A review of open pit mine production scheduling and a guide for using Excel Solver in modeling MIP problems

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Abstract

Optimization of production scheduling is important for managing the substantial cash flows inherent in open pit mining ventures. Mixed integer programming (MIP) models are used for production scheduling of open pit mines. In this method, formulations are based on binary variables for mining blocks. In this paper the uncertainty-based methods to optimizing open pit mine design and scheduling have been reviewed and then integer programming (IP) and mixed integer programming (MIP) have been discussed. Finally, a simple MIP model has been solved with Excel Solver and the results have been presented.

1. Introduction

Optimization and mathematical formulation have been exploited to solve long-term production scheduling problems since the 1960s (Ramazan *et al.*, 2003). There are two mathematical optimization approaches to solve these kinds of problem: deterministic and uncertainty based approaches. The uncertainty-based approach to optimizing open pit mine design and scheduling was developed in the 1990s (Golamnejad *et al.*, 2006).

Ravenscroft discussed risk analysis in mine production scheduling (Golamnejad *et al.*, 2006). This method can show only the impact of grade uncertainty on production scheduling using the alternative scenarios of the orebody, which are provided by conditional simulation. Dowd proposed a framework for risk assessment in open pit mines. He also considered some other random variables such as commodity price, mining costs, processing costs, etc (Dowd, 1994). Denby and Schofield proposed an algorithm, which considers ore grade variance in open pit design and scheduling using the Genetic algorithm. They used a multi-objective optimization method: maximizing value and minimizing risk (Denby *et al.*, 1995).

Dimitrakopoulos and Ramazan discussed a linear programming (LP) approach that considered grade uncertainty, equipment access and mobility constraints. This formulation was based on expected ore block grades and the probabilities of different element grades being above required cut-offs, both derived from simulated orebody models. Gody and Dimitrakopoulos presented an algorithm, which addresses the generation of an optimal condition under uncertainty. First, they generated production schedules on each simulated orebody and then they combined the mining sequences to produce a single schedule that

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minimizes the chance of deviating from the production target. This was done using the Simulated Annealing Meta-Heuristic method (Godoy *et al.*, 2004).

Ramazan (Ramazan *et al.*, 2004) suggested an MIP model that accommodates grade uncertainty. In this method, after obtaining simulated orebody models, scheduling patterns on each model is generated using traditional MIP formulation (with the objective of NPV maximization). Then the excavation probability of each block in a given time period is calculated. The block with probability between zero and one, are considered in a new optimization model.

Caccetta and Hill solved a binary integer programming (BIP) formulation with an efficient branching scheme and briefly outlined some aspects of a specialized branch-and-cut algorithm (Caccetta *et al.*, 2003). Golamnejad (Golamnejad *et al.*, 2006) presented a chance constrained binary integer programming model. The model integrates ore grade uncertainty explicitly and economic and mining considerations to generate an optimal life of mine production schedule to meet the required targets with a high level of confidence and low risk.

Boland (Boland *et al.*, 2006) extend the BIP formulation of Caccetta and Hill to include more than two ore attributes and develop knapsack cover inequalities that significantly decrease the computational requirements to obtain the optimal integer solution.

Fricke (Fricke, 2006; Boland *et al.*, 2009) described an MIP formulation, using ideas from the formulation of Menabde et al., which is a generalisation of the BIP formulation of Caccetta and Hill and Boland. The computational experiments conducted by Fricke show that this generalization is particularly effective.

Mixed integer programming (MIP) has become a common approach for optimizing production schedules of open pit mines. However, MIP has been found to be limited by: (a) feasibility in generating optimal solutions with practical mining schedules; and (b) inability to deal with in-situ variability of orebodies. In long-term production scheduling of open pit mines, MIP models are usually constructed to maximize the overall net present value (NPV) of the mining project (Ramazan *et al.*, 2004).

