Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/13378
DOI URL: http://dx.doi.org/10.21474/IJAR01/13378

RESEARCH ARTICLE

A FAST DYNAMIC PROGRAMMING ALGORITHM FOR STOPE BOUNDARY LAYOUT FOR UNDERGROUND MINE

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Manuscript Info

Manuscript History
Received: 05 July 2021
Final Accepted: 09 August 2021
Published: September 2021

Key words:-
Algorithm, Optimal, Stope, Dynamic Programming, Ore Body

Abstract

We developed an efficient algorithm that generates optimal stope layout for an underground mine. After a mining site has been identified and an exploration has been done, the data gathered is analysed and a modelling technique is applied to produce an ore body. The ore body is divided into thousands of mining blocks in three dimensions. The blocks are assigned values per tonne. The miners desire a stope layout which maximizes the mine value. In this paper, we present a fast algorithm that generates the stope layout efficiently without violating the physical constraints.

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Introduction:-

Techniques for mining optimization have being in existence since early 1960's. A variety of algorithms and methodologies have changed the way surface mine is designed and scheduled. However, underground mine optimisation has attracted more attention in the last 10 to 15 years with focus on three main areas: optimisation of development and infrastructure, Optimisation of stope boundaries and optimisation of production schedule using predefined stope boundaries [8]. The research on development optimisation mainly focused on cost minimisation. In other words, it optimizes a cost function over space of feasible solutions in underground. The proposed analytical solution for the problem is based on network optimisation model. In this model, the given draw points and surface portal correspond to fixed nodes of the network and known as terminals. The ramp in the mine represented by links in the network and junctions at which three or more ramps meet are represented by variable nodes in the model and known as Steiner points. Construction and haulage costs of each link in the network are modelled andsolved. Other than main assumptions within the model, the other main shortcoming of the research so far is not being able to consider the grade distributions of the ore body and not being able to put the development in high grade ore zone first for net present value (NPV) maximization [1, 3, 5]. Limited number of studies has been carried out on stope scheduling. Trout formulated a Mixed-Integer Programming (MIP) model for scheduling sublevel stopping operation. The model was applied to a representative data set which came from Mount Isa, containing 55 stopes. Although the generated schedule was not optimal, it showed some merit of employing MIP techniques over manual techniques for improved scheduling and sequencing of stopes [9]. Nehring and Topal [7] advanced the model in [9] by formulating a new constraint to limit multiple fill mass exposures without violating other constraints to make the model more applicable. Small case study demonstrates the benefits of using MIP for generating production schedules over a common manual method of selecting production from the next highest available cash flow stope. Little et al. revised the same model to reduce the number of variables and thereby reduce the solution time. The proposed model can reduce the number of variables by 80% by utilising natural sequencing and natural commencement between phases.The proposed model allows to solve the scheduling problem for large scale stoppingoperations [6].While several studies have beenconducted on the underground development and stope

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scheduling optimisation, this paper primarily focuses on stope boundary optimisation.On some occasions, each stope may individually be economical, but the overall envelope may not [1, 2]. Ataee-pour [3] introduced heuristic approach called “Maximum Neighbourhood Value (MNV)” for stope boundary optimisation. The method works in a

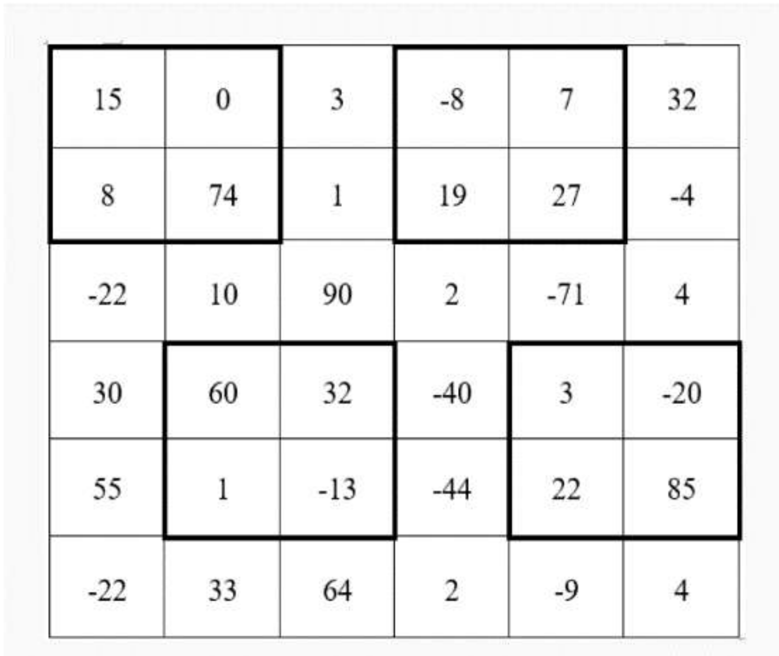


Figure 1:- Schematic of stope layout.

similar fashion to the floating stope but it uses deferent approach to define the envelope. [4] introduced a mixed integer programming model (MIP) to optimise stope boundaries. Themodel locates the optimal starting and ending locations for mining within a row (mining panel) in a block model and in this way establishes the optimum stope boundaries. To determine the optimum starting and ending location of each panel, two piece-wise linear cumulative functions are calculated. The advantage of this technique compared to the others noted is that the block geometry is not required to be regular or orthogonal. Its disadvantage is, however, that the algorithm optimises the stope boundary along the row of blocks in only one-dimension.

