = Revenue - Costs$$

The revenue of a block is directly related to the metal content, recovered from the block and the market price of the product. The metal content is further a function of the assay value as well as the volume and density of the block as described in the following relations:

$$\begin{aligned} Block\ revenue &- Price \times Product \\ &= Price \times Recovery \times Melal \\ &\sim Price \times Recovery \times Grade \times Ore \\ &= Price \times Recovery \times Grade \times Volume \times Density \end{aligned}$$

This is simply expressed by Equations (1).

$$Block\_\ \mathrm{Re}\ venue = P\ rgVp \qquad (1)$$

where

P: the price of the product (metal) to be sold, in \$/t of the metal,
r. total proportion of the metal recovered form the ore, including mining, processing and refining recoveries,
g: *grade* of the metal estimated for the block, in "%" or "ppm",
V: the volume of the block, $B_{,Jk}$, in cubic meters and
p. the density of blocks, in t/m^3.

Costs, on the other hand, can be divided into two categories, ie *"ore_based"* costs and *"metal_based"* costs.

$$Costs = Orejjased\ costs + Metal\_based\ costs$$

The first category contains those costs, which relates to mining of a block from the (surface or underground) deposit and delivering it either to the processing plant if it is an ore block or to the dump site if it is a waste block. *"Ore_based"* costs are calculated for each tonne of rock (ore or waste) contained in the block as described by:

Ore_.basedcosls=Unitproduction cost xTonnage (F

= Unit production cost x Volume X Densit

This may be expressed by Equation (2):

$$Ore\_based \text{ costs} = C_{ore} V p \qquad \textbf{(2)}$$

where C_{ore} is the cost of mining a tonne of ore (or waste), in $/t of rock.

The second category refers to those costs, which are necessary to extract the metal content of the ore through concentrating, processing, refining and preparing the product for sale. *"Metal_based"* costs are calculated for each tonne of the metal contained in the block as shown in the following relations:

MetalJ>ased costs -Unit costxRecoveryxTonnage (Metal)

= Unit cost XRecovery xGrade xOre

= Unit cost x Recovery x Grade x Volume x Density

This may be expressed by Equation (3):

$$Metal\_based \text{ costs} = C/\wedge\ rgVp \qquad \textbf{(3)}$$

where C_M represents those costs required for processing a tonne of metal, refining it and preparing it for sale, in $/t of the metal. Substituting the revenue and costs in the basic relation for calculating the block value, the relation can be reduced to:

$$BEV = PrgVp-(C_{ore}Vp-l-C_u rgVp)$$
$$= (P-C_M)rgVp-C_{ore}Vp$$

or simply:

$$BEV = Vp[(P -C_M)rg-C_{ore}] \qquad (4)$$

In general, considering different densities for ore and waste blocks, the formula for calculating the net value of a typical block, B_{ijk}, may be obtained through Equation (5).

$$BEV_{ijk} = \begin{cases} V\ \rho_o\ [(P - C_M)rg_{ijk} - C_{ore}] & if\ g_{ijk} \geq g_c \\ V\ \rho_w\ [(P - C_M)rg_{ijk} - C_{ore}] & if\ g_{ijk} < g_c \end{cases} \qquad (5)$$

where

BEV_{ijk}: the economic value of the block, *B/jt,* in $,

ρ_o: the density of ore blocks, in t/m^3,

ρ_w: the density of waste blocks, in t/m^3,

g_{ijk}: the grade of the metal estimated for the block, *Byk,* in "%" or "ppm" and

g_c: the cut-off grade.

Among the above parameters and for blocks of the same cost estimation category, only the grade value is variable from block to block. Other parameters may be considered constant at least in a certain zone. Therefore, Equation (5) can be modified to a linear function (y = *ax + b),* in which the block economic value is a function of the block grade (provided that the unit costs are constant), as expressed by Equation (6).

$$BEV_{ijk} = BRR\ g_{ijk} - BMC$$
$$given:$$
$$BRR = (P-C_M)rVp \qquad (6)$$
$$BMC = C_{ore}Vp$$

where

BRR: the "block revenue ratio", as the multiplier in the formula and

BMC: the "block mining cost", as the constant of the formula.

