Simultaneous Optimization of Underground Mine Layout and Production Scheduling In Sublevel Stoping Method

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Abstract: As the demand for mineral resources increases, the need to underground mining is promoted and due to technological advances, deeper deposits with lower grade mineralization are becoming valuable. In underground operations, it is common practice that each area is planned individually. As these techniques often ignore how designing and planning one section can affect other sections, , optimum individual planning fails to provide an overall optimum design. In recent years, there has been a growing interest in simultaneous optimization that may assist with integrating different areas of the mine planning process and providing more profitable mines plans. In this paper, a mathematical IP model has been developed that simultaneously optimizes stope layout designs and production schedules for sublevel stoping (SLS) iron ore operations, and it is demonstrated that an integrated scheduling method can produce the globally optimal scheduling result by taking into account all interactions that occur across the stope layout optimization and scheduling. In this case, the application of the optimal integrated scheduling approach increases final NPV by 16 percent in comparison with the isolated approach.

Keywords: Integrated optimization, stope layout, production scheduling.

1- INTRODUCTION

Nowadays, as the need for mineral resources increases, deeper deposits are becoming more valuable and the demand for underground mine design and planning processes is growing (Copland and Nehring 2016). Mathematical algorithms and optimization tools developed and implemented in underground mining have received more attention in the last few decades (Topal and Sens 2010). Stope layout optimization and production scheduling are the most important activities in underground mine planning stage that have attracted increasing attention in recent years, as the optimal stope layout impacts the maximization of the value in the subsequent step (stope production scheduling). According to recent studies, stope layout algorithms struggle to produce truly optimal results and scheduling is hindered by excessive solution times (Little, Knights, and Topal 2013).

According to the existing literature, it can be found that it is a common practice for the underground mine plans to be created sequentially in a way that each area is planned individually, while the solution of the first problem forms the input to the following problem, until a mine plan is completed (Little, Knights, and Topal 2013). By undertaking experiences on 15 different mining operation over six years, Whittle concluded that optimizing the parts of the mining value chain in isolation is not acceptable; mining operations must be made based on integrated considerations of their consequences (Whittle 2010). In this regard, Nehring et al. (2010; 2012) integrated the optimization of short-term production plans and long-term plans and short-term plans with medium-term plans, respectively, in a single mathematical model. They concluded that if two scheduling phases of mine production are carried out in isolation, only a

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local optimum can be achieved. The globally optimal solution, however, can be achieved by integrating scheduling phases and simultaneously, accounting for the interactions between two scheduling phases (Nehring et al. 2010a, Nehring et al. 2012)

Little et al developed an integrated optimization of stope design and production scheduling decisions, stating that more profitable results will be provided by taking into account the interactions and influences between each underground mine planning area during optimization, and a comprehensive view of the operation is created (Little, Knights, and Topal 2013). Little and Topal presented four strategies to reduce the number of variables which successfully applied to simultaneously optimize stope layouts and production schedules for a sublevel stopping operation, including: defining each stope as opposed to each block; removing unprofitable stopes; using concise constraints; and employing efficient decision variables (Little and Topal 2011). In further research, Copland and Nehring improved the model of integrated optimization for shorter solution times. The authors successfully reduced solution time in two ways: structuring data, and employing a summary variable (Copland and Nehring 2016). This paper presents a mathematical IP model that simultaneously optimizes stope layout designs and production schedules for SLS iron ore operations, which has demonstrated the benefits of using integrated optimization approach, considering NPV maximization as an objective.

2- METHODS

The issue of planning stope layout and production in underground mines can be formulated using available operations, research techniques, and computing power. In this regards, a mathematical model was developed that uses IP techniques to generate long-term mine plans, focusing on optimizing stope layouts and production schedules for an SLS operation. IP is a common mathematical programming tool used for underground mine production scheduling, since it has the ability to handle multi-constrained problems, providing a multi-period production. The model used in this paper is based on a model developed by Trout (1995) and then revised by Nehring (2007) and seeks to maximize project NPV subject to numerous operational constraints. Production is modelled according to four separate phases, including two extractions phase, one void, and one backfill phase (Trout 1995, Nehring and Topal 2007). The model is defined as follows:

Subscript notation:

s	Each stope is named by the location of the first and last blocks within the stope.
t	schedule time period: $t = 1, 2, 3, \ldots, T$