In the next few sections, a new methodology to find the best stope layout for a given deposit is detailed using dynamic programming. Then, we apply the proposed methodology to a synthetic block model with several deferent scenarios. We end the article with conclusion.

Existing Methods

A number of methods have been used to solve the basic open underground mining optimization problem, especially for stope layout, in recent years. These algorithms include rigorous and heuristic approaches. Some of these methods are highlighted below

Branch And Bound (B&B)

[4] used a separable programming with Branch and Bound (B&B) technique for economic optimization of stope boundary. An optimal economic stoping boundary was developed by optimizing the starting and ending locations for mining within each row of blocks. To determine these locations, two piecewise linear, cumulative functions are used for each row. The first function sums block values along the row for inclusion within the stope boundary, while the second function sums block values for exclusion. In this algorithm the stope boundary model is optimized by a mixed integer approach known as “special ordered sets”.

Probable Stope (PS)

Jalali and Ataee-pour established a technique (named Probable Stope) based on Riddle DP algorithm to optimize the stope limits of the mining methods which are feasible for vein deposits. There is a main deference between PS technique and the others. This algorithm is implemented basis on a particular economic block model including the constraints of stope dimensions. Therefore, the most significant constraints within the objective function are eliminated. It resulted in the algorithm being simple in concept, easy to program and reaching a solution quickly.

Floating Stope (FS)

Floating Stope (FS) was implemented on a fixed economic block model of the orebody.The FS is the tool developed by Datamine to define optimal limit for mineable ore or stope envelope which can be economically extracted by underground stoping methods. The general concept of the FS method was established by [1].

Maximum Value Neighbourhood (MVN)

Ataee-pour [3] proposed the MVN algorithm to optimize stope boundaries using a three-dimensional fixed economic block model to locate the best neighbourhood of a block, which guarantees the mine geometry constraints. The neighbourhood concept is based on the number of mining blocks equivalent to the minimum step size. Since several neighbourhoods are available for each block, the one that provides the maximum net value is located for inclusion in the final stope. It can apply to any underground mining method, although it does not guarantee the true "optimum" stope layout.

Proposed Method

In this paper, we develop a new algorithm based on dynamic programming for stope boundary optimization. Initially, the DP algorithm was used by Riddle (1977) to optimize stope layout of block caving method. This method was developed by modifying the Johnson and Sharp (1971) approach. The DP algorithm by Riddle is a multi-section two-dimensional solution for three dimensional problems. It means the approach provided an optimum stope in two-dimension, but it has failed to determine the actual optimal stope in three dimensions. It is notable that this method is limited to the block caving mines and cannot be able in optimizing the layout of other underground stopping methods.

The 2D model

Here, we have developed both two and three dimensional models based on LP for the stope boundary problem. For the sake of simplicity, we first develop the mathematical formulation in 2D here and extend it to 3D in the next subsection. The following assumptions are made in creatingthe 2D mathematical model:

1. Let the mining area be represented by a grid with dimension $n \times m$.
2. The grid is made up of distinct blocks with predefined values.
3. The stope dimension is fixed for 2D case, say $\alpha \times \beta$.
4. The decision variable is binary.
5. To ensure that the stopes are on the same level for easy mining, we use the following strategy: If $x_{ij} = 0$, then move to x_{ij+1}; If $x_{ij} = 1$, then move to $x_{ij+\beta}$; Once the level has been exhausted, move to x_{i+j}, and repeat the steps.

