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A Heuristic Traditional MIP Solving Approach for Long Term Production Scheduling in Open Pit Mine

Vahid Rafiee and Omid Asghari
Department of Mining and Metallurgy Engineering, Amirkabir University of Technology,
P.O. Box 45875-4413, 424 Hafez Ave., Tehran, Iran

Abstract: The aim of this study is optimization of long term production scheduling by solving the traditional MIP formulation that the objective function and all of constrains are satisfied. The economic viability of the modern day mine is highly dependent upon careful planning and design. Appropriate planning and operation of large open pit mines are enormous and complex task. Optimization techniques can be successfully applied to resolve a number of important problems that arise in the planning and management of a mine. Optimization of long-term production planning needs correct selection of equipments and labor forces and reducing capital and operation costs. Mixed Integer Linear Programming (MILP) methods are used for optimizing production planning in open pit mines with objective of maximizing the total discounted net present value. But MIP formulation of the production scheduling in open pit mines, particularly in large open pit with many numbers of blocks needs too many variables causing it very difficult or impossible to solve. To over come this problem a new heuristic approach by reducing schedule period and applying primary guess is developed based on mixed integer linear programming to reduce the periods of planning and decrease the number of variable and the number of constraint needed in the formulation. The results of this method compared to existing methods shows the significant reduction of binary variable in MIP formulation and higher chance to obtain the optimal Net Present Value (NPV).

Key words: Optimization, long-term production scheduling, mixed integer linear programming, reducing schedule period, primary guess, net present value

INTRODUCTION

Planning and designing of large open pit mines are difficult and complex task. In last decade, number of important issues that arise in planning and designing of open pit mines introduced various optimization techniques have been used to solve the problem. Some of these issues are: ore-body modeling, grade and tonnage estimation, finding optimal pit limits, calculation of stable pit slope, determination of short term, intermediate and long term optimal production, selection and appropriate main and auxiliary equipment, maintenance and replacement policies, selection of suitable places for installation of crushers and ore dressing plant and appropriate location for allocation of waste material that must be removed during mine life operation.

Since 1980 various methods have been used for optimization of these group of mining problems (Caccetta, 2007). For example; LP and MIP (Caccetta and Hill, 2003; Ramazan and Dimitrakopoulos, 2003, 2004a, b), dynamic programming (Tolwinsky and Underwood, 1996), graph and net work theory (Fan *et al*., 2003) and simulation (Dimitrakopoulos, 2006; Sturgul and Li, 1997). In addition to several commercial software packages which can be use for optimization of mine planning and design; such as NPV Scheduler, Whittle 4-D and 4-X, etc. Among of these optimization techniques, mixed integer linear programming are recognized as having significant potential for optimizing production planning in large open pit mines with the objective of maximizing the total Net Present Value (NPV). The scheduling problem can be easily formulated as a mixed integer linear program. Typically, the constraints relate to the mining extraction sequence are; mining, milling and refining capacities; grades of mill feed and concentrates; stockpile-related restrictions; a range of logistics issues and various operational requirements such as minimum pit bottom width and maximum vertical depth. In addition, cut-off grade can be optimized by allowing the model to decide whether or not extracted ore is milled or treated as waste. However, in real applications the resulting formulation is

Corresponding Author: Vahid Rafiee, Department of Mining and Metallurgy Engineering,
Amirkabir University of Technology, P.O. Box 45875-4413, 424 Hafez Ave., Tehran, Iran

too large. In open pit mines with many numbers of blocks, modeling and formulation of production planning need too many binary variables making it very difficult or impossible to solve. Several heuristic approaches have appeared in the literature including methods based on Lagrangian relaxation (Caccetta, 2007), parameterization (Francois-Bongarcon and Guibal, 1984; Bastante *et al*., 2004); dynamic programming (Tolwinsky and Underwood, 1996); MILP (Chanda and Dagdelen, 2006; Caccetta and Hill, 2003; Ramazan and Dimitrakopoulos, 2004, a, b; Osanloo and Gholamnejad, 2007); simulated annealing and genetic algorithms (Clement and Vagenas, 2006; Pendharkar and Rodger, 2000; Denby *et al*., 1998), Fundamental Tree Algorithm (Ramazan, 2006) and horizon control (Rojas *et al*., 2007). All these approaches suffer from one or more of the following limitations:

- Most of them can not satisfy constraint of problem
- Most of them find only near optimum solution
- Only solve small problems

The difficulty in solving the MILPs that arise in mining is their size. An effective way of solving a large-scale problem is to partition the problem into a number of smaller problems that are easier to solve. In this study, new hermitic approach by reducing schedule period and using primary guess is applied. By applying this method, number of binary variables in MIP formulation is reduced and the search space to finding optimal solution is fined. Reducing schedule periods shows that how it can be applied in realistic situation. In our case the relaxed sub-problems are linear programming problems with some variables fixed. These sub-problems can easily be solved using a commercial linear programming package such as SOLVER. For showing the application in real mine, Sungun copper mine of Iran with more than one billion ton ore deposit is selected. The calculation procedure of periodic production schedule is shown and produced mining plans is drawn.