A key limitation in past MIP models has been difficulty in solving large problems, as these require a substantial number of binary variables. The attempted LP-based models often generate fractional mining of blocks, leading to the design becoming infeasible and/or non-optimal. Ramazan (Ramazan *et al.*, 2004) proposed a new method based on the fundamental tree concept, and substantially decreases the number of binary variables in MIP formulations for long-term production scheduling. Ramazan(Ramazan *et al.*, 2004) presented alternative methodologies useful in reducing the number of binary variables in MIP models. Although the above methods significantly decrease the number of binary variables required and enhance the application of MIP in large mineral deposits, in-situ orebody variability is not considered and all inputs are considered without uncertainty.

2. Theoretical framework and models

2.1. Introduction to LP and IP programming

A major element of mine planning is the optimization of production scheduling. The aim is to maximize the overall discounted economic value of a mine within operational constraints such as mining slope, grade blending, ore production and mining capacity. Integer programming (IP) and linear programming (LP) mathematical models are considered to be powerful tools in optimizing mine scheduling, and there have been major efforts in applying them to mining projects (Ramazan *et al.*, 2004).

2.1.1 Linear programming (LP)

Linear programming uses a mathematical model to describe the problem of concern. The adjective linear means that all the mathematical functions in this model are required to be linear functions. The word programming does not refer here to computer programming; rather, it is essentially a synonym for planning. Thus, linear programming involves the planning of activities to obtain an optimal result, a result that reaches the specified goal best (according to the mathematical model) among all feasible alternatives (Hillier, 2005).

2.1.2 Integer programming (IP)

In many practical problems, the decision variables actually make sense only if they have integer values. If requiring integer values is the only way in which a problem deviates from a linear programming formulation, then it is an integer programming (IP) problem. The mathematical model for integer programming is the linear programming model with one additional restriction that the variables must have integer values. If only some of the variables are required to have integer values (so the divisibility assumption holds for the rest), this model is referred to as mixed integer programming (MIP). With just two choices, we can represent such decisions by decision variables that are restricted to just two values, say 0 and 1. Thus, the jth yes-or-no decision would be represented by, say, x_j such that

$$x_j = \begin{cases} 1 & \text{If decision } j \text{ is yes.} \\ 0 & \text{If decision } j \text{ is no.} \end{cases}$$

Such variables are called binary variables (or 0–1 variables). Consequently, IP problems that contain only binary variables sometimes are called binary integer programming (BIP) problems (or 0–1 integer programming problems) (Hillier, 2005).

3. MIP formulation for extraction sequencing

 MIP models are generally used to maximize the overall discounted economic value, or net present value (NPV), of a mining project. For this purpose and production scheduling for a bench of mine the following objective function can be used.

$$\text{Maximize} \sum_{t=1}^{T} \sum_{n=1}^{N} \frac{BEV_n^t}{(1+i)^t} \times X_n^t \qquad (2)$$

Where T is the maximum number of scheduling periods, N is the total number of blocks to be scheduled, BEV_n^t is the block economic value of block n in period t, i is interest rate and X_n^t is a binary variable, equal to 1 if the block n is to be mined in period t, otherwise 0.

3.1. Grade blending constraints

The average grade of material sent to the mill has to be less than or equal to a certain grade value, G_{max} , for each period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^{N} (g_n - G_{max}) \times Ot_n \times X_n^t \leq 0 \qquad (3)$$

Where g_n is the average grade of block n, and Ot_n is the ore tonnage in block n.

The average grade of the material sent to the mill has to be greater than or equal to a certain grade value, G_{min} , for each period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^{N} (g_n - G_{min}) \times Ot_n \times X_n^t \geq 0 \qquad (4)$$

3.2. Reserve constraints

Reserve constraints are constructed for each of the blocks to state that all the blocks in the model considered have to be mined once (Ramazan *et al.*, 2004).

$$\sum_{t=1}^{T} X_n^t = 1 \qquad (5)$$

3.3. Processing capacity constraints

The total tonnage of ore processed cannot be more than the processing capacity (PC_{max}) in any period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^{N} (Ot_n \times X_n^t) \leq PC_{max} \qquad (6)$$

The total tonnage of ore processed cannot be less than a certain amount (PC_{min}) in any period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^{N}(Ot_n \times X_n^t) \geq PC_{min} \qquad (7)$$

3.4. Mining capacity

The total amount of material (waste and ore) to be mined cannot be more than the total available equipment capacity (MC_{max}) for each period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^{N}(Ot_n + W_n) \times X_n^t \leq MC_{max} \qquad (8)$$

Where W_n is the tonnage of waste material in block n.

