IOP Conf. Series: Earth and Environmental Science **95** (2017) 042077 doi:10.1088/1755-1315/95/4/042077

Application of Three Existing Stope Boundary Optimisation Methods in an Operating Underground Mine

Gamze Erdogan [1], Mahmut Yavuz [1]

[1] Eskisehir Osmangazi University, Eskisehir, Turkey

myavuz@ogu.edu.tr

Abstract. The underground mine planning and design optimisation process have received little attention because of complexity and variability of problems in underground mines. Although a number of optimisation studies and software tools are available and some of them, in special, have been implemented effectively to determine the ultimate-pit limits in an open pit mine, there is still a lack of studies for optimisation of ultimate stope boundaries in underground mines. The proposed approaches for this purpose aim at maximizing the economic profit by selecting the best possible layout under operational, technical and physical constraints. In this paper, the existing three heuristic techniques including Floating Stope Algorithm, Maximum Value Algorithm and Mineable Shape Optimiser (MSO) are examined for optimisation of stope layout in a case study. Each technique is assessed in terms of applicability, algorithm capabilities and limitations considering the underground mine planning challenges. Finally, the results are evaluated and compared.

1. Introduction

A typical underground mining project follows a series of significant technical stages. These stages span from the initial detection of a deposit from mineral exploration to the final mine reclamation stage (figure1). Among these stages, mine planning is done throughout the life of a mining operation. Optimization in term of underground mining focuses on basic three main areas: Optimisation of stope boundaries, optimisation of production schedule using predefined stope boundaries and finally optimisation of development [1].

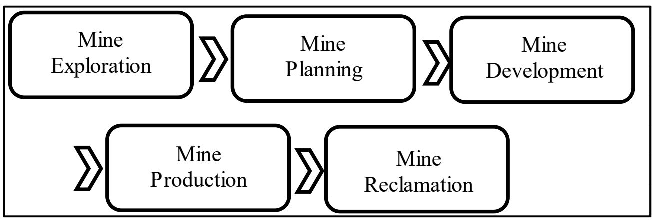

Figure 1. The main stages of a typical underground mining operation

Stopes can be defined as an excavation void created in an underground mine to remove the ore from surrounding rock. Figure 2 demonstrates a shape of stope in a typical underground mine. Boundary optimisation of it is a significant step of underground mine optimisation due to its direct impact on the economics of the project. It focuses on maximizing the economic profit by selecting the best possible layout; by considering operational, geotechnical and physical constraints. Moreover, it may be considered as a starting point in the full optimisation process when optimisation for both development and production schedule are also taken into account. This paper specifically focuses on stope boundary optimisation.

2. Stope Boundary Optimisation Methods

Although current industry practice is to make determination of the stope boundary manually, numerous methods have been developed for optimisation of ultimate stope boundaries [2]. Ovanic and Young [3, 4] offered the application of the branch and bound method for the economic optimisation of stope boundaries. In this method, the boundaries of stope are determined by optimising the starting and ending locations of mining within each row of blocks, by using two piecewise linear cumulative function. The algorithm uses "type-two special ordered sets" to facilitate the integration of constraints like stope length and Mixed Integer Programming to formulate search of a stope. The branch and bound method allows regular or orthogonal block geometry so blocks can be formed following the geologic variation and discontinuities. However, it optimises the stope boundary in one dimension and neglects the wall slope constrains.

Alfrod [5] developed the Floating Stope algorithm to determine the boundaries of mineable ore. The algorithm is implemented on a fixed ore body block model and discriminate blocks as ore or waste. Then it tries to maximise ore tonnes, contaminated metal, ore grade or economic value within given ore body model. It is described as a heuristic algorithm.