The 2D model is presented below

$$Maximize \sum_{i=1}^{n-p} \sum_{j=1}^{m-q} V_{ij} X_{ij}, \quad \ldots(1)$$

subject to:

$$\sum_{i}^{i+p} \sum_{j}^{j+p} X_{ij} \leq 1 \forall i \in \{1, \ldots, n-p\}, \quad \forall j \in \{1, \ldots, m-q\}, \quad \ldots(2)$$

$$X_{ij} - \sum_{j'=j+1}^{j+q} X_{ij'} = 1 \forall i \in \{1, \ldots, n-p\}, \quad \forall j \in \{1, \ldots, m-q\}, \quad \ldots(3)$$

$$X_{ij} - \sum_{i'=i+1}^{i+p} X_{i'j} = 1 \forall i \in \{1, \ldots, n-p\}, \forall j \in \{1, \ldots, m-q\}, \quad \ldots(4)$$

$$X_{ij} - \sum_{i'=i+1}^{i+p} \sum_{j'=j+1}^{j+q} X_{i'j'} = 1 \forall i \in \{1, \ldots, n-p\}, \forall j \in \{1, \ldots, m-q\}, \quad \ldots(5)$$

$$\text{where } V_{ij} = \sum_{i}^{i+p} \sum_{j}^{j+q} U_{ij}, p = \alpha - 1 \; and q = \beta - 1, X_{ij} \in \{0,1\}. \quad \ldots(6)$$

The 3D Model

The stope boundary layout is a three-dimensional problem. One other advancement in this realm is that our 3D model allows for variable stope dimension. The 2D model above can easily be extended to 3D as follows.

$$\text{Maximize} \sum_{i=1}^{n-p} \sum_{j=1}^{m-q} \sum_{k=1}^{s-r} V_{ijk} X_{ijk}, \quad \ldots(7)$$

subject to:

$$\sum_{i}^{i+p} \sum_{j}^{j+p} \sum_{k}^{k+r} X_{ijk} \leq 1 \forall i \in \{1, \ldots, n-p\}, \forall j \in \{1, \ldots, m-q\}, \forall k \in \{1, \ldots, s-r\}, \quad \ldots(8)$$

$$X_{ijk} - \sum_{j'=j+1}^{j+q} X_{ij'k} = 1 \forall i \in \{1, \dots, n-p\}, \forall j \in \{1, \dots, m-q\}, \forall k \in \{1, \dots, s-r\}, \ldots\ldots\ldots..(9)$$

$$X_{ijk} - \sum_{i'=i+1}^{i+p} X_{i'jk} = 1 \forall i \in \{1, \dots, n-p\}, \forall j \in \{1, \dots, m-q\}, \forall k \in \{1, \dots, s-r\}, \ldots\ldots\ldots(10)$$

$$X_{ijk} - \sum_{k'=k+1}^{k+s} X_{ijk'} = 1 \forall i \in \{1, \dots, n-p\}, \forall j \in \{1, \dots, m-q\}, \forall k \in \{1, \dots, s-r\}, \ldots\ldots..(11)$$

$$X_{ijk} - \sum_{i'=i+1}^{i+p} \sum_{j'=j+1}^{j+q} \sum_{k'=k+1}^{k+s} X_{i'j'k'} = 1 \forall i \in \{1, \dots, n-p\}, \forall j \in \{1, \dots, m-q\}, \forall k \in \{1, \dots, s-r\},..(12)$$

where $V_{ijk} = \sum_{i}^{i+p} \sum_{j}^{j+q} \sum_{k}^{k+r} U_{ijk}$, $p = \alpha - a, q = \beta - b and r = \gamma - 1, X_{ijk} \in \{0,1\} a = 1, \dots, n; b = 1, \dots, m$..(13)

Fast Dynamic Programming (FDP) Algorithm

We developed a very fast and efficient dynamic programming algorithm based on the 2D model. This heuristic is inspired by the Dynamic Programming idea of sub-dividing a large problem into smaller ones, solving them, and then combining the solutions to get a solution to the large version of the problem. The algorithm is presented in the sequel.

1. Input: Array containing the value of each block, stope size, mining site dimensions. Let K be the stope size, fd, the width of the site, and fl the length of the site.
2. STEP 1: Create an array $(fd - k + 1 \times fl - k + 1)$ that stores all the possible stopes.
3. STEP 2: Get the value of each possible stope.
4. STEP 3: Get all the possible configurations with their values, skipping stopes with negative values.
5. STEP 4: Pick the stope layout with the highest revenue.

Results and Discussion:-

We implemented the FDP algorithm and tested it on a synthetic mine site. We took our stope length and breadth to be 2. The dimension of the mine is 14 × 9. Figure 2 shows the economic values of

