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Introducing a User-friendly Computer Program for Determining the Location of Underground Stopes

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ABSTRACT

Determining the limit of underground mining and stope layout is one of the most important points in underground mining and production planning. Numerous algorithms have been offered to address the stope layout optimization problem both in two-dimensional and three-dimensional space based on economic value. In this paper, a new heuristic algorithm with different strategies was developed to generate optimal and sub-optimal underground stope layouts. In this algorithm, all possible stopes were created based on an entirely economic block model considering stope dimensions in the three-dimensional space. Afterward, the algorithm generated a family of non-overlapping stopes over all possible stopes and selected the highest economic value as the final solution. Also, a user-friendly computer program named Stope Layout Optimizer (SLO3D) was designed in C# object-oriented program, and two separate examples were set for a better understanding of the algorithm. The application of the proposed computer program was implemented on a real copper deposit, considering three different strategies. The final output consisted of 29 stopes with a value of US$ 37 million. The results proved that the new heuristic algorithm was able to increase the final economic value by 49.04% compared to the floating stope method. Furthermore, the three proposed strategies were investigated for the same deposit. The results of this procedure illustrated that the probabilistic approach could generate higher economic values and sub-optimal values compared with the other two strategies discussed in previous studies regarding this issue.

Keywords : *Underground Mining, Production Planning, Stope Layout Optimizer, Optimization, Heuristic Algorithm*

1. Introduction and literature review

In recent years, the demand for mineral resources due to the growth of industry and population has increased drastically. Hence, it has forced the mining industry to explore underground ore reserves to meet the demand of societies. In order to maintain a reasonable balance between market demand and mineral production, the design and management of underground mines should be carried out in an optimum way to minimize overall costs [1]. Over the last decades, underground mine design and management have improved in three main areas: 1: determining underground mine limit and optimizing stope layout, 2: development and placement of underground infrastructures, and 3: scheduling underground mineral production [2]. Among these areas, the first step has particular importance due to the optimal production of ore reserve and production planning over the mine lifespan. However, the development of special methods for determining the optimal layout of underground mines is a complicated issue due to a variety of constraints and economic values of blocks, which is also dependent on the location of blocks in a specific stope. Recently, numerous algorithms have been proposed to determine underground stope layouts, which most of them are established in the two-dimensional (2D) space. The first algorithm was presented by Riddle [3] based on Dynamic Programming (DP). Riddle [3] developed his algorithm for the determination of stope boundaries in block cave mines. Putting some blocks with negative values as pillars to provide separate stopes is the main difference between this algorithm and DP. This algorithm is applied to 2D models and is not able to solve 3D problems. Also, due to various results of this algorithm on 2D models, it has been suggested to solve it separately in two East-West and North-South derections and choose the best solution as the final result. Cheimanoff et al. [4] developed an algorithm called octree division. During the procedure of this algorithm, after gathering data obtained by drillholes, geostatistical data, and minerals forms, the final limit is investigated by the algorithm. Then, using the constructed geometric model, the algorithm establishes valuable reserves and identifies the mining sequence. Finally, the mining volume is determined as a successive removal of sub-volumes within the octree division, considering the minimum dimension of stopes. The main drawback of their algorithm is that the minimum dimensions of blocks, which have a lower amount of minerals, are included in the final limit. This issue affects the overall profit of the operation due to the existence of several waste blocks [5]. Ovanic and Young introduced the Branch and Bound technique [6, 7]. In this algorithm, the boundaries of extraction stopes are determined by exploring the starting and ending points in a defined row. In order to facilitate the integration of constraints, including the length of stopes and their continuity, a complex integer programming called Type-Two Special Ordered Sets (SOS2) is used, which is an ordered set of non-zero variables and optimizes piecewise linear functions [8]. It applies to all models regardless of their dimension. However, it has been designed to optimize stope length in only one direction without considering the slope of walls. Also, as the problem grows, the solution time increases due to the complex integer programming variables. In 1995, Alford [9] introduced an optimization model called floating stope. This algorithm is available in the Datamine software [10]. In this algorithm, a stope with predefined dimensions is floated all over the block model in the 3D space. During the flotation process, the average grade of each stope is calculated by grades of internal blocks. The stopes that must be appeared in the final

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underground mining limit can be based on an objective function, which can be defined as the highest tonnage, economic value, or ore grade value. In 2001, Cawrse [11] improved the efficiency of the floating stope method and called it the Multiple Pass Floating Stope Process (MPFSP). In this method, the input data, including maximum grades, cut-off grade, and maximum tonnage of wastes, are defined by a user. Then, after producing several stopes, the final statistical results are saved in an excel format (CSV). However, this method facilitates the selection of the final stopes, but it does not guarantee the optimum limit. Deraisme et al. [12] implemented the downstream geostatistical approach in a uranium underground mine. They used large panels considering non-linear geostatistics to analyze the grades of mining units. This method could consider the slope angle, which has been ignored in most of the proposed methods. Ataee-pour [13,14] developed a maximum value neighborhood (MVN) algorithm based on the primary concepts of the floating stope. This algorithm uses the concept of the highest neighborhood value to satisfy the minimum stope size constraints. In the next step, a set of blocks is recognized as a feasible solution. However, this algorithm has eliminated the drawbacks of the floating stope method and has been considered as one of the most popular methods in underground mining. The main drawbacks of MVN are listed as follow:

(1): Moving the starting location of evaluation alters the set of stope layouts generated from the same orebody.

(2): Blocks that are examined earlier in the process are given preferential treatment.