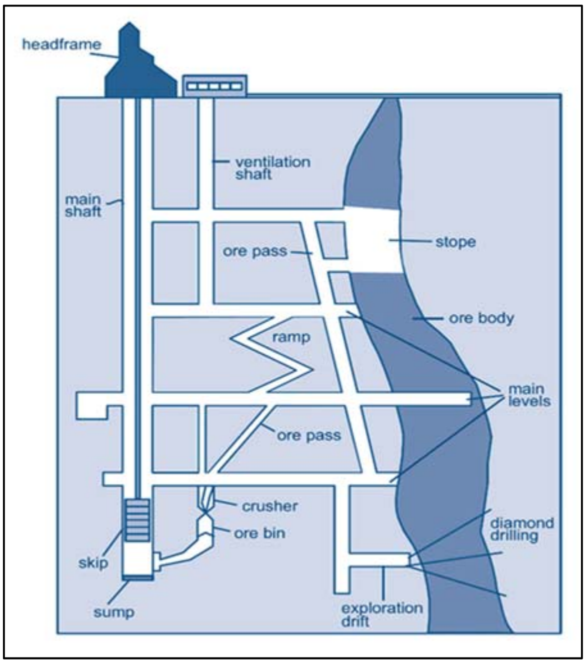

Figure 2. Cross-section through a typical underground mine **[6]**

Cawrse [7] developed the Multiple Pass Floating Stope Process (MPFSP) to help overcome some of the shortcomings of the Floating Stope Algorithm. In this modified method, sets of multiple input parameters are defined that each includes i.e. head grade, cut-off grade, and maximum waste inclusion. Then, a stope envelope is created for each set of parameters. These envelopes provide extra information that can be used during the mine design process to improve the efficiency and hence profitability of mine designs. The method can assist stope boundary selection and design but it does not generate optimum stope layouts [7].

Ataee-Pour [8] developed a heuristic approach, described as the Maximum Value Neighbourhood method (MVN) in order to optimise stope boundaries. The algorithm works according to the neighbourhood concept that searches the optimal neighbourhood based on an economic value for each block in ore body model.

Alford and Hall [9] developed a method for automated stope design**.** In this method, the stope optimisation is run at a sequence of cut-off grades to generate a series of 'nested stopes' which is a similar concept in the pit optimisation where 'nested pits' are generated. The method is able to define the best set of extraction levels and stope heights. However, it does not take into account mining cost as a function of the size and the shape of the stope. It specifies a fixed cut-off grade in the design process, which does not allow an optimum solution.

Sens and Topal [10] developed a heuristic approach for stope boundary optimisation. The algorithm consists of three basic parts that are block converter, stope optimizer and visualizer. The block converter process convert a block model contain blocks with different sizes to a regularised block model with uniform block sizes. The stope optimiser uses this regularised block model to determine the optimum stope boundaries based on the assumed economic parameters, such as costs and metal price. The optimum stope boundaries can be created using fixed and variable stope sizes and different selection strategies. Finally, visualizer shows the results to examine. The algorithm eliminates overlapping stopes in the solution unlike floating stope algorithm. However, stopes are selected in order of user's preference, such as, from maximum to minimum economic values. This limits the consideration of all combinations of stope designs.

Bai et al. [11] developed a stope optimisation method that is based on graph theory and specifically applicable for the sublevel stopping method. The algorithm called as network flow is based a cylindrical coordinate system, which is defined around a specified vertical raise. In the process, an individual mining block is selected for a stope by considering reference distance to the raise along width stope width design parameter under geotechnical constraints on hanging wall and footwall slopes. Then the algorithm optimises the stope profit as a function of location and height of the raise. However, the algorithm is limited to relatively small sub vertical deposits mined by the sublevel stopping method.

Sandayaneke et al. [12] proposed a new 3D heuristic algorithm for the stope layout optimisation. It finds a unique solution that maximises the economic value of the stope layout under physical and geotechnical constraints. The suggested algorithm recommends the unique solution for stope layout and generates non-overlapping stopes. Moreover, it includes variable stope sizes with or without pillars and satisfies the mining and geotechnical constraints. However, in order to find the optimal solution, algorithm needs to evaluate all the possible unique combinations, which require significant computational power in large-scale applications. This limits the algorithm to find the optimal solutions in large-scale data sets.

Apart from these algorithms, in recent years there has been a growing trend for developing and improving software tools to overcome design, plan and operation problems of underground mines. Minable Shape Optimizer is one of them and it is already commercially available. This optimizer is a strategic mine planning tool which is a module within Datamine Studio 3 [13]. It searches for the optimal mineable shapes taking into account the orebody geometry and tries to generate the optimal size, shape and location of stopes for underground mine design in a block model based upon input parameters by the user such as minimum and maximum stope widths, cut-off grade, etc. [14].