MIP FORMULATION FOR OPEN PIT LONG TERM PRODUCTION SCHEDULING

Each linear programming model includes objective function and constrains. The open pit mine production scheduling problem can be defined as specifying the sequence in which blocks should be removed from the mine to maximize the total discounted profit from the mine subject to a variety of physical and economic constraints. Typically, the constraints relate to the mining extraction sequence; mining, milling and refining capacities; grades of mill feed and concentrates; stockpile-related restrictions; a range of logistics issues and various operational requirements such as minimum pit bottom width and maximum vertical depth. The scheduling problem can be easily formulated as a Mixed Integer Linear Program (MILP).

The objective functions in traditional MIP formulations for open pit long term production scheduling can be maximize Net Present Value (NPV) or minimize risk of capital costs or maximize mine life. Constraints include: mining slope, grade blending, ore production and mining capacity etc.

The objective function: The objective function is a function that a optimal solution minimizes or maximizes it. depend on project targets the objective function is defined. In open pit scheduling the objective function can minimize the total cost or maximize the total cash flow. In our model the objective function maximize the net present value of mine in specific period.

$$\text{Total NPV} = \text{Maximize} \sum_{t=1}^{T} \sum_{i=1}^{n} V_i^t \times X_i^t \tag{1}$$

where, T is the maximum number of scheduling periods, N is the total number of blocks to be scheduled (in ultimate pit or in pushback), V_i^t is the NPV to be generated by mining block n in period t and X_i^t is a binary variable, equal to 1 if the block n is to be mined in period t, otherwise 0.

Grade blending constraints: One of most important problem in production planning is keeping steady ore grade for mill. For this, the grade of ore that send to mill should be define between two bound.

Upper bound constraints: The average grade of the material sent to the mill has to be less than or equal to a certain grade value, G_{max} for each period, t:

$$\sum_{n=1}^{N} (g_n - G_{max}) \times O_n \times X_n^t \leq 0 \tag{2}$$

where, g_n is the average grade of block n and O_n is the ore tonnage in block n.

Lower bound constraints: The average grade of the material sent to the mill has to be greater than or equal to a certain value, G_{min}, for each period, t:

$$\sum_{n=1}^{N} (g_n - G_{min}) \times O_n \times X_n^t \geq 0 \tag{3}$$

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.

$$\sum_{t=1}^{T} X_n^t = 1 \quad (4)$$

Generally, the orebody model contains many blocks and it is very difficult, or impossible, to generate a solution through MIP formulations if they are applied to the whole orebody model. Therefore, it is often necessary to consider only applying the formulations to the blocks within the ultimate pit limits and requiring all the blocks to be mined in one of the periods.

Processing capacity constraints

Upper bound: The total tons of ore processed cannot be more than the processing capacity (PC_{max}) in any period, (t):

$$\sum_{n=1}^{N} (O_n \times X_n^t) \le PC_{max} \quad (5)$$

Lower bound: The total tons of ore processed cannot be less than a certain amount (PC_{min}) in every period (t):

$$\sum_{n=1}^{N} (O_n \times X_n^t) \ge PC_{min} \quad (6)$$

Mining capacity: The total amount of material (waste and ore) to be mined cannot be more than the total available equipment capacity (PC_{max}) for each period (t):

$$\sum_{n=1}^{N} (O_n + W_n) \times X_n^t \le MC_{max} \quad (7)$$

where, W_n is the tonnage of waste material within block n.

A lower bound may need to be implemented if it is important for the MIP model to produce balanced waste production throughout the periods are:

$$\sum_{n=1}^{N} (O_n + W_n) \times X_n^t \ge MC_{min} \quad (8)$$

Slope constraints: All the overlying blocks that must be mined before mining a target block must be determined. This can be implemented through one or more cone templates representing the required wall slopes of the open pit mine. There are two ways of implementing these constraints:

- Using one constraint for each block per period:

$$YX_k^t - \sum_{y=1}^{Y} \sum_{\tau=1}^{t} X_1^\tau \le 0 \quad t = 1, 2, 3, \ldots, T \quad (9)$$

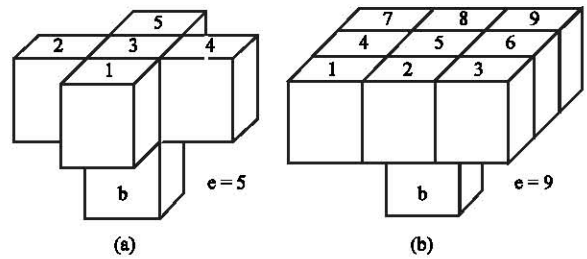


Fig. 1: Slope constraints in 3D shape, (a) y = 5 and (b) y = 9

where, k is the index of a block considered for excavation in period t, Y is the total number of blocks overlying block k.