To force the MIP mod el to produce balanced waste production throughout the periods, a lower bound (MC_{min}) may need to be implemented as follows (Ramazan *et al.*, 2004):

$$\sum_{n=1}^{N}(Ot_n + W_n) \times X_n^t \geq MC_{min} \qquad (9)$$

Note: In this formulation mine equipment mobility has not been considered.

4. Illustrative example

A plan view of 24 blocks and average grade of ore in each block are shown in Figures 1 and 2, respectively. In calculating the values per ton(st) of blocks, it is assumed that the product price is \$250/t, ore and waste mining cost are \$25/t, processing cost is \$40/t, the recovery factor is 70% and the specific weight of ore and waste are 2.7 and 2.4 t/m^3 respectively.

The goal is to schedule the extraction of blocks in three periods. The objective is to maximize the summation of discounted economic block values, while extracting all the 24 blocks. Table 1, shows each block economic value calculated by Equation (10).

Dimension of each block=15 m × 15 m × 15 m

BL1	BL2	BL3	BL4	BL5	BL6
BL7	BL8	BL9	BL10	BL11	BL12
BL13	BL14	BL15	BL16	BL17	BL18
BL19	BL20	BL21	BL22	BL23	BL24

Fig 1. Plan view is showing blocks configuration

0.87	waste	0.64	0.67	0.52	waste
0.51	0.70	0.55	0.73	0.67	0.59
0.95	0.78	0.84	0.71	waste	0.62
waste	0.65	waste	0.62	0.71	0.74

Fig 2. Plan view is showing the average grade (MWT %) of each block.

MWT (magnetic weight recovery)

$$BEV_n = (Ot_n \times g_n \times P \times R) - (Ot_n \times C_p) - [BT_n \times C_m] \qquad (10)$$

Where Ot_n is the total amount of ore in the block n (t), g_n is the average grade of nth block (%), P is the price of product ($/t), R is the proportion of the product recovered by processing the ore (%), C_p is the cost of the processing ($/t), Wtn is the total amount of waste in the block n (t), BT_n is the block tonnage that is equal to (Ot_n + Wt_n) and C_m is the cost of the mining for ore and waste ($/t).

To solve this problem, Excel Solver was used. Solver is a free add-in package for Excel. A more powerful version – Premium Solver – is commercially available for optimization on an industrial scale. Solver allows us to specify restrictions, or constraints, for cell values. For example, we can specify that certain cell values must be equal to, higher than, or lower than a given number. In fact, we can specify up to 500 constraints in a Solver problem, consisting of up to two constraints with up to 200 changing cells per constraint, plus 100 additional constraints. Actually, when the Solver Options dialog box's Assume Linear Model check box is selected, there is theoretically no limit to the number of constraints.

The number of binary variables required for the MIP model is equal to the number of blocks in the model (in this case=24) multiplied by the total periods (in this case=3) to be scheduled, as can be seen in the formulations above.

For mining capacity constraints, following boundaries were used:

$$1^{st}, 2^{nd}, 3^{rd} \ years \qquad 65,000(t) \leq Mining \ capacity \leq 75,000(t)$$

Processing capacity that was used as constraint for all periods was same and it was between 55,000 (t) and 60,000 (t).

To use Excel to solve LP problems the Solver add-in must be included. Typically this feature is not installed by default when Excel is first setup on your hard disk. To add this facility to your Tools menu you need to carry out the following steps:

1. Select the menu option Tools → Add-Ins (this will take few moments to load the necessary file).

2. From the dialogue box presented check the box for Solver Add-In.

Table 1. Economic Block Value (volume of each block is equal to $15 \times 15 \times 15$ (m^3))