3. Material and methods

Traditional ways for design of the underground production areas (stope boundaries) can be very time consuming because it requires a large number of iteration [15]. Moreover, manual methods for determination of these boundaries depend on individual engineers' experiences and judgments that do not always give true optimum results. Thus, as mentioned above, numerous studies have been developed to solve the problems of ultimate stope limits. In this paper, three of these studies, which are called Floating Stope Algorithm, Maximum Value Algorithm and Mineable Shape Optimiser tool, are examined in detail. They applied into a realistic ore body model for a gold deposit and their capabilities of producing optimum results are investigated. Furthermore, their restrictions and applicability are evaluated in given orebody model.

The examined ore body model that represents a gold deposit is main input for all methods. It contains 1,214,124 blocks of regular size with 1m x 2.5m x 2.5m dimensions along x, y, z respectively. The minimum and maximum grade of ore as the equivalent gold (EQAU) is 0g/t and 30.46g/t, respectively. In addition, the material density ranges from 2.5 to 3.73 ton/m^3. It was necessary to express blocks in their net worth for a common implementation of the selected stope optimisation algorithms since some of them required the economic value for each block as input. Thus, the given ore body model (figure 3) was converted into an economic block model with a gold price of 1144 $/oz., mining and processing cost of 72.80 $/t and 34.55 $/t, a mine dilution of 13%, and processing recovery of 77%.

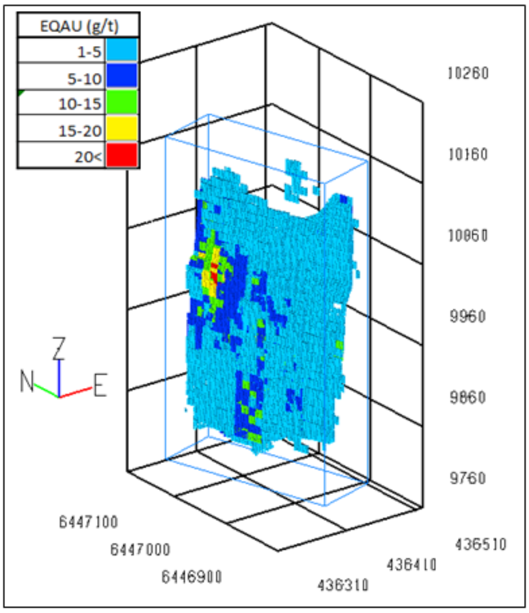

Figure 3. The orebody block model of a gold deposit

The other significant input for all methods is stope size and it was determined as 6m x 20m x 25m along the x, y and z directions from the feasibility studies of operating underground mine. Sublevels were developed at 25m spacing because of the limit of the drilling accuracy of long-hole production drill rigs. Stopes lengths were limited to a hydraulic radius that is neither too conservative nor aggressive.

3.1 Implementation of the Floating Stope algorithm

Floating Stope algorithm’s logic is similar to moving cone method for open pit optimisation. At the beginning of the optimisation process, a cut-off grade is determined to classify a block either as ore or as waste based on economic assumptions. Addition to this, a target head grade is also specified to evaluate any given stope in question later in the process. The process also specifies a stope geometry (in 3D), which represents the required minimum stope dimension. The Floating Stope Algorithm creates two distinct envelopes. The first one is called inner envelope that is constructed by adding blocks that are above the specified cut-off grade. This represents the union of the best grade shapes. The second envelope, which is called 'outer' envelope, is also constructed on top of inner envelope and it is the union of all possible stope positions for each block above cut off. Figure 4 gives a sectional example of inner and outer envelopes. The final stope design should be as close to the inner envelope, and fall within the outer envelope.