When a block is barren, ie the grade is zero, there is a cost required to mine the block. This is called the "block mining cost" *(BMC)* and is the same for all blocks. Therefore, the value of barren blocks would be negative. It is equal to this base cost and is the minimum block value. The metal content of mineralised blocks will pay for all or part of the base cost, *BMC,* which is related, linearly, to the grade value of the block. However, the grade value compensates for the cost with a ratio (its multiplier, *[(P-CMJrVp],* in Equation (6), which is called the "block revenue ratio" *(BRR).* At a certain grade value, the block revenue can pay for total block mining cost, in which the block net value is zero. Accordingly, for blocks with higher-grade values, the block economic value would be positive. Fig. 1 shows linear variation of block values *(BEV)* as a function of grade, *g,* of blocks.

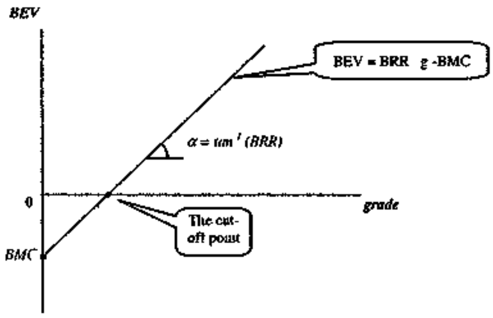

Figure 1: The block value function

4 EQUIVALENT GRADE

In many cases, there is more than one (metal) product in the deposit while the block value formula uses the grade value of only one metal. Therefore, it is required to determine an equivalent grade that substitutes grade values of all products and is used in the block valuation formula. Consider that there are one main product and "n" by-products in the deposit, of which the grade, recovery and price are known. The gross value obtained from the metal content can be calculated using the relation:

$$Gross\ value = Grade \times Recovery \times Price$$

This may be expressed for each product within the deposit by Equation (7).

$$GV_i = g_i\, r_i\, P_i \qquad i = 0,1,\ldots,n \qquad (7)$$

where
GV_i: the gross value of the i^{th} product,
g_i: the grade of the i^{th} product,
r_i: total recovery of the i^{th} product,
P_i: the unit price of the i^{th} product and
n: the total number of hitproducts (for the main product, $n = 0$).

Considering one of the products as the base, a factor can be defined for each of the other products to obtain the base product equivalent grade. In practice, the main product is usually set as the base and the grade of each by-product is converted to its *"main product equivalent grade" (MPEG)*. The equivalence factor, *EF*, for each by-product is defined as the ratio of its gross value to the gross value of the main product.

$$EF = \frac{Gross value\ of\ the\ by\text{-}product}{Gross\ value\ of\ the\ main\text{-}product}$$

As a result, the equivalence factor for the main-product would be equal to 1. Equation (8) denotes the *EF* formula.

$$EF_i = \frac{GV_i}{GV_0} = \frac{g_i\, r_i\, P_i}{g_0\, r_0\, P_0} \qquad i = 0,1,\ldots,n \qquad (8)$$

The equivalence factor for a by-product is the factor that has to be multiplied by the grade of the main-product to produce the *MPEG* of that by-product. The main product equivalent grade is, therefore, obtained using Equation (9).

$$MPEG_i = EF_i\,(g_0) = \frac{g_i\, r_i\, P_i}{g_0\, r_0\, P_0}.(g_0) \qquad i = 0,1,\ldots,n \qquad (9)$$

Finally, the total equivalent grade of the main-product is obtained through summation of *MPEGs* of all products as shown below.

$$MPEG_{Total} = \sum_{i=0}^{n} MPEG_i = \sum_{i=0}^{n} EF_i\,(g_0) = EF_0\,(g_0) + \sum_{i=1}^{n} EF_i\,(g_0)$$

Recalling that the equivalence factor of the main (base) product equals to 1 $(EF_0 = /)$, Equation (9) reduces to Equation (10).

$$MPEG_{Total} = (g_0)\left(1 + \sum_{i=1}^{n} EF_i\right) \qquad (10)$$

As a simple example, consider a deposit containing a main-product and two by-products. Having known the grade, recovery and price of each (metal) product, their gross values, equivalence factors and *MPEGs* are calculated based on the above formulae and shown in Table 1.