Grieco and Dimitrakopoulos [15] introduced a probabilistic algorithm based on mixed-integer programming. In this method, first, the block model is divided into several layers. Next, each layer is separated into several panels and rings. Every ring is defined as a binary variable in mixed-integer programming, whose objective function is maximizing the metal content over a predefined period. Grieco and Dimitrakopoulos implemented their model in the Kidd Creek mine in Canada, for which the orebody model was generated for 40 times using conditional simulation. Their model considered the geological uncertainty during optimization. In addition, the solution time of this method depended on the number of variables in the complex mixed integer programming model, which could limit its application in a real industry operation [16]. Topal and Sens [17] presented a heuristic algorithm to determine the underground stope layout. In this method, at first, the constructed block model was regularized to similar dimensions. The algorithm was implemented in MATLAB software based on the economic values of blocks. The main disadvantage of their algorithm was the elimination of stopes with lower values while removing the overlapping stopes. Little et al. [1] developed a mathematical model based on Integer Programming (IP) for optimizing stope boundaries in sublevel stope mines. They used a simultaneous approach in order to optimize both the stope layout and production planning. The model was established on a real gold mine in Australia. The results of their study showed that the total profit obtained by the integrated approach provided a 36% higher Net Present Value (NPV) compared to traditional methods. Bai et al. [18] proposed an algorithm based on the graph theory to optimize underground mining limits. This method has been only applicable to sublevel stoping mines. In this method, a raise is defined, and each block in the coordinate system can be expressed in the cylindrical system (r, θ, z). The final result can be obtained by establishing the best position of the raise and vertical extent. The main defect of their algorithm was that it was limited to underground mines extracted by the sublevel stoping method. Jalali [19] presented an algorithm called OLIPS, complying with all technical and geometric constraints. This algorithm applies to a special form of 2D economic block model, derived from a fixed economic block model of a panel or level. In the second stage of their studies, another algorithm called GOUMA was developed, which was able to optimize both stope boundaries in each level/panel and their number simultaneously. Jalali and Hosseini [20] introduced a greedy algorithm to determine the optimal stope layout. The algorithm's logic follows a searching method on a graph model corresponding to an economic block model and is solved using Dijkstra [21] as a powerful solver. Sandanayake et al. [22] proposed an algorithm based on heuristics considering various possible stopes to optimize underground stope layout. In this method, while the problem becomes more complex, the number of non-overlapping stopes increases dramatically. They used a special strategy to overcome this problem. They implemented their model on an actual case study and demonstrated that the final profit of their model would provide 10.7 % higher economic value compared to the MVN algorithm [23]. Erdogan et al. [24] utilized four developed algorithms, including Floating Stope, Maximum Value Neighborhood, Sens and Topal, [2], and Sandanayake et al. [22] on a real underground mine. They compared the capabilities of these algorithms and analyses the existing limitations.

In this paper, first, a new heuristic algorithm with several strategies is presented. In order to provide a better understanding of the algorithm's function, it was applied to a 2D example and a real case study (vein deposit), and the results were compared with those obtained from the floating stope and maximum value neighborhood methods. Eventually, a computer program, which can locate underground stopes with variable dimensions, was developed in C# object-oriented programming language.

2. Proposed algorithm

As described in the literature review, numerous methods have been developed to optimize the underground stope layouts. The use of heuristic algorithms and search methods can be an excellent way to locate underground stopes all over the orebody. In the following, the main separate steps of the proposed algorithm, whose concept is based on the Sandanayake et al. [22] model, are presented:

2.1. Preparation of geological model

This algorithm requires a geological model, which can be obtained by the estimation of constructed blocks using drillhole data.

2.2. Construction of Block Economic Value (BEV)

In this step, the generated block model in the first step is converted to an economic model using equation 1.

$$BEV = \{(P - R) \times g \times Y - (C_m + C_p)\} \times T \quad (1)$$

Where P is metal price ($/ton metal), C_m is mining costs ($/ton ore), C_p is processing costs ($/ton ore), R is refining costs ($/ton metal), Y is recovery (%), BEV is the block economic value ($), g is grade of blocks and T is the tonnage of blocks.

2.3. Generating all possible stopes with predefined dimensions

In this step, all possible stopes are generated for the model. In order to facilitate this process, three specific characteristics (i j k) are used, which $(i' \, j' \, k')$ and $(i'' \, j'' \, k'')$ is the origin and the last block of a particular stope respectively. The block located in $(i_{max} \, j_{max} \, k_{max})$ is the last block of the ore model (Figure1).

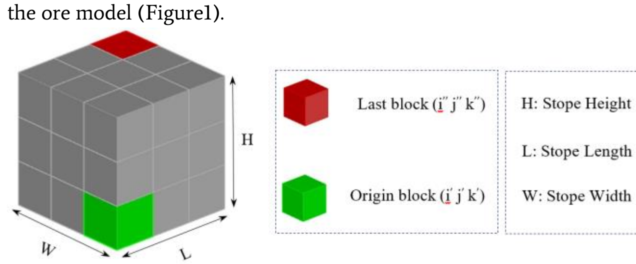

Fig 1. Parameters of underground stope in 3D space [23].

After producing all possible stopes, the overall economic value of each stope is calculated from the sum of all economic values of its confined blocks. Also, the grade of each stope is defined by dividing the sum of all grades on the number of its confined blocks.

2.4. Generating of all set of non-overlapping stopes and optimum solution

In the fourth step, in order to determine the optimum location of underground stopes, all possible sets of non-overlapping stopes are generated. Two major null families of sets, S_T and S_E are created. S_T is all possible sets of non-overlapping stopes that are generated during the algorithm and S_E is a unique derived set of S_T. In this algorithm, each stope is compared with all stopes within any set of non-overlapping stopes (S_P). If the imported stope does not overlap with other stopes, all stopes are combined to form a new set of non-overlapping stopes (S_{Pnew}). While the algorithm iterated once, all sets are inserted into a new set called S_O. This process is iterated until all positive stopes participated in the algorithm. Finally, the high value of the non-overlapping stopes set is selected as the optimum solution. Figure 2 shows the steps of this algorithm.