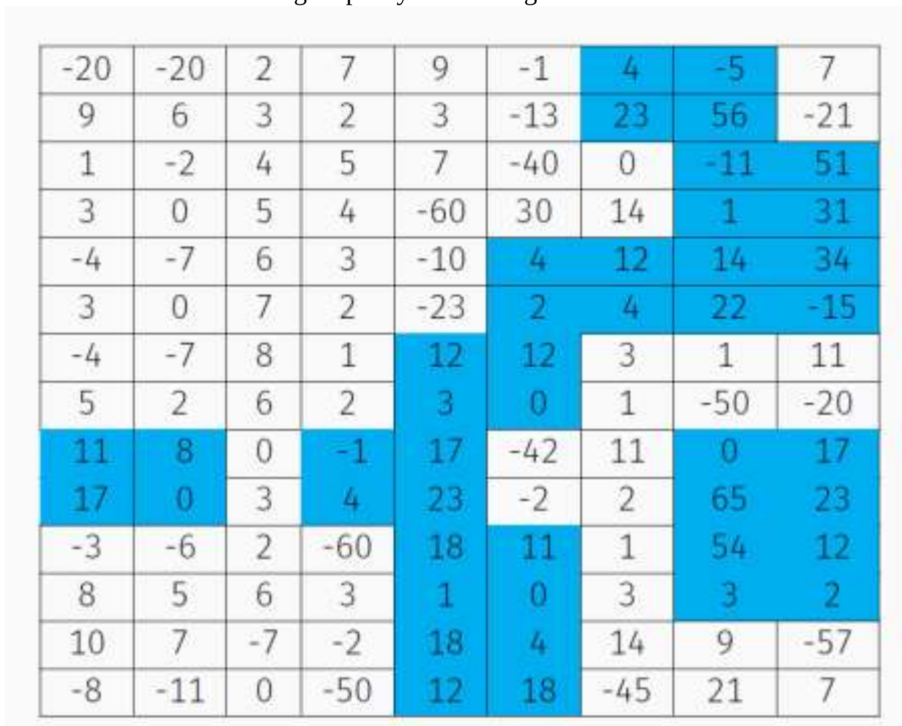
$$\begin{pmatrix}
-20 & -20 & 2 & 7 & 9 & -1 & 4 & -5 & 7 \\
9 & 6 & 3 & 2 & 3 & -13 & 23 & 56 & -21 \\
1 & -2 & 4 & 5 & 7 & -40 & 0 & -11 & 51 \\
3 & 0 & 5 & 4 & -60 & 30 & 14 & 1 & 31 \\
-4 & -7 & 6 & 3 & -10 & 4 & 12 & 14 & 34 \\
3 & 0 & 7 & 2 & -23 & 2 & 4 & 22 & -15 \\
-4 & -7 & 8 & 1 & 12 & 12 & 3 & 1 & 11 \\
5 & 2 & 6 & 2 & 3 & 0 & 1 & -50 & -20 \\
11 & 8 & 0 & -1 & 17 & -42 & 11 & 0 & 17 \\
17 & 0 & 3 & 4 & 23 & -2 & 2 & 65 & 23 \\
-3 & -6 & 2 & -60 & 18 & 11 & 1 & 54 & 12 \\
8 & 5 & 6 & 3 & 1 & 0 & 3 & 3 & 2 \\
10 & 7 & -7 & -2 & 18 & 4 & 14 & 9 & -57 \\
-8 & -11 & 0 & -50 & 12 & 18 & -45 & 21 & 7
\end{pmatrix}$$

Figure 2:- A matrix showing the value of each mine block.

$$\begin{pmatrix}
-25 & -9 & 14 & 21 & -2 & 13 & 78 & 37 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 7 & 18 & -44 & -63 & 4 & 4 & 72 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-8 & 6 & 18 & -28 & -27 & 22 & 52 & 55 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-4 & 9 & 17 & 18 & 27 & 16 & -45 & -58 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
36 & 11 & 6 & 43 & -4 & -31 & 78 & 105 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
4 & 7 & -49 & -38 & 30 & 15 & 61 & 71 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2 & -11 & -59 & -22 & 52 & -9 & -1 & -20 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

Figure 3:- A matrix showing the value of each stope.

each mine blocks. The *ij*th entry of the matrix in Figure 3 gives the values of each stope starting at ij. We applied FDP algorithm to this mine and the resulting stope layout is in Figure 4.



-20	-20	2	7	9	-1	4	-5	7
9	6	3	2	3	-13	23	56	-21
1	-2	4	5	7	-40	0	-11	51
3	0	5	4	-60	30	14	1	31
-4	-7	6	3	-10	4	12	14	34
3	0	7	2	-23	2	4	22	-15
-4	-7	8	1	12	12	3	1	11
5	2	6	2	3	0	1	-50	-20
11	8	0	-1	17	-42	11	0	17
17	0	3	4	23	-2	2	65	23
-3	-6	2	-60	18	11	1	54	12
8	5	6	3	1	0	3	3	2
10	7	-7	-2	18	4	14	9	-57
-8	-11	0	-50	12	18	-45	21	7

Figure 4:- Optimal Stope Layout.

Conclusion:-

This paper has presented a new optimisation approach to stope layout problem. The major advantage of this method over existing methods is that it can find true optimum stope layout. Furthermore, we presented an extension of the model to 3D. Future work can look at the way to extend the implementation of FDP algorithm to 3D.

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