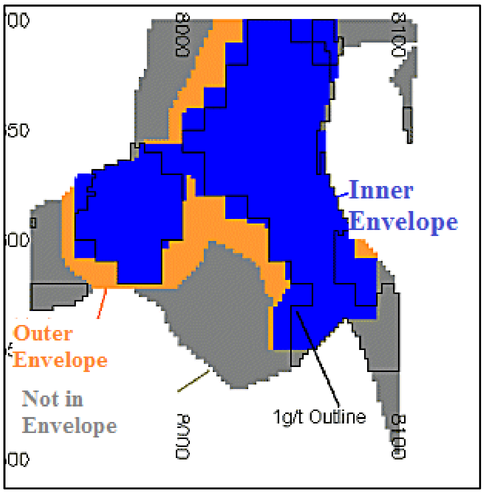

Figure 4. The "inner" and the "outer" envelope [15]

The Mineable Reserves Optimiser (MRO) is a tool based on the 'Floating Stope' algorithm in DATAMINE software [16]. For this study, MRO uses the economic block model of the gold deposit to present Floating Stope algorithm's performance. It sets both cut-off grade and head grade to 3.85 g/t and selects the optimization method as maximizing grade to select the best minimum mining unit (stope dimension) position. The MMU dimensions are specified as a stope size of 6m x 20m x 25m. Besides the minimum mining Unit (MMU), it requires that a step size should be defined. This is used to float the MMU within the block model. For this study, individual block dimension of 1m x 2.5m x 2.5m is used.

After optimization process, two envelopes, which include overlapping stopes, is created which can be seen in figure 5. Each envelope is assigned to a colour that depends on its envelope number. The optimal solutions that is generated using this approach contain $ 42,826,547.00 net profit and 0:02:13 (h:min:s) solution time.

This algorithm is a simple and general process that does not consider any specific underground mining method. However, it generates overlapping stopes when two or more stopes share high-grade blocks [5, 17]. In addition, it does not take into account any geotechnical and operation constraints. Therefore, it requires engineers' manual adjustment to define the ultimate boundary that can be considered as optimal shape. The algorithm can only be used to guide the mine designs; it cannot be directly used for final stope layout. Furthermore, it does not consider variable stope sizes, inclusion of mining levels and barrier pillars.

3.2 Implementation of the Maximum Value Neighbourhood algorithm

The MVN method works with a fixed 3D block model to find the best neighbourhood of a block, which guarantees the maximum net value while imposing certain geotechnical and mining constraints, such as, the minimum stope size and the maximum stope height. During the optimisation process, first the economic values of each block are determined. Then the economic value of each block combined with surrounding blocks is calculated and are considered the neighbourhood block value (NBV) in each neighbourhood.

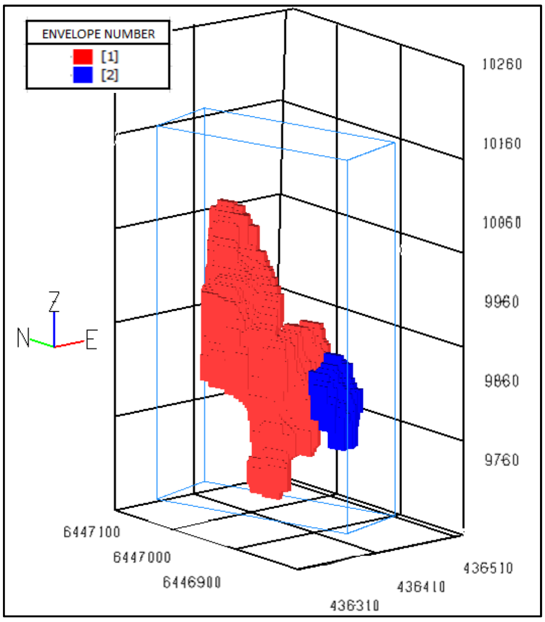

Figure 5. Output outline of Floating Stope algorithm.

The size of the neighbourhood is equal to the minimum stope size (in blocks). figure 6 depicts an example of minimum stope size and possible neighbourhoods for a block. Then, the neighbourhood values are compared and the neighbourhood with the highest total economic value (NBV) is considered the maximum net value, accumulated into an economic stope boundary and given a code indicating such.