In large and complex problems, the sets of non-overlapping stopes (S_P) increase drastically. Therefore, the solution time increases as well. Three strategies are added to the presented algorithm to overcome this problem. The first strategy is sorting all of the sets (S_T members) based on their economic value and selecting a percentage of the sorted collection. The major drawback of the first strategy is removing some stope sets with low economic value. While this strategy discarded the possibility of a combination of removed sets and other stopes that may be a set with a higher total value. In order to resolve this disadvantage, two strategies with probabilistic backgrounds are proposed and analyzed in this study. These two strategies are:

- Selecting a percentage of S_T members randomly and frequently.
- Selecting a percentage of S_T members based on the number of stopes in each set.

The example provided in Figure 3 presents a better understanding of the collections of non-overlapping stopes. In this figure, a block model consisting of 16 blocks in which the numbers are representative of their coordinates is assumed in a two-dimensional space. Considering the size of 2 × 2 (2 blocks in both x and y directions), nine possible stopes can be produced. Table1 shows the characteristics of these stopes, including their origin block, last block, and their economic value.

At the beginning of the algorithm, all possible stopes with negative economic values (S_4, S_6, S_7, and S_9) should be eliminated. Therefore, in this example, positive stopes (S_1, S_2, S_3, S_5, and S_8) are considered as algorithm inputs. Then, S_1 will be investigated as the first stope. Since no specific sets exist, the first imported stope will fill S_T, S_O and SE. In the following, the next stope (S_2) is imported to the algorithm. Since S_1 has been previously set in S_T, both stopes should be analyzed regarding their overlapping issue. These two stopes have two mutual blocks in (2 1) and (2 2). Hence, they cannot appear in one specific set. Subsequently, S_3 is imported as a new stope and investigated with previous members of S_T. Since S_3 and S_2 have two mutual blocks named (3 1) and (3 2), these stopes cannot appear as members of an independent set.

Table 1. Specifications and economic value of each stope.

Stope	Origin block	Last block	value (USD)
S_1	(1 1)	(2 2)	2
S_2	(2 1)	(3 2)	4
S_3	(3 1)	(4 2)	5
S_4	(1 2)	(2 3)	-2
S_5	(2 2)	(3 3)	3
S_6	(3 2)	(4 3)	-1
S_7	(1 3)	(2 4)	-3
S_8	(2 3)	(3 4)	4
S_9	(3 3)	(4 4)	-1

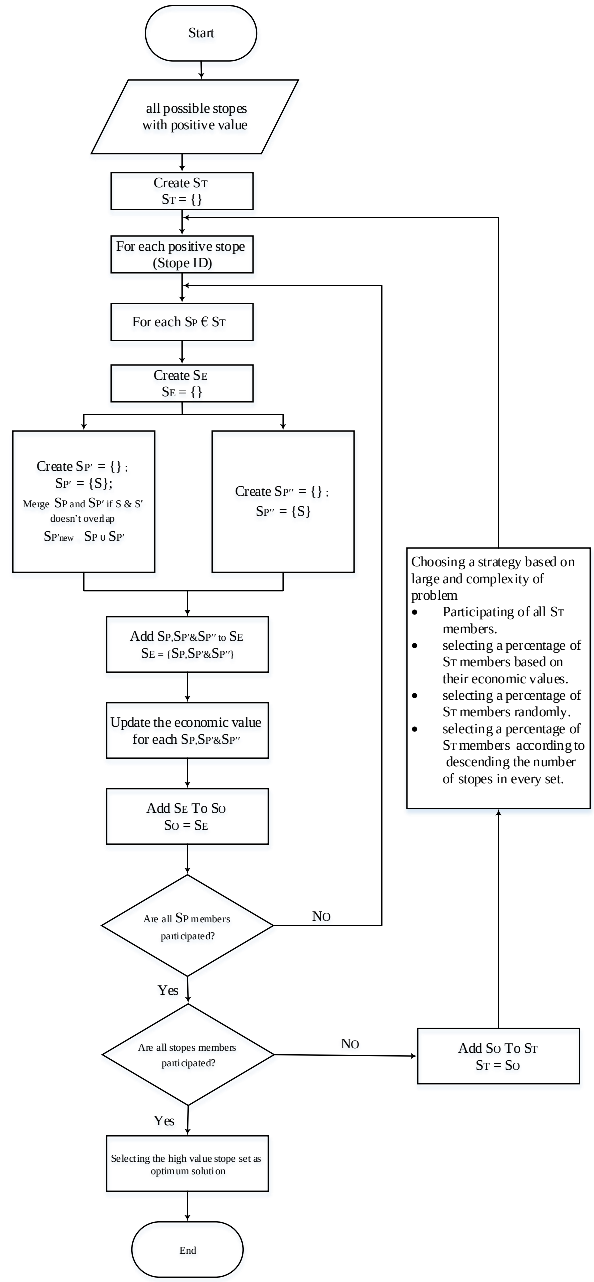

Fig 2. Modified Underground stope layout algorithm after [22,23].

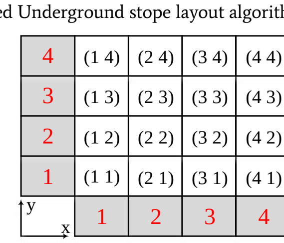

Fig 3. A 2D block model.

On the other hand, S_3 and S_1 do not share any mutual block. Hence, these two stopes can appear in one set. Table 2 illustrates these three procedures. This process is iterated while all positive stopes participate in the algorithm procedure. Table 3 shows all produced sets considering their value. According to this table, the final result is a combination of S_1, S_3, and S_8, as demonstrated in figure 4.