- Using Y-constraints for each block per period:

$$X_k^t - \sum_{\tau=1}^{t} X_y^\tau \le 0 \quad y = 1, 2, \ldots, Y \text{ and } t = 1, 2, \ldots, T \quad (10)$$

For removing each block, there are tow models. For example, to removing block b, 5 or 9 block over it should be removed (Fig. 1).

CASE STUDY: SUNGUN COPPER MINE

To validate of model, testing the model in real cases is necessary. For this, Sungun copper mine to find the efficiency of model is selected.

History of Sungun copper mine: The Sungun copper mine is managed by the Sungun Copper Project (SCP) and is located in the East Azarbaijan Province in the North West of Iran. Historical documents confirm a long and ancient mining tradition in this region. In 1987 geophysical and geochemical investigations confirmed the high levels of copper and molybdenum in the Sungun copper deposit. NICICO initiated a comprehensive exploration program in 1991. A pre-feasibility study made in 1992 incorporating almost 8900 m of diamond drilling and some 1200 m tunneling. After continued exploration, the first feasibility study was completed in 1996. The resource model incorporated approximately 45000 m of diamond drilling and 2100 m tunnels which indicated 700 Mt of ore at a grade of 0.63% Cu using a 0.3% Cu cut-off grade. The initial mine planning made by the classic method was based on a production profile of 7 Mt year^{-1} in the initial years, rising to 14 Mt year^{-1} in year 7 until year 27. In accordance with this scenario the total ore production and overall stripping ratio were 340 Mt and 2.1, respectively. There has been an estimated 150 Mt pre-stripping over

5 years and an annual mining rate of 44 Mt, producing 7 Mt of ore in the first 6 years of production. No optimization study was carried out and hence there was a huge amount of pre-stripping and high capital investment on plant and equipment. In 2000 the Sungun Copper Project (SCP) reviews the feasibility study using pit optimization methods. They revised the resource model by incorporating further drilling information as well as updated geological interpretations. The mine planning based on the original ore production profile (7 Mt year^{-1} in the initial years rising to 14 Mt year^{-1} in year 7) and that using pit optimization method, which indicated a large number of improvements, both technical and economic. The recent pit optimization has been performed focusing on; final pit limit, life of mine, pushback combination and mining schedule. The results showed a lower stripping ratio for early years of production which can hopefully lower CAPEX and OPEX for Sungun mine in future plans. (Farshchi *et al.*, 2005).

Geological settings: The orebody surrounding area is located within Alpine-Himalayan metalogenic belt. Sub-volcanic rocks have intruded into cretaceous limestone and andesite volcanics. Mineralization in monzonite and volcanic host rocks is disseminated and stockworks in nature. Characteristic vertical zoning of porphyry deposits as Leached, Supergene, Hypogene and Skarn zones, have been recognized as being significant in regard to grade. Three ages of dykes injected into the orebody which are considered waste. The blocks are encoded with these codes to enable lithological constraints to be applied in interpolation of grades. A block model was constructed with the following dimensions, 25×25×12.5 m. This corresponds to one quarter the average borehole spacing and the planned bench height. With sub-blocking this also allows adequate definition of lithological boundaries minimizing volumetric errors. The resource model incorporates approximately 63000 m of diamond drilling and 3400 m tunnels which contains 796 Mt of ore at a grade of 0.6% Cu. In order to improve the resource model a supplementary drilling program is currently being undertaken at Sungun.

Economic block model: Base on optimization, to maximize total NPV of mine, pit design problem is to find the set of blocks that have maximum value. So the economic value of blocks is more important. Mine stability and extraction constraint is also considerable.

If economic value of blocks is calculated wrong, then optimal design is also calculated wrong. Therefore in calculation of economic value of blocks more preciseness is necessary. The economic value of a block is calculated as follow:

$$BEV = GV - TC \tag{11}$$

$$GV = RR \times P - P_{by\text{-}product} \tag{12}$$

$$RR = RM - RS - RL \tag{13}$$

$$RM = CC \times Y \tag{14}$$

$$CC = g \times 1000 \tag{15}$$

$$RS = RM - SL \tag{16}$$

$$SL = \frac{\text{Smelt loss}}{r_1} \tag{17}$$

$$RL = \frac{\text{Refine loss}}{r_2} \tag{18}$$

$$r_1 = \frac{\text{Contained copper (g) in a ton of concentre}}{\text{Recovered copper (g) in a ton of ore}} \tag{19}$$

$$r_2 = \frac{\text{Refined copper (g) in a ton of meltedcopper}}{\text{Recovered copper (g) in a ton of ore}} \tag{20}$$