BL No.	Grade (%)	waste (st)	Ore(st)	Cost ($)	Revenue($)	EBV$\times 10^8$ ($)
BL 1	87	0	9112.5	592312.5	138,145,500.00	1.38
BL 2	waste	8100	0.0	202500.0	-202,500.00	-0.002
BL 3	64	0	9112.5	592312.5	101,467,687.50	1.01
BL 4	67	0	9112.5	592312.5	106,251,750.00	1.06
BL 5	52	0	9112.5	592312.5	82,331,437.50	0.82
BL 6	waste	8100	0.0	202500.0	-202,500.00	-0.002
BL 7	51	0	9112.5	592312.5	80,736,750.00	0.81
BL 8	70	0	9112.5	592312.5	111,035,812.50	1.11
BL 9	55	0	9112.5	592312.5	87,115,500.00	0.87
BL 10	73	0	9112.5	592312.5	115,819,875.00	1.16
BL 11	67	0	9112.5	592312.5	106,251,750.00	1.06
BL 12	59	0	9112.5	592312.5	93,494,250.00	0.93
BL 13	95	0	9112.5	592312.5	150,903,000.00	1.51
BL 14	78	0	9112.5	592312.5	123,793,312.50	1.24
BL 15	84	0	9112.5	592312.5	133,361,437.50	1.33
BL 16	71	0	9112.5	592312.5	112,630,500.00	1.13
BL 17	waste	8100	0.0	202500.0	-202,500.00	-0.002
BL 18	62	0	9112.5	592312.5	98,278,312.50	0.98
BL 19	waste	8100	0.0	202500.0	-202,500.00	-0.002
BL 20	65	0	9112.5	592312.5	103,062,375.00	1.03
BL 21	waste	8100	0.0	202500.0	-202,500.00	-0.002
BL 22	62	0	9112.5	592312.5	98,278,312.50	0.98
BL 23	71	0	9112.5	592312.5	112,630,500.00	1.13
BL 24	74	0	9112.5	592312.5	117,414,562.50	1.17

3. On clicking OK, you will then be able to access the Solver option from the new menu option Tools → Solver

An optimization model has three parts: the target cell, the changing cells, and the constraints.

- Target cell: The target cell represents the objective or goal. We want to either minimize or maximize the target cell. In our example of a mine production scheduling, we want to maximize the discounted cash flow.

- Changing cells: The changing cells are the spreadsheet cells that we can change or adjust to optimize the target cell. In the other word, these cells are solution of the problem.

- Constraints: The constraints are restrictions you place on the changing cells. Software must adhere to these constraints as it tries to change the adjustable cells to meet the objective.

- Model: A model is the set of target cell, all changing cells and any constraints for the current problem that you want to solve.

To solve this problem, first the solution section was setup as illustrated in figure 3. The cells C3:E26 are changing cells or solution of the problem. In column F, each cell from F3 to F26 is equal to sum of solutions in related row. For instance cell F3=sum (C3:E3) and cell F25=sum (C25:E25). Sum of solutions for each period is written in row 28 and under each period in front of total. For instance cell C28=sum (C3:C26).

Figure 4 shows how constraints of grade blending have been set up in Excel. There are two different parts. Cells H3:J26 for equation (4) and cells K3:M26 for equation (3). In this problem, according to grades in table 1, $G_{min} = 0$ and $G_{max} = 0.95$. Value of each cell H3 through to J26 is calculated as follows:

H11=(B11-0)×G11×C11,   I11=(B11-0) ×G11×D11 ,   J11=(B11-0) ×G11×E11

For equation (4), value of each cell K3 through to M26 is calculated as follows:

K18=(B18-0.95) ×G18×C18, L18=(B18-0.95) ×G18×D18,   M18=(B18-0.95) ×G18×E18

The cells H28 to M28 are equal to sum of cell values from row 3 to row 26 above each of them. The cells H28 through to J28 indicate equation (4) in periods 1, 2 and 3 and the cells K28 through to M28 indicate equation (3) in periods 1, 2 and 3.