Table 2. Procedure of the proposed algorithm, applied on 2D block model.

For S_1:			
$S_T = \{\}$	$S_E = \{\}$	$S_P \in S_T = \{\}$	$S_O = \{\}$
$S_{P'} = \{S_1\}$	$S_{P''} = \{S_1\}$	$S_E = \{\{S_1\}\}$	$S_O = \{\{S_1\}\}$
$S_T = \{\{S_1\}\}$			
For S_2:			
$S_P \in S_T = \{S_1\}$	$S_E = \{\}$	$S_O = \{\}$	
overlapping test: S_1 and S_2 have two mutual blocks named (2 1) and (2 2)			
$S_{P'} = \{S_2\}$	$S_{P''} = \{S_2\}$	$S_E = \{\{S_1\},\{S_2\}\}$	$S_O = \{\{S_1\}\}$
$S_T = \{\{S_1\},\{S_2\}\}$			
For S_3:			
for $S_P \in S_T = \{S_1\}$:			
overlapping test: S_1 and S_3 do not have mutual blocks.			
$S_E = \{\}$	$S_{P'} = \{S_3\}$	$S_{P'new} = \{S_1,S_3\}$	
$S_{P''} = \{S_3\}$	$S_E = S_O = \{\{S_1\},\{S_3\},\{S_1,S_3\}\}$		
for $S_P \in S_T = \{S_2\}$:			
overlapping test: S_1 and S_2 have two mutual blocks named (3 1) and (3 2)			
$S_E = \{\}$	$S_{P'} = \{S_3\}$		
$S_{P''} = \{S_3\}$	$S_E = \{\{S_1\},\{S_3\}\}$		
$S_T = \{\{S_1\},\{S_2\},\{S_3\}, \{S_1,S_3\}\}$			

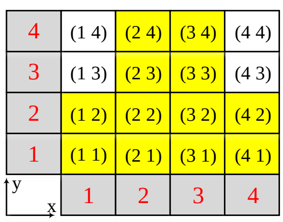

Fig 4. Final underground stope layout.

Table 3. Economic value of final sets of underground mining limit.

S_T	Value (USD)
$\{S_1\}$	2
$\{S_2\}$	4
$\{S_3\}$	5
$\{S_5\}$	3
$\{S_8\}$	4
$\{S_1, S_3\}$	7
$\{S_1, S_8\}$	6
$\{S_2, S_8\}$	8
$\{S_3, S_8\}$	9
$\{S_1, S_3, S_8\}$	11

3. Computer Program

Various computer programs have been developed for underground stope layout optimization in 2D and 3D spaces. Table 4 shows a summary of the proposed computer programs in underground stope layout optimization.

Table 4. Summary of developed computer programs for underground stope layout optimization.

Computer Program	Year	Algorithm	Dimension	Mining Method	Optimality
FORTRAN	1977	Riddle	2D	Block Caving	Yes
DATAMINE	1995	Floating Stope	3D	All	No
LINGO –CPLEX	1999	Branch and Bound	1D	All	Yes
SLO	2000	MVN	3D	All	No
SBO	2007	OLIPS	2D	All	No
MATLAB	2010	Heuristic algorithm	3D	All	No
GOUMA-CP	2016	GOUMA	2D	All	No

In this study, in order to facilitate the implementation of this algorithm with some strategies discussed in the previous section, a user-friendly interface (UI) computer program (Figure 5) was developed in the C# programming language [25] named Stope Layout Optimizer 3D (SLO3D).

Fig 5. Stope Layout Optimizer 3D .

This computer program has three main steps:

3.1. Creating Block Economic Value (BEV)

In this step, after importing data, the economic parameters including mining cost, processing cost, refining cost, metal price, recovery, density, and cut-off grade, the geological model is converted to an economic model based on the formula in section 3.2. Also, the number of ore blocks and waste blocks are displayed in predefined boxes (Figure 6)

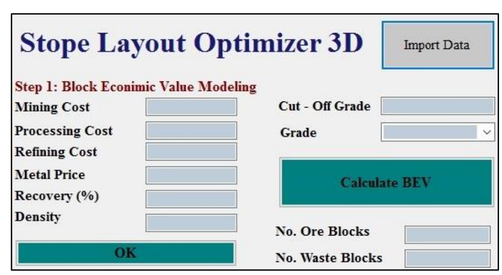

Fig 6. Creating block economic value.

3.2. Generating possible stopes

All possible stopes with specified dimensions are generated based on the underground mining method and geotechnical stability parameters. By clicking on the generate tab, the algorithm specifies the origin block of the economic model as the starting block. Then, considering block increment in X, Y, Z directions as stope dimension parameters, the last block of the stope is determined. Finally, the constructed stope is floated through the economic model, all possible stopes are generated, and finally, the number of positive and negative stopes are calculated (Figure 7).

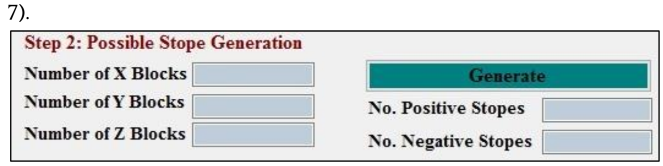

Fig 7. Possible stope generation.

3.3. Optimization of final stope layout

In this step, it is required to remove all negative stopes. Then, according to classified strategies in the selection type combo box, the program finds the best solution which contains non-overlapping stopes. The total economic value of the underground mining limit and stopes' identification number are shown in Figure 8.

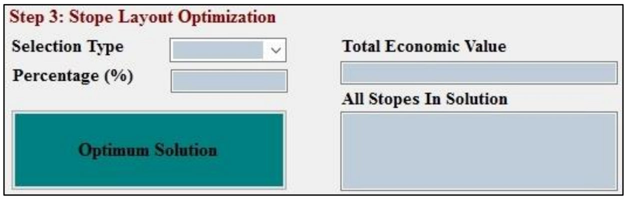

Fig 8. Stope layout determination.