$$TC = OC + A \text{ and } D + TRS \tag{21}$$

$$OC = MC + PC + GC \tag{22}$$

$$TRS = CT + SC + BT + RC + S \text{ and } D + GP \tag{23}$$

where, BEV is the block economic value ($), GV is the groove value ($), TC is the total cost ($/ton ore), RR is the copper removed by the refinery (kg ton^{-1} ore), P is the price of copper ($), $P_{by\text{-}product}$ is the additive value of valuable metal ($/kg copper), RM is the copper removed by the mill (kg), RS is the copper removed by the smelter (kg), RL is the refining loss (kg ton^{-1} ore), SL is the smelting loss (kg ton^{-1} ore), y is the recovery in processing plant (%), CC is the contained copper in ore (kg), g is the grade of block (%), r_1 is the concentration ratio, r_2 is the none refining ratio, OC is the operation cost ($ ton^{-1} rock), A and D is the amortization and depreciation cost ($ ton^{-1} rock), TRS is the treatment, refining and selling costs ($ ton^{-1} concentrate), MC is the mining cost ($ ton^{-1} rock), PC is the processing cost ($ ton^{-1} ore), GC is the general cost ($ ton^{-1} rock), CT is the concentrate transport ($ ton^{-1} concentrate), SC is smelting cost ($ ton^{-1} concentrate), BT is blister transport ($ ton^{-1} none refined), RC is the refining cost ($ ton^{-1} none refined copper), S and D is the selling and delivery cost ($ kg^{-1} copper), GP is the general plant cost of ($ kg^{-1} copper).

Copper price: One of the most difficult problems in pit design and production planning is estimation of metal price in future. Solving of this problem is possible in three ways:

- Current pricing method
- Trend method
- Econometric Method

The most simple and also the worst method is current pricing method. Because the price of most metals is periodly. However, if the estimator of this method is being in maximum or minimum of the period, the result is far from reality and may the profitable project is shown unprofitable project.

The trend method is almost primary proper method. In this method following notes should be considerate:

- Trend Analysis should contain several period
- In Trend analysis sensitivity analysis should be done
- Correlation between price and time generally is not depended correlation. The trendline is cumulative effect of all market and production condition. When these condition change, trend analysis change

Econometric method of estimating price is modeling of supply and demand of costly element of one or several product. These models can be so complex. The most advantage of these models is ability to forecasting price in short tem periods.

However, we use trend method to determine economic block model.

Recoveries: It is necessary to determine the copper content in a block and the recovery rates for each different ore type in all mining and processing (concentrating, smelting and refining) operations. Current assumptions are a mining recovery of 90% with processing recoveries of 77 and 82% for Supergene and Hhypogene ore, respectively.

Costs: The costs are an estimate based on a review of available data from other operations in NICICO's projects. The unit mining costs used for the purpose of this optimization were developed using the most up to date details available from the Sarcheshme copper mine.

Mineral processing and metallurgical costs used in the optimization study were derived from the financial model in the latest version of Sungun feasibility study.

Discount rate: The straight line discount rate used by most international commercial banks will vary between 8% (now probably around 4 and 5%) for a stable country with a stable currency and up to 18% for the converse. In this study a discount rate of 10% is assumed which seems reasonable in the Sungun circumstances.

So, that the geological model converted to economic model and then the ultimate pit is defined by well known 3D Lerch and Grossman technique. The ultimate pit specification of mine is shown in Table 1 and Fig. 1a.

Table 1: Ultimate pit specification of Sungun copper mine

No. of blocks	115,203
Ore (million ton)	702
Waste (million ton)	1,328
Stripping ratio	1.89
Mining costs (million dollars)	2,537
Processing costs (million dollars)	1,960
Profit (million dollars)	5,558
Revenue (million dollars)	10,057
Mine life (years)	50
Supergene economic cutoff grade (%)	0.1229
Hypogene economic cutoff grade (%)	0.1148

Table 2: Pushbacks specification of Sungun copper mine

	Pushback				
	1	2	3	4	5
No. of blocks	8608	13964	18197	27327	46907
Ore (million ton)	59	121	146	178	195
Waste (million ton)	77	116	172	308	649
Stripping ratio	1.31	0.96	1.17	1.73	3.32
Mining costs (million dollars)	170	298	399	608	1,056
Processing costs (million dollars)	164	340	410	498	546
Profit (million dollars)	856	1,069	1,117	1,234	1,281
NPV (million dollars)	690	508	237	75	0.928

Pushbacks design: After ultimate pit determination, pushbacks should be defined. The targets of defining pushbacks are:

- Create smallest nested pits of scheduling
- Satisfaction of minimum allowed distance between pushback boundaries
- Satisfaction of minimum bottom width of each pushback
- NPV of each pushback must not be negative
- Maximize total NPV for all pushbacks

So based on these consideration 5 pushbacks are generated for Sungun copper mine. The pushbacks specification is shown in Table 2 and Fig. 1b.