Figure 5 shows how constraints of mining capacity and processing capacity have been set up in Excel. There are two different parts. Cells S3:U26 for equations (8) and (9) and cells W3:Y26 for equations (6) and (7). Value of each cell S3 through to U26 is calculated as follows:

S14=R14 ×C14,   T14=R14 ×D14,   U14=R14×E11

Value of each cell W3 through to Y26 is calculated as follows:

W7=V7×C7,   X7=V7 ×D7,   Y7=V7×E7

The cells S28 through to Y28 are equal to sum of cell values from row 3 to row 26 above each of them. The cells S28 through to U28 indicate equations (8) and (9) in periods 1, 2

and 3 and the cells W28 through to Y28 indicate equations (6) and (7) in periods 1, 2 and 3.

	A	B	C	D	E	F
1				Solution		Sum
2		grade	T=1	T=2	T=3	
3	block1	0.87	0	0	0	0
4	block2	0	0	0	0	0
5	block3	0.64	0	0	0	0
6	block4	0.67	0	0	0	0
7	block5	0.52	0	0	0	0
8	block6	0	0	0	0	0
9	block7	0.51	0	0	0	0
10	block8	0.7	0	0	0	0
11	block9	0.55	0	0	0	0
12	block10	0.73	0	0	0	0
13	block11	0.67	0	0	0	0
14	block12	0.59	0	0	0	0
15	block13	0.95	0	0	0	0
16	block14	0.78	0	0	0	0
17	block15	0.84	0	0	0	0
18	block16	0.71	0	0	0	0
19	block17	0	0	0	0	0
20	block18	0.62	0	0	0	0
21	block19	0	0	0	0	0
22	block20	0.65	0	0	0	0
23	block21	0	0	0	0	0
24	block22	0.62	0	0	0	0
25	block23	0.71	0	0	0	0
26	block24	0.74	0	0	0	0
27						
28	Total		0	0	0	

Fig 3. The part of worksheet that was used for setting up solution of problem

	A	G	H	I	J	K	L	M
1			Min grade			Max grade		
2		Ore tonnage	T=1	T=2	T=3	T=1	T=2	T=3
3	block1	9112.5	0	0	0	0	0	0
4	block2	0.0	0	0	0	0	0	0
5	block3	9112.5	0	0	0	0	0	0
6	block4	9112.5	0	0	0	0	0	0
7	block5	9112.5	0	0	0	0	0	0
8	block6	0.0	0	0	0	0	0	0
9	block7	9112.5	0	0	0	0	0	0
10	block8	9112.5	0	0	0	0	0	0
11	block9	9112.5	0	0	0	0	0	0
12	block10	9112.5	0	0	0	0	0	0
13	block11	9112.5	0	0	0	0	0	0
14	block12	9112.5	0	0	0	0	0	0
15	block13	9112.5	0	0	0	0	0	0
16	block14	9112.5	0	0	0	0	0	0
17	block15	9112.5	0	0	0	0	0	0
18	block16	9112.5	0	0	0	0	0	0
19	block17	0.0	0	0	0	0	0	0
20	block18	9112.5	0	0	0	0	0	0
21	block19	0.0	0	0	0	0	0	0
22	block20	9112.5	0	0	0	0	0	0
23	block21	0.0	0	0	0	0	0	0
24	block22	9112.5	0	0	0	0	0	0
25	block23	9112.5	0	0	0	0	0	0
26	block24	9112.5	0	0	0	0	0	0
27								
28	Total		0	0	0	0	0	0

Fig 4. The part of worksheet that was used for setting up constraints (3) and (4)

	A	R	S	T	U	V	W	X	Y
1				Mining capacity				Processing Capacity	
2		Waste + Ore	T=1	T=2	T=3	ore	T=1	T=2	T=3
3	block1	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
4	block2	8100.0	0.00	0.00	0.00	0	0.00	0.00	0.00
5	block3	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
6	block4	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
7	block5	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
8	block6	8100.0	0.00	0.00	0.00	0	0.00	0.00	0.00
9	block7	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
10	block8	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
11	block9	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
12	block10	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
13	block11	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
14	block12	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
15	block13	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
16	block14	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
17	block15	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
18	block16	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
19	block17	8100.0	0.00	0.00	0.00	0	0.00	0.00	0.00
20	block18	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
21	block19	8100.0	0.00	0.00	0.00	0	0.00	0.00	0.00
22	block20	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
23	block21	8100.0	0.00	0.00	0.00	0	0.00	0.00	0.00
24	block22	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
25	block23	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
26	block24	9112.5	0.00	0.00	0.00	9112.5	0.00	0.00	0.00
27									
28	Total		0.00	0.00	0.00		0.00	0.00	0.00
29									