4. Example

In this section, in order to clarify the application of this computer program, a two-dimensional conceptual model is presented (7 blocks in the x direction and 6 blocks in the y direction). Figure 9A shows this model in which the values inside the blocks are representative of copper grade. Considering US$ 8000 for the metal price, US$ 35 for mining and processing costs, US$ 170 for refining costs, and 90% for recovery, the cut-off grade is equal to 0.5%. So, the blocks that have grades lower than this value are considered as waste blocks. The economic model of this conceptual model is made by assumed values, which vary between US$ -9375 and US$ 81950 (Figure 9B).

(A)

6	0.032	0.004	1.538	0.786	0.274	0.003	0.012
5	0.001	0.002	0.356	0.001	1.214	0.001	0.397
4	0.231	0.001	0.003	0.234	0.681	0.766	0.001
3	0.386	0.002	1.325	4.218	0.276	0.009	0.021
2	0.328	0.591	0.001	0.315	0.082	3.451	0.052
1	0.134	0.003	0.972	0.052	0.977	0.001	1.876
y / x	1	2	3	4	5	6	7

(B)

6	-9375	-9375	22932	6371	-9375	-9375	-9375
5	-9375	-9375	-9375	-9375	15797	-9375	-9375
4	-9375	-9375	-9375	-9375	4059	5931	-9375
3	-9375	-9375	18241	81950	-9375	-9375	-9375
2	-9375	2077	-9375	-9375	-9375	65060	-9375
1	-9375	-9375	10467	-9375	10577	-9375	30375
y / x	1	2	3	4	5	6	7

Fig 9. A: Grade model (%) B: Economic model (US$).

In the following, 20 possible stopes can be generated considering three blocks in the x direction and three blocks in the y direction for each stope. Figure 10 shows the average grade and economic value of each stope. According to the algorithm discussed previously, three stopes, including S_2, S_5, and S_{18} with a total value of US$ 117911, are located in the underground limit. In the final step, after determining the boundary of stopes, the blocks in the adjacent waste blocks can be removed. Therefore, after the rejection of the blocks (2 3), (6 3), (7 2), (7 3), and (5 6), the optimum layout, which its value is equal to US$ 155411, can be generated. Figure 11 shows the final result of the optimization process.

5. 3D Model

5.1. Orebody modeling

In order to introduce the capability of the SLO3D program in the three-dimensional space, the program was implemented on a real copper deposit, located in the north-west of the Zahedan province, Iran. The mineralization host rocks are greywacke, siltstones, and shales that are bordered to the Cretaceous ophiolitic mélange in the west and to the middle Eocene limestones in the east [26]. Several igneous suites and dikes of granodiorite to quartz monzodiorite and granite affinity have intruded into the sedimentary sequence of the area. The data on this area were obtained from 35 drill holes samples.

In this paper, a part of this area (a vein of an N23°W direction) with enough exploration data was considered as the main study area. This vein has a thickness of 20m, a surface length of 400m, and a vertical length of 100m. Datamine was used to generate an orebody model of 6400 blocks, of which 2259 were of ore blocks, according to cut-off grade value. All blocks were dimensioned 5m × 5m × 5m. All blocks were estimated according to exploration datasets. The output file retrieved from Datamine contained the block center coordinate, density, and the average grade of each block and was prepared as an input file for SLO3D. Economic parameters for converting the geological model into the economic model (BEV) are provided in Table 5. The value of all blocks was calculated based on these assumptions. Consequently, the economic value varied from US$ 994234 to US$ 2763576.

Table 5. Economic parameters during the optimization.

Parameter	Value
Mining Cost ($/ton)	20
Processing Cost ($/ton)	10
Refining Cost ($/ton)	90
Copper Price($/ton)	6500
Recovery (%)	90
Cut-Off Grade (%)	0.52

5.2. Stope Generation

The mining method in this ore deposit is longitudinal stoping, a similar method to the sublevel stoping method. In longitudinal stoping, the direction of mining is in the same way as sublevel stoping along the strike of the orebody (longitudinal direction). This method is designed for ore bodies of 5-20m thick [27]. In most cases, determining the stope dimension in these methods can be achieved by designing stopes with high vertical and short horizontal dimensions or stopes with short vertical and long horizontal dimensions [28]. In this study, stope dimensions were considered 50m×20m×25m. As calculated by the computer program, 1136 possible stopes were generated, of which 974 stopes had positive values and the remaining 162 stopes had negative values. Table 6 shows a summary of the stope generation step.

5.3. Stope Layout Determination

After generating all possible stopes, the stopes with negative economic values were removed, and all positive stopes were imported as an input file in order to produce all combinations of non-overlapping stopes. A unique set of non-overlapping stopes containing 29 stopes was selected as the optimum solution and a value of US$ 37 million. Tables 7 and 8 show the summaries of the stope layout optimization step and the final underground mining limit, respectively (Figure 12).