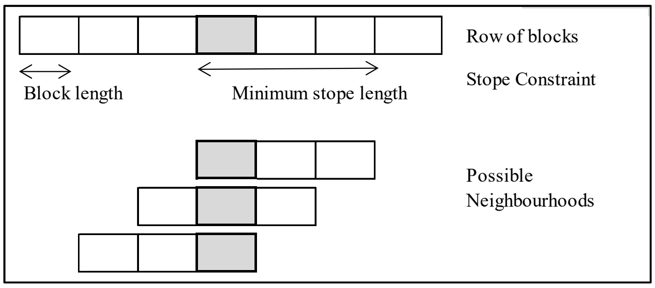

Figure 6. Example of minimum stope size and the neighbourhoods in one dimension

MineSight Stope (**MSStope**) is an underground mine evaluation and scheduling tool within MineSight 3D software package [18]. MSStope utilizes the MVN (Maximum Value Neighbourhood) algorithm to search for the best possible combination of blocks that will produce maximum profits. In this study, the algorithm uses the economic block model that was calculated at the beginning of this study. In addition, it works with a fixed stope size that was determined for the given deposit. The stope dimensions in MSTOPE must be defined as the number of blocks. So, 6x8x10, which is equivalent to 6m x 20m x 25m, is implemented.

In MineSight Stope (MSStope), the basic stope dimensions can be set for each level and select that levels to use and exclude. In this study, all levels with the same stope dimensions are used to generate stope boundary. At the end of the process, the algorithm produces a set of mining blocks, which is colour coded based on its grade. This particular method cannot outline mineable stope but it gives a shape that could be mined economically. Figure 7 illustrates the stopping boundary generated. The solutions of this approach contain 44,998,078 ($) net value that is more profitable than the results of Floating Stope algorithm. It solve this optimisation problem in 0:01:56 (h:min:s) solution time and gives 18 stopes (total block sets).

The Maximum Value algorithm guarantees that the overlapping stope problem introduced in Floating Stope algorithm is not produced as part of the optimisation process. However, changing the starting location can changes the set of stope layouts generated from the same orebody. Furthermore, it does not take into account, variable stope sizes and some geotechnical and operation constrains such as barrier pillars, slope constraints etc.

3.3 Implementation of Mineable Shape Optimizer

The Mineable stope optimizer needs an input block model that provides the grade or value and density data of the mineral resource. Then it generally uses a cut-off grade value to find optimal mineable shapes. In Mineable Shape

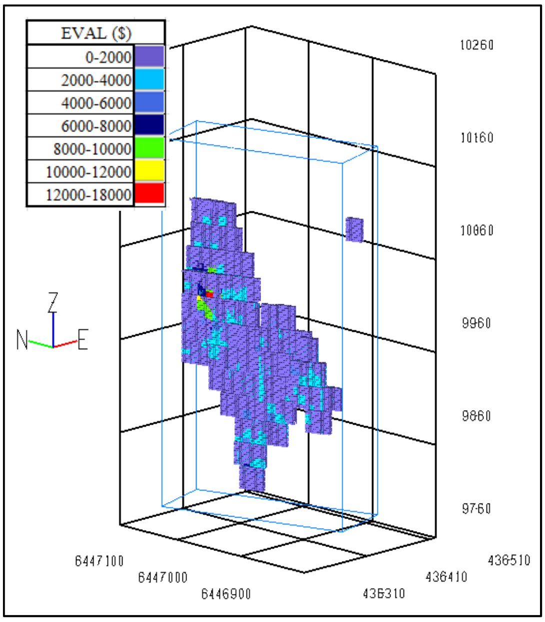

Figure 7. Output outline of Maximum Value Neighbourhood Algorithm

Optimizer, optimization process identifies a shape framework that describes the volume within which mineable shapes are generated. In Shape Framework, firstly approximate size, location and basic stope shape (the seed shape) are determined by respecting some design constrains as set by user. This seed shapes are created by using slices aligned with the dip and strike of the orebody. Above the defined cut-off, the MSO aims to create a seed shape that is optimal combination of slices but it is very basic and only defines potential stopes or pillars. Therefore, once seed shape has been created, the second stage anneals the seed shape to the final stope shape subject to stope and pillar geometry constraints. This stage of optimisation creates practical stope shapes that more accurately fit the geology.