Sets:

b_s	set of all stopes that share common blocks with stope s
j_s	set of all stopes that are adjacent to stope s
o_s	set of all stopes which should be offset from stope s
e_s	set of all stopes which have practical extraction levels with stope s
tp_t	set of time periods including all time periods up to and the current period t

Parameters:

Gs	Ore grade (%) for stope s
R	Metallurgical recovery (%)
M_s	Extraction tonnage for stope s
ρ	Density of backfill
vs	Backfill volume for stope s
PVt	Present value discount factor applied to time period t
FCs	Cash flow generated by stope s
Lt وUt	Minimum and maximum contained metal tonnage target in time period t
BF	Backfill supply limit in time period t
Q_s	Ore handling tonnage limit for time period t

Decision variables:

e_{st} 1 if extraction from stope s is scheduled in time period t
0 otherwise

Objective function:

$$f = Max[\sum_{s=1}^{S}\sum_{t=1}^{T} PV_t \,.\, FC_S . e_{st}] \qquad (1)$$

Subject to:

$$\sum_{t} e_{st} + \sum_{t} e_{s\prime t} \leq 1 \qquad \forall s|s' \in o_s \qquad (2)$$

$$\sum_{t} e_{st} + \sum_{t} e_{s\prime t} \leq 1 \qquad \forall s|s' \in b_s \qquad (3)$$

$$\sum_{t} e_{st} + \sum_{t} e_{s\prime t} \leq 1 \qquad \forall s|s' \in e_s \qquad (4)$$

$$e_{st} + e_{s\prime t} \leq 1 \qquad \forall s|s' \in j_s \qquad (5)$$

$$\sum_{t\prime \in tpt} e_{St\prime} + \sum_{S\prime \in j_s} e_{S\prime t} \leq 2 \qquad \forall s,t \qquad (6)$$

$$\sum_{t=1}^{T} M_s \,.\, e_{s,t} = Q_s \qquad \forall t \qquad (7)$$

$$\sum_{s=1}^{S} v_s . e_{st} \leq BF \qquad \forall t \qquad (8)$$

$$\sum_{s=1}^{S} G_s . R . M_s . e_{st} \leq U_t \qquad \forall t \qquad (9)$$

$$\sum_{s=1}^{S} G_s . R . M_s . e_{st} \geq L_t \qquad \forall t \qquad (10)$$

$$e_{st} \text{ and } e_{s\prime t} = binary\ ineger \qquad (11)$$

In equation 1, the objective function seeks to maximize NPV. Constraint (2) prevents all horizontally offsets stopes of the same size that lies directly above another, and prevents vertical boundaries between backfilled stopes, which results in the failure of backfill material. Constraint (3) ensures that among all stopes sharing at least one block, only one stope is allowed to be produced. It also ensures that an individual stope cannot be in more than one phase during any time period. Constraint (4) ensures practical drawpoint levels are established by preventing the selection of adjacent stopes with not sharing common drawpoints levels. Constraint (5) prevents the simultaneous production of adjacent stopes. Constraint (6) limits any form of production to just one adjacent stope after backfilling has been completed in that stope. Constraint (7) ensures the quantity of ore extracted over any time period is restricted by the capacity of the mining operation handling system. Constraint (8) enforces the quantity of backfill supply into the mine is limited to a predetermined value. Constraint (9) and (10) ensure that the contained metal tonnage lies between an upper and lower limit in any time period the stope is in extraction, which result in reducing grade fluctuations of the feed received by plant. Constraint (11) enforces non-negativity and integrity, as appropriate.

3- FINDINGS AND ARGUMENT

An integer programming model is proposed that allows both integrated and isolated optimization. Both approaches were separately applied to a block model. Optimization was done using the isolated model's formulation and then simultaneous optimization of stope layouts and production schedules using the formulation of the proposed model. Two models were generated under the same constraints and parameters. Two different models were solved using a mathematical solver package CPLEX 12.6 and were applied to a hypothetical iron deposit of SLS operations. Finally, the results of these two models were compared. The hypothetical iron deposit containing 1,453 blocks, 772 of which were ore blocks. Stope sizes were considered to be 30m*30m*30m, thus1,390 stopes existed within the block model bounds. The capacity of ore production in each period was140,000 t. The mill feed head grade requirement must not exceed plant specifications of 80,000 kg per period, but must also be higher than 50,000 kg per period. Backfill availability per time period was limited to 30,000 m^3, assuming a backfill density of 2.05 t/m^3. Ore and waste density were assumed to be 5.013, and 3 t/m^3, , respectively. Variable costs, which are normally quoted in $/unit, were therefore incurred throughout the operation of each activity. Extraction and backfill variable costs were also assumed to be 15 $/t and 10 $/t, respectively. Fixed costs, however, were incurred at the start of each phase. The assumed values for1,fixed costs of extraction and backfilling were 200,000 and 1,050,000 $/stope. Considering an average iron price of 40 $/t, and an average recovery factor of 95%, revenues for each stope were calculated. Undiscounted values for each stope were then found. A discount factor of 10 percent per annum was applied.