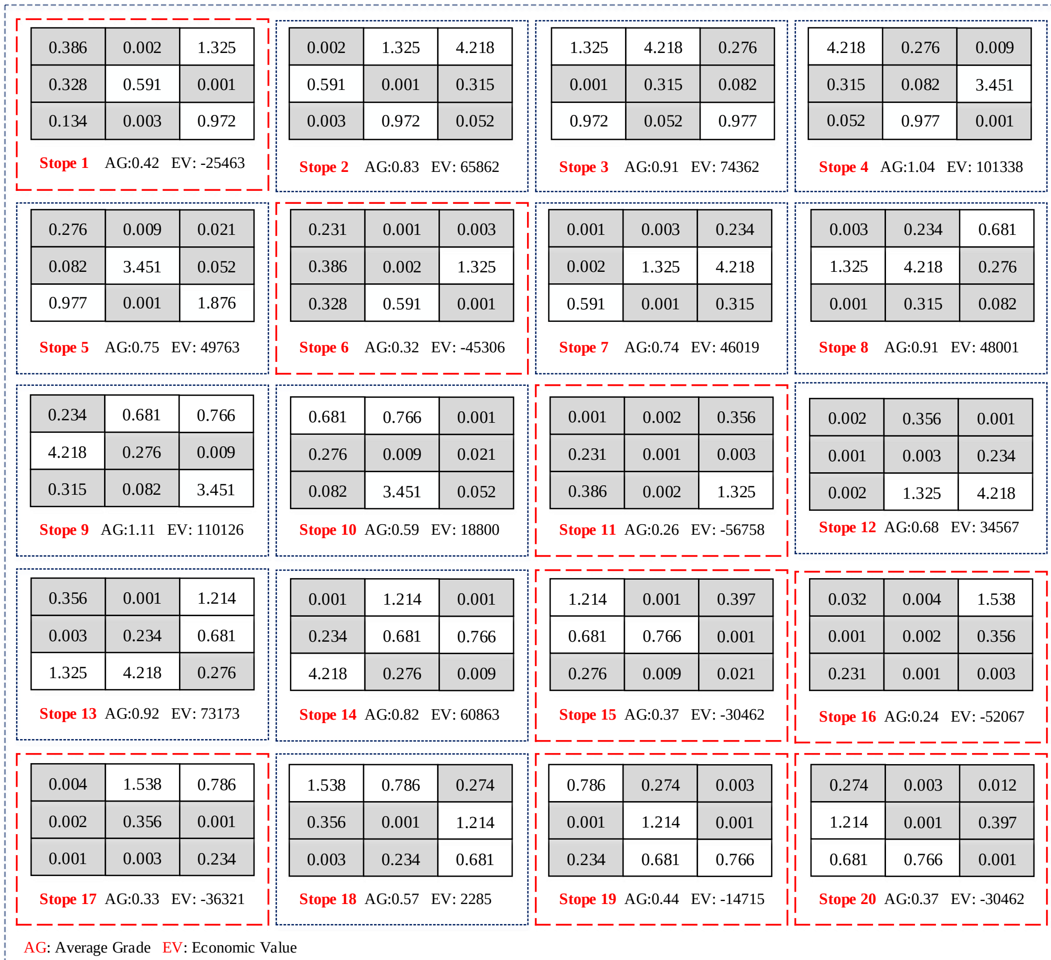

Fig 10. An example of producing 20 possible stopes.

y \ x	1	2	3	4	5	6	7
6	0.032	0.004	1.538	0.786	0.274	0.003	0.012
5	0.001	0.002	0.356	0.001	1.214	0.001	0.397
4	0.231	0.001	0.003	0.234	0.681	0.766	0.001
3	0.386	0.002	1.325	4.218	0.276	0.009	0.021
2	0.328	0.591	0.001	0.315	0.082	3.451	0.052
1	0.134	0.003	0.972	0.052	0.977	0.001	1.876

Fig 11. Optimum underground mining limits.

In order to compare the results of this approach, the floating stope method was applied to this case study as well. According to Table 9, it is observed that the total economic value increased by 49.04 %. Although the CPU time increased in this new method, other existing problems in the previous algorithms were resolved. An investigation of the proposed strategies was carried out based on the selection of the percentage of S_T members, and their results were compared.

5.4. Application of Strategies

Through this investigation, in the first strategy, all sets of S_T members were documented based on their economic values (from the highest to the lowest value). The input files for running the algorithm varied from a percentage of 10% to 90%. The second and third strategies were applied through the same procedure based on randomly selected and the number of stopes in each set, respectively. The outcome of these analyses showed that the first strategy, investigated by Topal and Sens [17] had an important drawback due to the elimination of several stopes mixed with other non-overlapping stopes to generate higher economic value. On the other hand, the second scenario was applied five times in the case study. According to Figure 13, it is obvious that the economic value considering 70%, 80%, and 90% of the recorded stopes have increased by 8.54%, 8.34% and 7.51% compared to the first strategy, respectively. Additionally, the second strategy with a probabilistic background has generated a better solution in the region between 70% and 90%. However, the third strategy could not generate an acceptable solution and its outputs were very close to the first strategy in the region between 30% and 60%. Table 10 shows the detailed results of three separate strategies. According to this table, it can be concluded that the second strategy was able to produce a near optimum value in very large-scale problems. For future works, it is suggested to analyze the first and the second strategies on a real large-scale problem.

Table 6. Summary of the stope generation process.

Parameter		Value
Number of Possible Stopes	Positive value	974
	Negative value	162
Grade (%)	Min	0.203313
	Max	1.764087
	Average	0.829831
Stope Economic Value (USD)	Min	-867419.141
	Max	4658403.177
	Average	1269307.126
Metal Weight (gram)	Min	129103840.6
	Max	1120195782
	Average	526942893.6

Table 7. Summary of generated stopes for optimum layout.

Parameter		Value
Number of Stopes		29
Total Economic Value (M$)		37.05
Grade (%)	Min	0.537283
	Max	1.284437
	Average	0.830843
SEV (USD)	Min	49579.29928
	Max	2905380.967
	Average	1277587.729
Metal Weight (gram)	Min	296724820.5
	Max	815617785.2
	Average	527585793.6

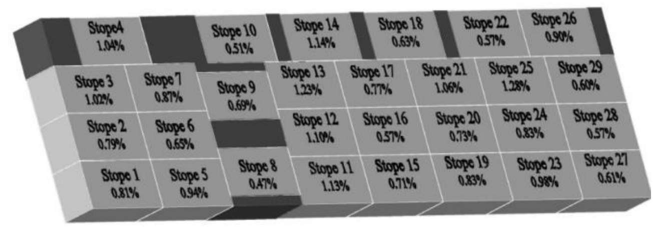

Fig 12. Underground stope layout for the case study.