Fig 5. The part of worksheet that was used for setting up constraints (6) to (9)

Setting up the objective function has been illustrated in figure 6. Value of cells N3:Q26 are calculated using equation (11) for each block according to the period of extraction.

$$\frac{BEV_n^t}{(1+i)^t} \times X_n^t \tag{11}$$

Where BEV_n^t is the block economic value of block n in period t, i is interest rate and X_n^t is a binary variable, equal to 1 if the block n is to be mined in period t, otherwise 0.

The cells O28 through to Q28 are equal to sum of cell values from row 3 to row 26 above each of them. The cell P30 is target cell that must be maximized and it is equal to sum of cells O28 through Q28.

	A	N	O	P	Q
1			Discounted economic value(i=15%)		
2		EBV (x10⁸)	T=1	T=2	T=3
3	block1	1.38	0.00	0.00	0.00
4	block2	-0.002	0.00	0.00	0.00
5	block3	1.01	0.00	0.00	0.00
6	block4	1.06	0.00	0.00	0.00
7	block5	0.82	0.00	0.00	0.00
8	block6	-0.002	0.00	0.00	0.00
9	block7	0.81	0.00	0.00	0.00
10	block8	1.11	0.00	0.00	0.00
11	block9	0.87	0.00	0.00	0.00
12	block10	1.16	0.00	0.00	0.00
13	block11	1.06	0.00	0.00	0.00
14	block12	0.93	0.00	0.00	0.00
15	block13	1.51	0.00	0.00	0.00
16	block14	1.24	0.00	0.00	0.00
17	block15	1.33	0.00	0.00	0.00
18	block16	1.13	0.00	0.00	0.00
19	block17	-0.002	0.00	0.00	0.00
20	block18	0.98	0.00	0.00	0.00
21	block19	-0.002	0.00	0.00	0.00
22	block20	1.03	0.00	0.00	0.00
23	block21	-0.002	0.00	0.00	0.00
24	block22	0.98	0.00	0.00	0.00
25	block23	1.13	0.00	0.00	0.00
26	block24	1.17	0.00	0.00	0.00
27					
28	Total		0.00	0.00	0.00
29					
30				0.00	

Fig 6. The part of worksheet that was used for setting up objective function

To use Excel Solver with the objective of discounted cash flow maximization of a mine production schedule, the following steps must be followed:

1.Click **Tools → Solver**

2. Click **Reset All**, and then click OK to clear Solver's existing settings.

3. Click the **Set Target Cell** box, and then click cell P30

4.Click **Max**

5. Click the **By Changing Cells** box, and then select cells C3 through E26

6. Click **Add**

7. Click the **Cell Reference** box, and then select cells C3 through E26

8. In the operator list between the Cell Reference and constraint boxes, select **bin**.

9. Click **Add**.

10. Click the **Cell reference** box, and then select cell F3

11. In the operator list , select =

12.click the **Constraint** box, and then type the number 1

(**Note**: Why one? because each block can be mined once)

13. Repeat steps 9 to 12 for cells F4 through F26

14.Click **Add**

15. Click the **Cell reference** box, and then select cell C28

16. In the operator list , select =

17. click the **Constraint** box, and then type the number 8

 (**Note**: Why 8? because we want to extract 8 blocks in each period)

18. Repeat steps 14 to 17 for cells D28 and E28

19. Click **Add**.

20. Click the **Cell reference** box, and then select cell H28

21. In the operator list , select >=

22.Click the **Constraint** box, and then type the number 0 (refer to equation (4))

23. Repeat steps 19 to 22 for cells I28 and J28

24. Click **Add**.

25. Click the **Cell reference** box, and then select cell K28

26. In the operator list , select <=

27.Click the **Constraint** box, and then type the number 0 (refer to equation (3))

28. Repeat steps 24 to 27 for cells L28 and M28

29. Click **Add**.

30. Click the **Cell reference** box, and then select cell S28

31. In the operator list , select <=

32.Click the **Constraint** box, and then type the number 75,000 (Maximum mining capacity)