MIP APPLICATION IN SUNGUN COPPER MINE

The main goals in MIP application are:

- Mine's plan dispersal must not be observe
- Partial or fractional mining blocks do not create
- Satisfaction of All model constraints (feasible and practical schedule)
- The solving time must be acceptable

Table 3: The MIP model specification of Sungun copper mine

No. of blocks	8608
No. of periods	7
No. of binary variable	60256
No. of grade blending constraints	7
No. of reserve constraints	8608
No. of processing capacity constraints	7
No. of mining capacity constraints	7
No. of slope constraints	60256

Table 4: The sub-problems' specification

	No. of blocks	No. of binary variables	No. of grade blending constraints	No. of reserve constraints	No. of processing capacity constraints	No. of mining capacity constraints	No. of slope constraints	Solving time (min)
Sub-problem 1	8608	17216	2	8608	2	2	17216	15
Sub-problem 2	7592	15184	2	7592	2	2	15184	48
Sub-problem 3	6535	13070	2	6535	2	2	13070	42
Sub-problem 4	5464	10928	2	5464	2	2	10928	31
Sub-problem 5	4429	8858	2	4429	2	2	8858	16
Sub-problem 6	3348	6696	2	3348	2	2	6696	5
Sub-problem 7	2252	4504	2	2252	2	2	4504	5

Table 5: First pushback of Sungun copper mine scheduling

Years	NPV (million $)	Ore (million ton)	Rock (million ton)	Average grade	Stripping ratio
1	67.09	4.99	15.27	0.84	2.05
2	65.93	6.99	16.99	0.67	1.43
3	76.04	6.99	16.97	0.82	1.42
4	71.66	6.42	16.99	0.85	1.64
5	98.95	6.99	16.45	1.14	1.35
6	86.24	6.99	16.94	1.05	1.42
7	113.34	13.95	25.50	0.79	0.83
Total	579.25	53.36	125.13	0.87	1.34

All solving process is done by Microsoft Excel 2007 and for solving the MIP formulation, SOLVER 7 (Frontline Systems Manual, 2006) is applied.

The target of production scheduling in Sungun copper mine are:

- Sending 6, 7 and 14 million ton ore to plant in year of one, year of two until six and year of seven until end of mine life, respectively
- Minimum average grade of ore must be 0.6%
- Balancing stripping ratio according to available equipment

As shown in Table 3, the model is really large and complex to solve. It is found that regular solving algorithm is not able to solve the model in primary runs. The reasons are:

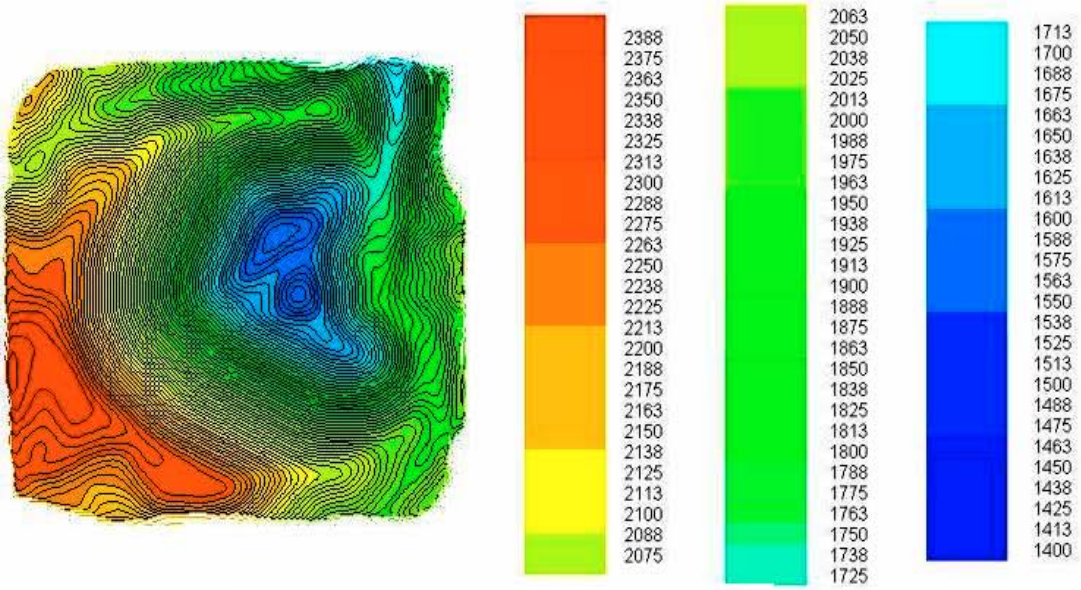
- Too many binary variables that have increased by No. of mining periods
- Too many slope constraints that extend in 7 periods
- Grade blending, processing and mining capacity constraints that extend in 7 periods
- There are not any primary guess for solving. Create a primary guess can help solving process considerably. It is the main reason for complexity of solving the problem

In accordance with above items, the following methods are considered:

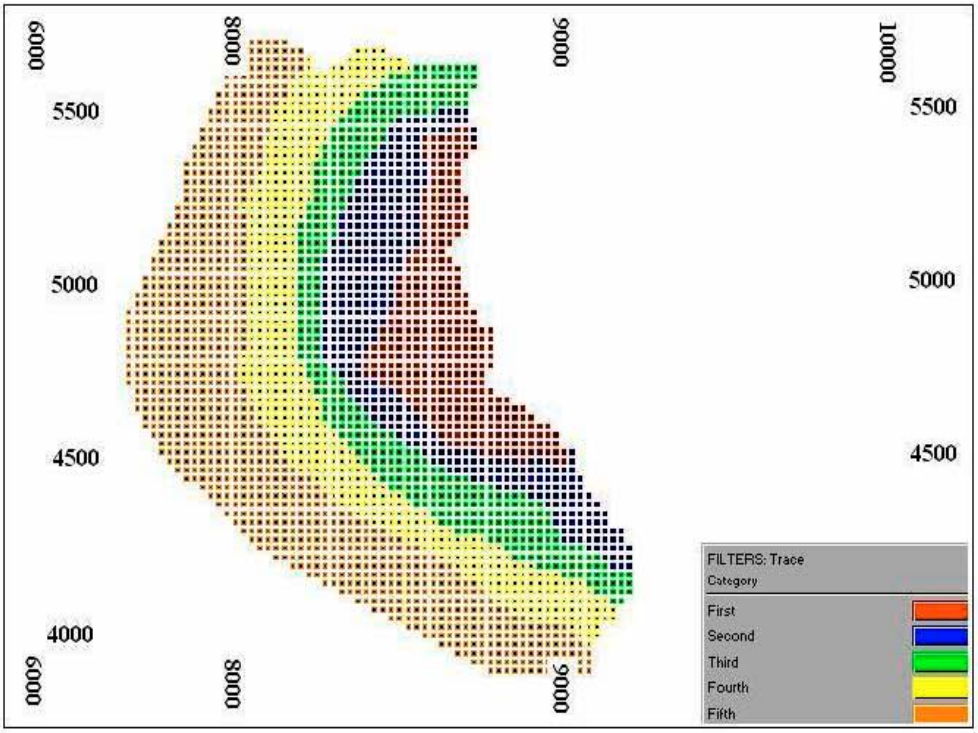
- There is no reason that 7 periods cab be solved at a same time. The model can solve for 2 periods (current year and other periods). So, No. of binary variables and constraints reduce to N/T−1 where, N is No. of binary variables and T is No. of periods. So, we convert the major problem to 7 sub-problems without the main elements change (Table 4)
- Import a primary guess in model. Primary guess fines the search space and helps to get an optimum solution
- Therefore, MIP formulations solved in 150 min (2 h and 30 min) and it's so hopefully. It can be seen the results in Table 5 and Fig. 2-4 and found that all of constraints and targets are satisfied.

The results of solving the model are shown in Table 4, 5 and Fig. 3-7 and the following results are obtain:

- In solving process, we could define the strategy that reduce binary variables and constraint that comes from them. The solving time is 162 min and it is very hopefully to develop the model with more constrains and parameters



(a)



(b)

Fig. 2: (a) Ultimate pit of Sungun copper mine and (b) Pushbacks of Sungun copper mine