Table 8. Values of underground stopes in the final solution.

No.	Stope ID	Grade (%)	SEV ($)	Metal (gram)	Origin Block			Last Block		
					X	Y	Z	X	Y	Z
1	1	0.810772351	1273906.816	514840442.7	1	1	1	10	4	5
2	6	0.792661868	1244680.488	503340286	1	1	6	10	4	10
3	11	1.018610954	2070867.724	646817956	1	1	11	10	4	15
4	80	1.045923158	1999699.462	664161205.4	5	1	16	14	4	20
5	161	0.940018318	1561925.662	596911632.1	11	1	1	20	4	5
6	166	0.654471502	549999.2011	415589403.9	11	1	6	20	4	10
7	171	0.874999877	1303862.937	555624921.8	11	1	11	20	4	15
8	322	0.537283182	49579.29928	296724820.5	21	1	2	30	4	6
9	330	0.694819214	900844.0652	441210200.9	21	1	10	30	4	14
10	368	0.545919638	138315.9739	321258970	23	1	16	32	4	20
11	481	1.134458481	2283708.359	720381135.5	31	1	1	40	4	5
12	486	1.100115023	2188453.484	698573039.5	31	1	6	40	4	10
13	491	1.233980495	2699146.127	783577614.1	31	1	11	40	4	15
14	560	1.144524423	2318046.64	726773008.3	35	1	16	44	4	20
15	641	0.710934532	781486.3839	451443427.9	41	1	1	50	4	5
16	646	0.569835253	319377.4155	361845385.7	41	1	6	50	4	10
17	651	0.773222656	1079351.313	490996386.7	41	1	11	50	4	15
18	752	0.632458194	549862.6853	401610953.5	47	1	16	56	4	20
19	801	0.831028073	1333063.971	527702826.1	51	1	1	60	4	5
20	806	0.730388068	985764.3348	463796423	51	1	6	60	4	10
21	811	1.067911107	2220607.588	678123553.2	51	1	11	60	4	15
22	944	0.571005591	375454.2742	362588550.1	59	1	16	68	4	20
23	961	0.981427118	1746695.373	623206219.9	61	1	1	70	4	5
24	966	0.83768377	1303448.075	531929193.6	61	1	6	70	4	10
25	971	1.284437457	2905380.967	815617785.2	61	1	11	70	4	15
26	1104	0.905009177	1475802.093	574680827.7	69	1	16	78	4	20
27	1121	0.603131553	464234.7939	382988535.8	71	1	1	80	4	5
28	1126	0.572767387	367185.6118	363707290.6	71	1	6	80	4	10
29	1131	0.604670898	559293.018	383966020	71	1	11	80	4	15

Table 9. Comparison of the results with the floating stope method.

Parameter	Proposed Algorithm	Floating Stope Method
Economic Value (USD)	37050044	24857539
Solution time	00:12:73	00:01:07

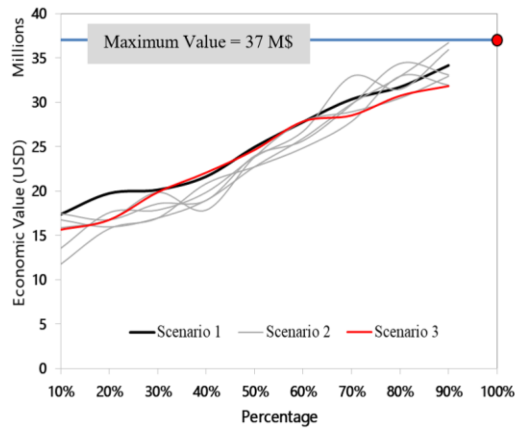

Fig 13. Comparison of three strategies with optimum value.

Table 10. Results of three strategies, applied to case study.

Economic Value (USD)							
Percentage (%)	Strategy 1	Strategy 2					Strategy 3
		#1	#2	#3	#4	#5	
10	17385284	16756452	13546281	15856734	11756491	17456372	15645731
20	19746529	15956731	17567836	16746572	15756354	16756483	16745623
30	20137951	16956712	17856425	19856341	16956713	18567376	19867821
40	21636976	18956724	19857134	17856725	20846528	18945624	22078571
50	24967539	22746547	23843523	23856746	22735463	23968721	24645766
60	27793673	25956756	26746574	27857638	24867698	25678576	27856792
70	30354827	29846726	32947836	28946725	27846574	29756365	28534692
80	31736519	32946815	31476194	30487294	32957284	34386482	30745261
90	34172413	36736593	35947287	32957883	31947616	33103481	31846731
100	17385284	16756452	13546281	15856734	11756491	17456372	15645731

Number of Stopes							
Percentage (%)	Strategy 1	Strategy 2					Strategy 3
		#1	#2	#3	#4	#5	
10	12	11	10	11	10	12	11
20	14	12	12	12	11	13	14
30	15	14	15	17	13	15	16
40	17	15	17	14	16	15	18
50	19	18	19	20	19	19	19
60	21	20	21	21	18	21	20
70	23	22	24	22	21	23	22
80	24	25	24	23	25	26	24
90	26	28	27	26	26	25	25