33. Click **Add**.

34. Click the **Cell reference** box, and then select cell S28

35. In the operator list , select >=

36. Click the **Constraint** box, and then type the number 65,000 (Minimum mining capacity)

37. Repeat steps 29 to 36 for cells T28 and U28

38. Click **Add**.

39. Click the **Cell reference** box, and then select cell W28

40. In the operator list , select <=

41.Click the **Constraint** box, and then type the number 60,000 (Maximum processing capacity)

42. Click **Add**.

43. Click the **Cell reference** box, and then select cell W28

44. In the operator list , select >=

45. Click the **Constraint** box, and then type the number 55,000 (Minimum processing capacity)

46. Repeat steps 38 to 45 for cells X28 and Y28

47.Click **OK**

48. Click **Option**

49. Select the **Assume Linear Model** and **Use Automatic Scaling** check boxes, and then click OK.

50. Click **Solve**

5. Results and Discussion

The production scheduling results obtained by applying the optimization formulation in equation (2) and constraints are shown in figure 7.

Figure 8 shows the optimal schedule for three scheduled periods. Summary of results have been presented in table 2. Comparisons between tonnages of ore and waste that are extracted in each period have been shown in figure 9. It is assumed that maximum and minimum mining capacities are 65,000 ts and 75,000 ts, respectively. For processing capacity, maximum and minimum capacities were assumed 55,000 ts and 60,000 ts, respectively. The obtained solution satisfies these conditions. This matter has been shown in figure 10.

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	A	B	C	D	E	F
1				Solution		Sum
2		grade	T=1	T=2	T=3	
3	block1	0.87	1	0	0	1
4	block2	0	0	1	0	1
5	block3	0.64	0	1	0	1
6	block4	0.67	0	0	1	1
7	block5	0.52	0	1	0	1
8	block6	0	0	0	1	1
9	block7	0.51	0	1	0	1
10	block8	0.7	0	1	0	1
11	block9	0.55	0	0	1	1
12	block10	0.73	1	0	0	1
13	block11	0.67	0	0	1	1
14	block12	0.59	0	0	1	1
15	block13	0.95	1	0	0	1
16	block14	0.78	1	0	0	1
17	block15	0.84	1	0	0	1
18	block16	0.71	1	0	0	1
19	block17	0	0	1	0	1
20	block18	0.62	0	0	1	1
21	block19	0	1	0	0	1
22	block20	0.65	0	1	0	1
23	block21	0	0	0	1	1
24	block22	0.62	0	0	1	1
25	block23	0.71	0	1	0	1
26	block24	0.74	1	0	0	1
27						
28	Total		8	8	8	