In this study, a cut-off grade of 3.85 g/t is used for determining the optimal stopes. The shape framework, which defines the volume within which mineable shapes are generated, is selected identical with this block model in terms of the rotation definitions and the origin. The level spacing and section spacing for stope evaluation is defined as height and length of the stope, respectively. For the orientation settings, general strike of the orebody is selected along YZ axis. MSO needs to define shape control that determines basic geometric parameters to be used in stope design calculations. In this paper, only minimum and maximum stope width are set to 6 and 20 meters, and minimum waste pillar width, near & far wall dilution, minimum & maximum dip angle and the other advanced parameters is not defined to match the comparison with other methods. The results that are generated using this approach contain 41 stopes, $ 50,294,808.84 net profit and 0:00:50 solution time. They show that the solution value obtained by using MSO farther profitable than the other methods. The output of the MSO can be also seen in figure 8. The mineable shapes are colour coded based Stope Values ($).

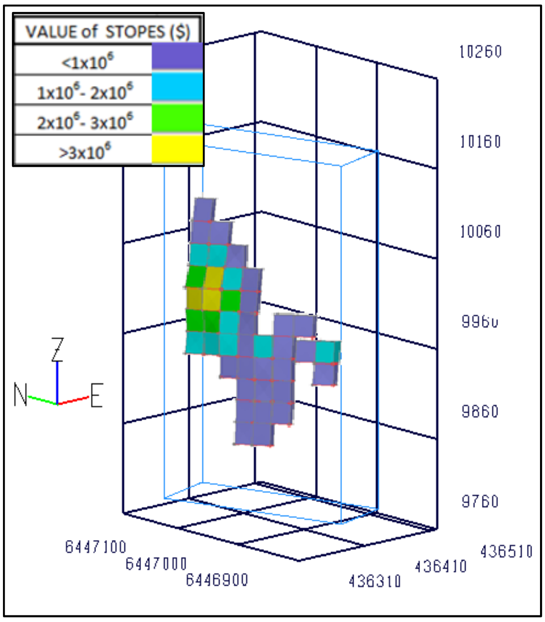

Figure 8. Output outline of Mineable Shape Optimiser

Mineable Shape Optimiser (MSO) can generate and evaluate thousands of iterations, in view of stope geometry, geological and geotechnical constraints to find the optimal shapes and pillar that maximise value [19].It is detailed application allowing constrains such as hanging wall and footwall dip angles, width, pillars between parallel stopes and more. These limitations can be also applied on the dip and strike of the final stope shape. Moreover, it can be used for a wide range of underground mining methods and it provides solution for massive, sub-vertical and flat horizontal deposits. However, the specification of a cut-off grade in mine design and planning, it automatically disrupts the optimality [20].

4. Results and discussion

This paper presents an implementation of three methods of stope boundary optimization (Floating Stope algorithm, Maximum Value algorithm and Mineable Shape Optimizer) in a real block model. All these methods take the orebody block model as a main input and try to find optimum solutions that maximize the economic value of the stope boundary. During their optimizations, Mineable Shape Optimizer can take into account many geotechnical and physical constrains, whereas Floating Stope algorithm considers hardly any constrains. In addition, Maximum Value algorithm needs to determine more constrains to achieve optimum solution.

It can be seen from the figure 9 that the highest net profit is obtained from Mineable Shape Optimizer for the same orebody block model. In addition, the solution times of methods are close to each other and all of them are less than 3 minutes. Finally, Floating Stope algorithm provides only envelops and Maximum Value algorithm produce only a set of mining blocks rather than a set of stope shapes that is an important part of underground mining. .

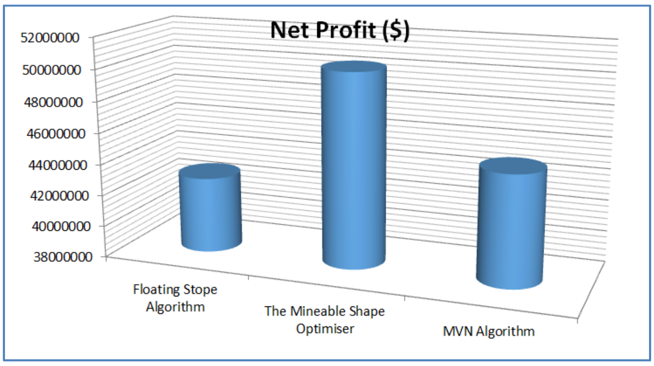

Figure 9. Net profit results of selected methods

5. Conclusion

The stope boundary optimization is vital part of an underground mine planning. However, methods that have been developed up to now are generally heuristics for solving 3D problems of stope boundary optimization. It means that they are based on searching for the optimal solution according to some rules [21]. In this paper, three heuristic methods of stope boundary optimization were examined, and it is observed that all of them generated approximate solutions rather than true optimum solutions. Therefore, there is a clear need for improved algorithms and software that guarantee optimal solutions. Moreover, the underground optimization techniques should be considered as a whole and techniques should be developed that covers all three areas of optimization: stope boundary optimization, development and production schedule optimization in the future.