Since the number of binary decision variables in the model was high, directly solving full optimization problem would take a lot of time. To tackle this problem, four solution time reduction strategies were employed including pre-processing data, formulating concise constraints, using decision variables efficiently, and natural sequence theory (Little and Topal 2011). In the first stage, using the isolated optimization approach, stope layout was determined to maximize economic value; then the selected layout was scheduled for maximizing NPV. Therefore the constraints described by equations 2, 3 and 7 were applied to generate the stope layouts. Once stope layouts were selected, all constraints in the model were applied to schedule when each stope has to be produced within the specified time period. As can be seen in figure 1 and Table 1, results showed that 11 stopes were selected in the first step, and in the second step, 10 out of 11 stopes were scheduled.. The NPV provided by this model was 4,597,031 $. In the next stage, stope layouts and production schedules were optimized simultaneously, considering maximum NPV as the objective function. The NPV obtained for this example was 5,334,256 $ which represents a 16.03 percent improvement on NPV.

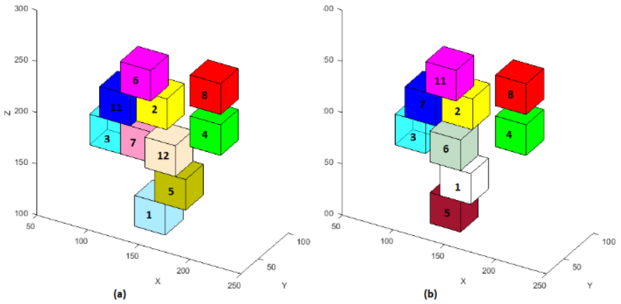

Figure 1. Stopes selected by each optimization models with their respective production start times: (a) isolated model; (b) integrated model.

TABLE I. STOPES SELECTED BY EACH OPTIMIZATION APPROACH

Isolated optimization		**Simultaneous optimization (maximum NPV)**	
Selected stopes (start block)	**Scheduling stopes(start time period)**	**Scheduling stopes (start time period)**	**Scheduling stopes(start time period)**
Stope 6 (90,40,170) Stope 17 (100,40,200) Stope 43 (120,40,170) Stope 49 (120,40,230) Stope 64 (130,30,140) Stope 91 (130,50,200) Stope 98 (140,30,110) Stope 136 (150,30,170) Stope 152 (160, 30, 40) Stope 188 (200,20,210) Stope 192(200,20,250)	Stope 6 (3) Stope 17 (11) Stope 43 (7) Stope 49 (6) Stope 91 (2) Stope 98 (1) Stope 136 (12) Stope 152 (5) Stope 188 (4) Stope 192(8)	Stope 6 (90,40,170) Stope 17 (100,40,200) Stope 49 (120,40,230) Stope 61 (130,30,110) Stope 67 (130,30,170) Stope 91 (130,50,200) Stope101 (140,30,140) Stope 188 (200,20,210) Stope 192(200,20,250)	Stope 6 (3) Stope 17 (7) Stope 49 (11) Stope 61 (5) Stope 67 (6) Stope 91 (2) Stope101 (1) Stope 188 (4) Stope 192(8)

4- CONCLUSIONS

Underground mine design and planning rely predominately on manual empirical techniques whereby each area is planed individually. These techniques provide locally optimal solutions since they ignore the interactive effects different underground areas while designing and planning. In recent years, there has been a growing interest in simultaneous optimization that would allow a holistic approach towards planning decisions thus providing more profitable mines plans than currently possible, and, therefore, capable of managing issues between mine planning areas. In this research, a mathematical IP model was formulated for simultaneous optimization of stope layout designs and production schedules in SLS operations, which demonstrated the benefits of using a multi-objective optimization. Consequently, underground mine scheduling that is carried out manually, cannot guarantee optimality, since it is not capable of satisfying the compounding complexities of all scheduling rules, when combined with several competing objectives. The application of the optimal integrated scheduling approach increased final NPV by 16 percent in comparison with the isolated approach.

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