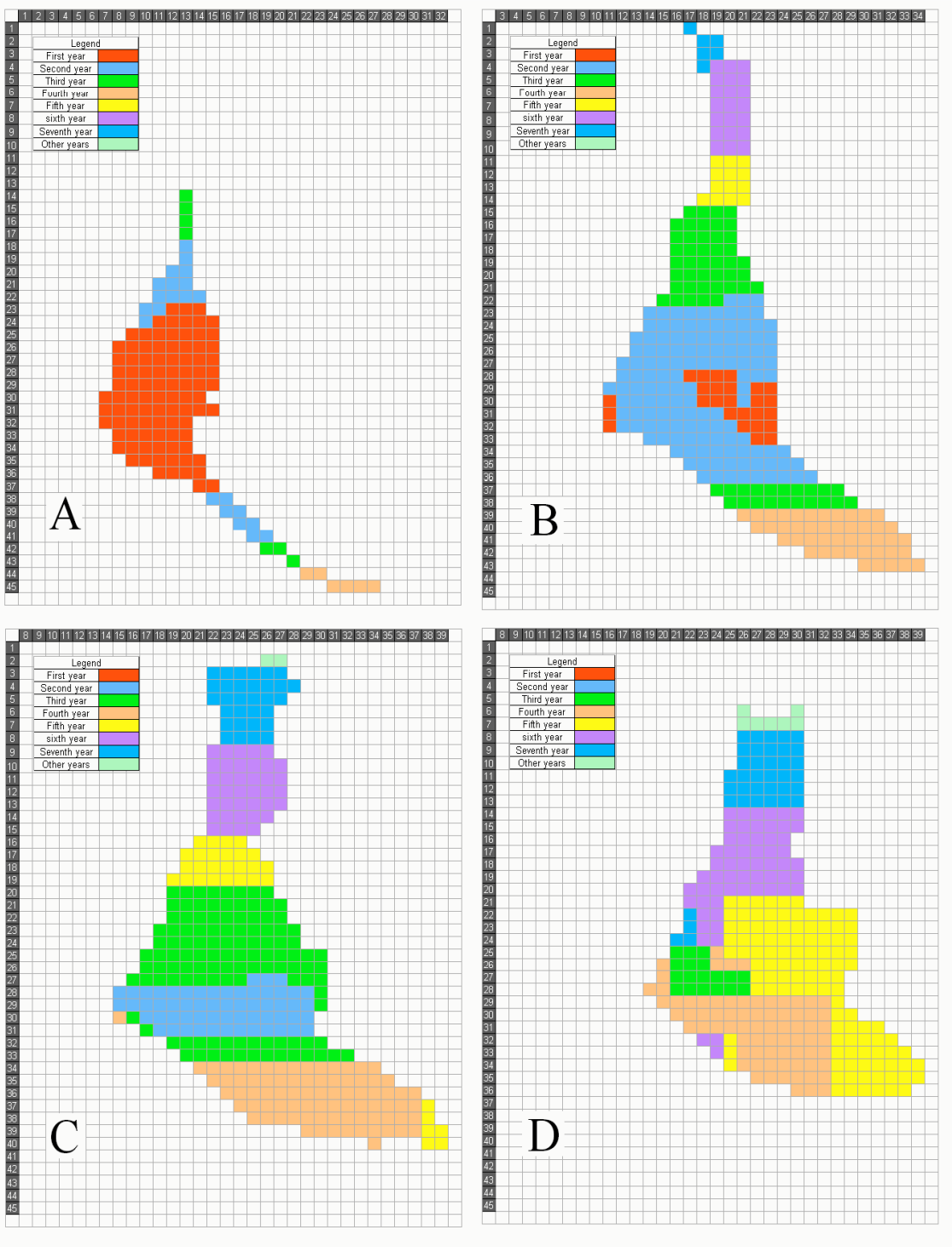


Fig. 3: The practical plans in different levels

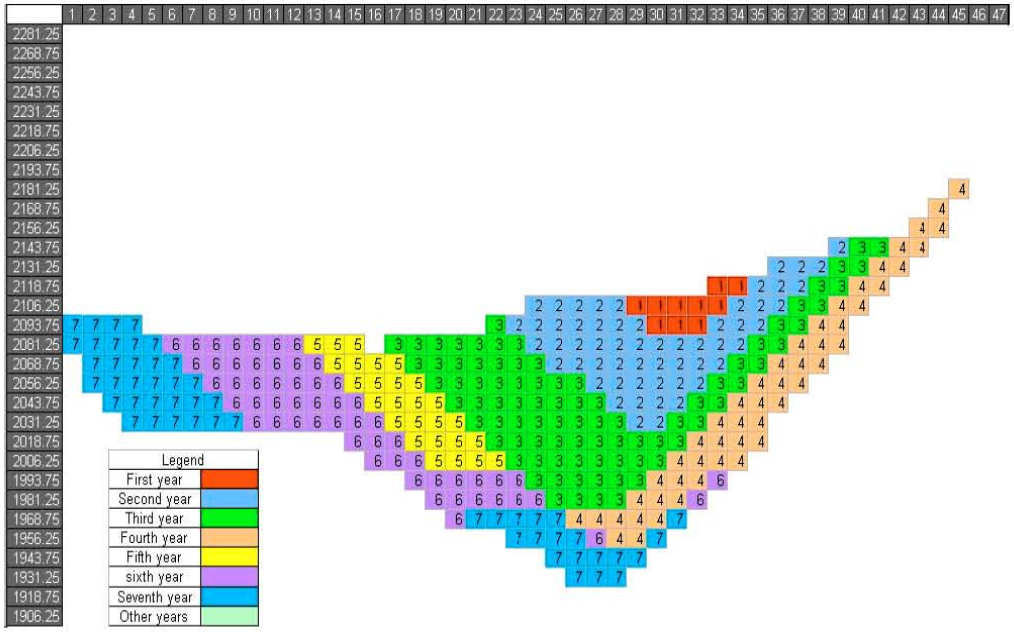


Fig. 4: North-South section

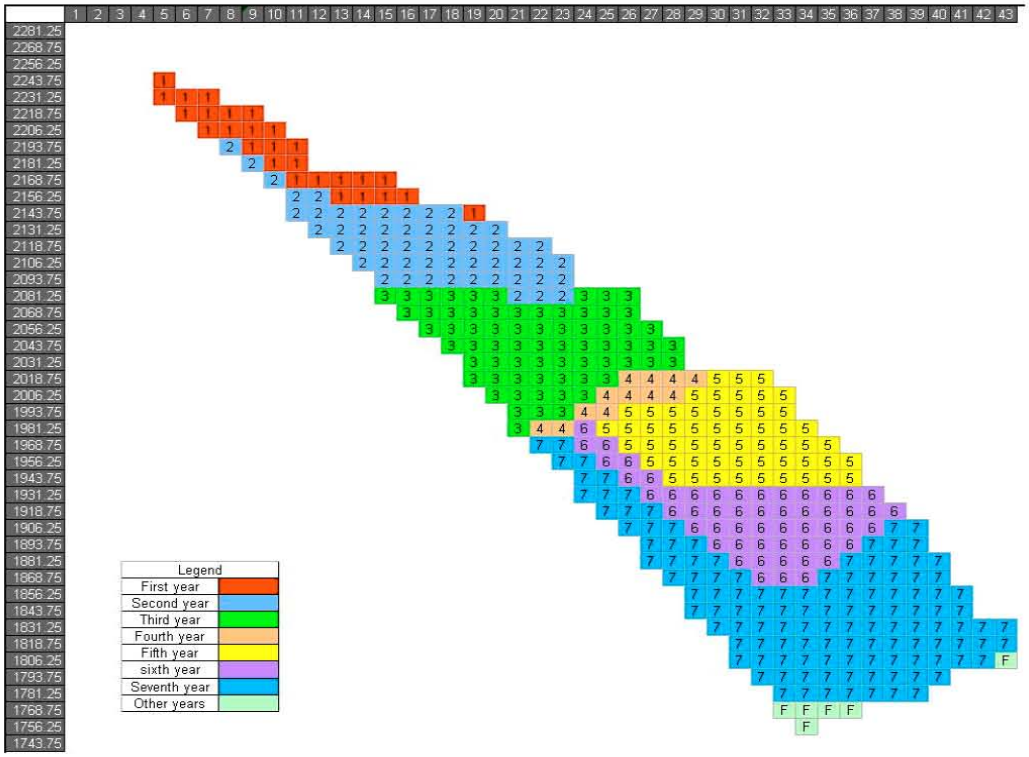


Fig. 5: East-West section

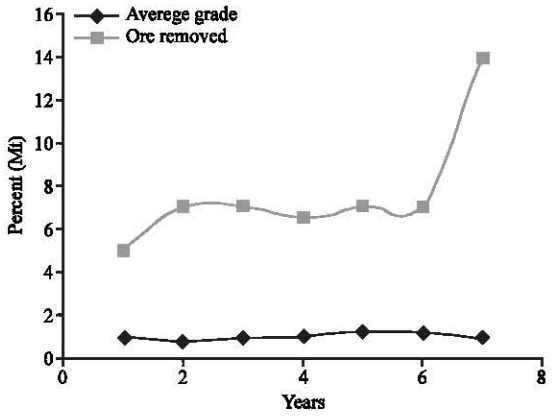


Fig. 6: Relation between remove of ore and average grade and their control

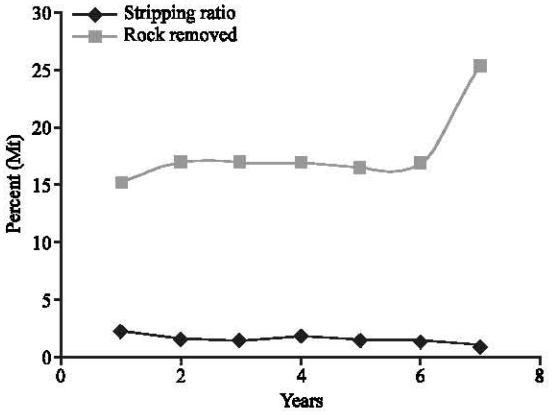


Fig. 7: Relation between remove of rock and stripping ratio and their control

- The model solves completely, the slop constrain is satisfied and practical plans to mining is obtained
- Rock removal is not more than mining capacity and the stripping ration has been controlled
- Ore tonnage that has been removed from mine is base on mill request and its grade has been controlled
- We get the maximum NPV in each period and in total periods

CONCLUSION

MIP models are one of the most popular algorithms for open pit mine scheduling, but because of too many binary variables involved in the formulation, the solving of them is difficult and complex. The main obstacle in solving the long term scheduling problems is slope constraint. It extremely increases number of constraint in problem. The major element of unsolving such problem is not binary variables, rather too many slope constraints that obtained from binary variable. However, by reducing scheduling period and importing primary guess, the problem can be solve with less binary variables. This method applied for first pushback of Sungun copper mine and calculation shows the total NPV of 579.25 million dollars. Extracted plans show in some area, because of lack of access, mining by this method is not possible. For over coming this, modifying the model is necessary.

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