In order to check the results, the grade of the main-product must be substituted with the total MPEG to obtain the equivalent gross value. The result should match the total gross value obtained earlier.

$$Equivalent\ gross\ value = Total\ MPEG \times r_0 \times P_0 = 0.309 \times 0.9 \times 100 = 27.84$$

Table 1: Equivalent grades calculated for a deposit with two by-products

	Main-product	by-product_l	by-products	Total
Grade (%)	20	5	4	
Total recovery (%)	90	80	80	
Price($/t)	100	150	120	
Gross Value ($)	18	6	3.84	27.84
EF	1	0.333	0.213	1.547
MPEG (%)	20	6.667	4.267	30.933

Products of the deposit may have different units for their prices or grades. Grades and prices are usually expressed in various units, which require additional factors to produce equivalent price and grade units. Two major units for grades include *"percent" (%)* and *"gram per tonne" (ppm).* Three major units for price values are *"dollar per tonne" ($/t), "cents per kilo" (c/kilo)* and *"dollar per ounce" ($/oz)*- Tables 2 and 3 show the grade factors and price factors used in the *MPEG* formulae, respectively.

Table 2: Grade factors applied for corrections in *MPEG* formulae

#	Grade unit	Grade factor
1	percent (%)	0.01
2	gram per tonne	0.000,001

Applying the above factors, the relation for gross value is modified to:

Gross value - (Grade x Grade factor) x Recovery xfPrice x Price factor)

This is expressed by Equation (11).

$$GV_i=(g,GF_l)r_l(P,PF_l) \quad ; \quad =0,1,....,« \qquad (11)$$

where
GFf. the grade unit factor for the i"[l] product and
PFj-, the price unit factor for the i[lh] product.

Table 3: Price factors applied for corrections in *MPEG* formulae

#	Price unit	Price factor
1	Dollar per tonne ($/tonne)	1
2	Cents per kilo (c/kilo)	10
3	Dollar per ounce ($/oz)	35,242

5 A NUMERICAL EXAMPLE

The model was implemented on a numerical example using *Stope Limit Optimiser (SLO),* a software tool developed for optimisation of the stope boundaries (Ataee-pour and Baafi, 2003). The deposit was assumed to contain a main product (Copper) and three by-products (Gold, Silver and Molybdenum). Table 4 shows the echo of inputs and the computed block economic value (BEV) for block No. 203, provided by *SLO.*

Table 4: An example of the input data and computed block net value in *SLO*

203			
1.37	0.00	0.00	0.00
0.010000	0.000001	0.000001	0.010000
2600.00	410.00	6.00	40000.00
1	35242	35242	1
0.90000	0.75000	0.80000	0.75000
32.06	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.01370			
82400.00	5191199.50		
-11280.57			

The line description of Table 4 is as follows

Line l specifies the sequential (ID) address of the block

Line 2 contains the assay values of Copper, Gold, c ver and Molybdenum, respectively

Line 3 contains the grade factor of the products, which indicate the proportion of the product m the ore

Line 4 contains the price value of the products

Line 5 contains the pnce factors, which represent the factors for converting the prices of the by-products into the price of the main product

Line 6 includes the total recoveries of the products in terms of their proportions

Line 7 includes the gross values obtained from the products

Line 8 contains the E factors of the products that represent the ratio of the gross values of the by-products compared to the main product

Line 9 includes the equivalent grade of the block

Line 10 contains the block mining costs *(BMC)* and the block revenue ratio *(BRR)*

Line 11 contains the obtained *BEV* of the block

Table 5 shows the result of block valuation for a number of blocks, computed in *SLO*

Table 5 Block valuation performed by *SLO*

ID	Grade Cu %	Au ppm	Ag ppm	Mo %	BEV ($)
201	1 36	82	103	0 17	2111380 25
202	1 35	91	151	0 16	2338590 75
203	1 37	0	0	0	-11280 57
204	1 63	0	315	0 17	233570 78
205	1 8	0	186	0 17	193984 92
206	6 44	0	77	0 1	347363 53
207	1 05	0	185	0	41534 11
208	0 78	0	25	0	-32526 69
209	0 02	32	0	0	687959 13
210	0 13	21	18	0 07	482558 03
211	0 03	0	0	0	-80842 64
212	1 96	5	179	0	206728 73
213	2 88	6	120	0	256387 66
214	1 43	0	420	0 05	182728 02
215	0 29	0	165	0 14	87750 8

6 CONCLUDING REMARKS

The approach used in the proposed model considers costs in two categories, le ore-based and metal-based costs It also takes into account the equivalence factor for multi-metal deposits Factors influencing the value of a block are expressed in two terms, the block revenue ratio and the block mining cost, to introduce a linear function for the block valuation The mining cost of blocks has been assumed fixed for a range of depths, eg a level in underground mines The approach is found to be simple and fast It would be useful for feasibility studies and preliminary resource appraisal

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