Fig 7. Solution of the problem that was obtained using Excel solver

BL1	BL2	BL3	BL4	BL5	BL6
BL7	BL8	BL9	BL10	BL11	BL12
BL13	BL14	BL15	BL16	BL17	BL18
BL19	BL20	BL21	BL22	BL23	BL24

■ Period 1
■ Period 2
■ Period 3

Fig 8. Block extraction sequence

Table 2. Summary of obtained results for each period using Excel Solver

	Period 1	Period 2	Period 3
Blocks Number	1,10,13,14,15 16, 19, 24	2,3,5,7,8, 17,20,23	4,6,9,11,12, 18,21,22
Waste (t)	8100	16200	16200
Ore (t)	63787.5	54675	54675
Waste+Ore (t)	71887.5	70875	70875
Average grade	0.8	0.62	0.62
$f = \sum \dfrac{BEV_n}{(1+i)^t}$	7.348×10^8	4.493×10^8	4.785×10^8
$\displaystyle\sum_{t=1}^{3}\sum_{n=1}^{24}\dfrac{BEV_n^t}{(1+i)^t}$		16.626×10^8	
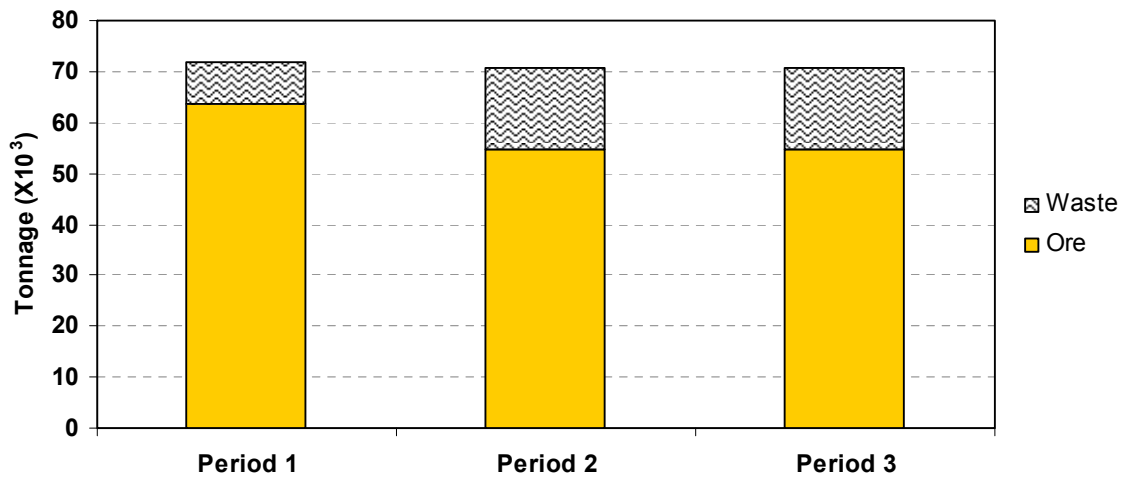
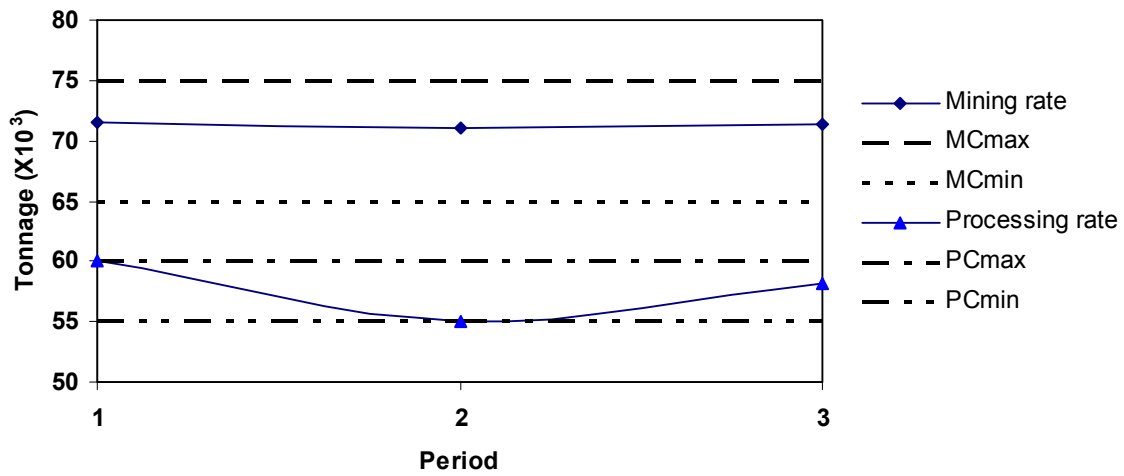**Fig 9.** Amount of ore and waste in each period

Fig 10. Relationship between PCmax, PCmin, MCmax, MCmin and obtained solution

6. Conclusions

This paper was a general review of open pit mining scheduling problem definition. Several optimization methods have appeared in the literature, but among of those optimization techniques, mixed integer programming is recognized as having significant potential for optimizing production planning in open pit mines with the objective of maximizing the discounted cash flow. Review of previous studies about MIP shows in open pit mines with many numbers of block, modeling and formulation of production planning need too many binary variables and this makes it very difficult or impossible to solve with the current state of hardware and software.

A step by step guideline for using the Excel Solver for solving MIP models was documented in conjunction with an illustrative example. The results show that we can use the Excel Solver software for a bench by bench short-term production scheduling.

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