References

[1] E. Topal, "Early start and late start algorithms to improve the solution time for long term underground mine scheduling," SAIMM, South African Institute of Mining and Metallurgy Journal, 108(2): 99-1079, 2008.

[2] T. Copland, M. Nehring, "Integrated optimization of stope boundary selection and scheduling for sublevel stopping operations," The Journal of the South African Institute of Mining and Metallurgy, Vol. 116, pp. 1135-1142, 2016.

[3] J. Ovanic, D. S. Young, "Economic optimization of stope geometry using separable programming with special branch and bound technique," 3rd Canadian conference on Computer Applications in the Minerals Industry, pp. 129-135, 1995.

[4] J. Ovanic, D. S. Young, "Economic optimization of open stope geometry," 28th international APCOM Symposium, pp. 855-862, 1999.

[5] C. Alford, "Optimization in underground mine design," 25th International APCOM Symposium, pp. 213–218, 1995.

[6] Environmental Code of Practice for Metal Mines, available at: https://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=CBE3CD59-1&offset=4 (accessed 08.04.2016).

[7] I. Cawrse, "Multiple pass floating stope process," Strategic Mine Planning Conference, pp. 87-94, 2001.

[8] M. Ataee-Pour, "A Heuristic Algorithm to Optimize Stope Boundaries," Doctor of Philosophy, University of Wollongong, 2000.

[9] C. Alford, B. Hall, "Stope optimization tools for the selection of optimum cut-off grade in underground mine design," Proceedings of Project Evaluation Conference, pp. 137-144, 2009.
[10] E. Topal, J. Sens, "A new algorithm for stope boundary optimization," Journal of Coal Science & Engineering, 16 (2) pp. 113–119, 2010.
[11] X. Bai, D. Marcotte, R. Simon, "Underground stope optimization with network flow method," Computer Geoscience, 52 pp. 361–371, 2012.
[12] D.S.S. Sandanayake, "Stope Boundary Optimization in Underground Mining Based on a Heuristic Approach," Doctor of Philosophy, University of Curtin, 2015.
[13] DATAMINE Studio RM v1.1, 2015, CAE Studio 3, Software available at www.dataminesoftware.com (accessed 20.05.2016).
[14] S. Keane, "Optimization Improvements in Whittle using Stope Optimization Software," Mine Planning and Equipment Selection (MPES) Conference, Fremantle, WA, pp. 121-128, 2010.
[15] M.T. Bootsma, "Cut-off Grade Based Sublevel Stope Mine Optimization, Introduction and evaluation of an optimization approach and method for grade risk quantification," TA Report number: AES/RE/13-44, Delft University of Technology, 2013.
[16] Copyright © Datamine Corporate Limited, Mineable Reserves Optimizer (MRO), available at: http://www.dataminesoftware.com/software/underground-planning-software/strategic-planning optimization/mineable-reserves-optimizer-mro/ (accessed 08.06.2016).
[17] C. Alford, M. Brazil, D. H. Lee, "Optimization in underground mining," Handbook of Operations Research in Natural Resources pp. 561-577, Available at: http://link.springer.com/chapter/10.1007%2F978-0-387-71815-6-30, 2007.
[18] MineSight ® v8, 10-60, 2015. Software available at http://www.minesight.com
[19] Alford Mining Systems, available at: http://alfordminingsystems.com/?page_id=74 (accessed 01.05.2016).
[20] L. Little, "Simultaneous optimisation of stope layouts and production schedules for long-term underground mine planning," PhD thesis, The University of Queensland, pp.15-38, 2012.
[21] M. Ataee-Pour, "A critical survey of the existing stope layout optimization techniques," Journal of Mining Science 41 pp. 447-466. 2005.