6. Conclusions

Determining the underground stope layout and production scheduling are the most important issues in underground mining. Stope layout optimization plays an important role in maximizing the profitability of the underground operation over the mine lifespan. A limited number of algorithms are available for underground stope layout determination. However, the complexity of underground mining methods has caused the lack of computer programs, and most of these computer programs do not produce marginal stope layouts, especially in the 3D space. In this paper, the existing algorithms for underground stope layout optimization were reviewed, and a computer program, called Stope Layout Optimizer 3D (SLO3D), was developed as a C# user interface. The goal of this program was to implement a heuristic algorithm for the determination of underground stope boundaries based on economic factors, cut-Off grade, and specified stope dimension. This algorithm was based on the non-overlapping concept and is not a mathematical logic. Hence, the solution is not truly optimum. However, it can produce better solutions compared to other 3D algorithms. SLO3D provides an interactive environment to define and edit important parameters related to the stope layout optimization, including block model parameters, stope geometry, and economic factors. Also, for large and complex problems, three strategies were added to a heuristic algorithm in order to save time solution. The Implementation of SLO3D on an actual copper deposit resulted in 29 stopes in an orebody of US$ 37 million worth.

REFERENCES

[1] Little J, Topal E, Knights P (2011) Simultaneous optimisation of stope layouts and long term production schedules. Mining Technology, 120(3):129-136.

[2] Sens J, Topal E (2009) A new algorithm for stope boundary optimisation. Proceedings of New Leaders. Australasian Institute of Mining and Metallurgy. 25-28.

[3] Riddle J M (1977) A dynamic programming solution of a block-caving mine layout. In Proceeding of the 14th International Symposium on Application of Computers and Operations Research in the Minerals Industries. Society for Mining, Metallurgy and Exploration. 767-780.

[4] Cheimanoff N M, Deliac E P, Mallet J L (1989) GEOCAD: an alternative CAD and artificial intelligence tool that helps moving from geological resources to mineable reserves. In 21st International Symposium on the Application of Computers and Operations Research in the Mineral Industry. 471-478.

[5] Ataee-Pour M (2005) A critical survey of the existing stope layout optimization techniques. Journal of Mining Science. 41(5):447-466.

[6] Ovanic J, Young D S (1995) Economic optimization of stope geometry using separable programming with special branch and bound techniques. Paper presented at the 3rd Canadian Conference on Computer Applications in the Mineral Industry, McGill University.

[7] Ovanic J, Young D S (1999) Economic optimisation of open stope geometry. Paper presented at the 28th International APCOM Symposium, Colorado School of Mines, Golden.

[8] Mirzaeian Y, Ataee-pour M (2011) Optimization of Stope Geometry Using Piecewise Linear Function and MIP Approach. Journal of Civil & Environmental Engineering and Science Technology. 43(1):79–87.

[9] Alford C (1995) Optimisation in underground mine design, Proceeding of the 25th International APCOM Symposium Australasian Institute of Mining and Metallurgy, Brisbane. 213-218.

[10] CAE Studio 3. (2014) software available at http://www.cae.com/mining/

[11] Cawrse I (2001) Multiple Pass Floating Stope Process. Paper presented at the 4th Biennial Strategic Mine Planning Conference, Melbourne.

[12] Deraisme J, De Fouquet C, Fraisse H (1984) Geostatistical orebody model for computer optimization of profits from different underground mining methods.18th APCOM IMM.

[13] Ataee-pour M (2000) A heuristic algorithm to optimise stope boundaries. Doctor of Philosophy University of Wollongong,

New South Wales, Australia.

[14] Ataee-pour M (2004) Optimisation of stope limits using a heuristic approach. Transactions of the Institution of Mining and Metallurgy Section a-Mining Technology.113 (2):123-128.

[15] Grieco N, Dimitrakopoulos R (2007) managing grade risk in stope design optimisation: probabilistic mathematical programming model and application in sublevel stoping. Mining Technology. 116(2):49-57.

[16] Dimitrakopoulos R, Grieco N (2009) Stope design and geological uncertainty: quantification of risk in conventional designs and probabilistic alternative. Journal of Mining Science. 45(2):152-163.

[17] Topal E, Sens J (2010) A New Algorithm for Stope Boundary Optimization. Journal of Coal Science & Engineering (china). 6(2):13-119.

[18] Bai X Y, Marcotte D, Simon R (2013) Underground stope optimization with network flow method. Computers & Geosciences. 52:361-371.

[19] Jalali S E (2006) Optimization of Underground Mines Limits in Vein Type deposits, PhD Thesis, Amirkabir University of Technology, Iran.

[20] Jalali S E, Hosseini H (2009) Optimization of Extraction Range in Underground Mining Using a Greedy Algorithm, Journal of Science and Research in Mining Engineering. 4(9):1–11.

[21] Cormen T H, Leiserson C E, Rivest R L, Stein C (2001) Greedy algorithms. Introduction to algorithms. 1:329-355.

[22] Sandanayake D S S, Topal E, Asad M W A (2015) Designing an optimal stope layout for underground mining based on a heuristic algorithm. International Journal of Mining Science and Technology. 25(5):767-772.

[23] Sandanayake, D S S, Topal E, Asad M W A (2015) A heuristic approach to optimal design of an underground mine stope layout. Applied Soft Computing. 30:595-603.

[24] Erdogan G, Cigla M, Topal E, Yavuz M (2017) Implementation and comparison of four stope boundary optimization algorithms in an existing underground mine. International Journal of Mining, Reclamation and Environment. 31(6):389-403.

[25] Visual Studio (2013) Software available at https://www.visualstudio.com.

[26] Maanijou, M, Lentz, D R, Rasa I (2009) Chemical compositions of carbonate minerals from Chehlkoreh ore deposit, Iran: implications for evolution of base-metal mineralization.

[27] Tatiya R R (2005) Classification Stoping Methods. In Surface and Underground Excavations', London: Taylor & Francis Group. 415–431.

[28] Villaescusa E (2000) A review of sublevel stoping, MassMin. 577–590.