Resources Optimization in Underground Gold Mining
Case Study the Kubang Cicau Gold Vein in Pongkor Area, West Java, Indonesia

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Abstract. Mining activities are typically controlled by the smallest mining units (SMU). These SMUs comprise mining blocks with dimensions that are generally adjusted to the mining equipment used as well as various geotechnical factors. In addition to SMUs, the smallest mining decision unit (SMDU), which is a collection of several SMU blocks, is usually established. In this paper, the SMDU is represented by an underground (UG) mining panel. This paper presents the results of a study on the optimization of gold resource in SMU blocks within SMDU and cut-off grade (CoG) variations. The study focuses on how to design a panel as an SMDU that is based on a weekly production quota that defines an optimum weekly rate of production that meets processing and milling capacities. The UG mining scheme in this paper is realized using a level, a panel, and SMU blocks. The level represents the progress of the mining in a vertical direction, while the panel represents the progress of the mining in a horizontal direction. Acting as the objective functions are the ore tonnage and gold mass. In relation to the gold mass, the goal is to reach the optimum level within the SMDU and fulfill the constraint function through the number of SMU blocks within the SMDU and the range of CoG variations. The optimization process was conducted using a genetic algorithm scheme. Kubang Cicau Vein B at Pongkor Gold Mine Business Unit was selected for the case study.

1. Introduction
In underground (UG) gold mining, resources are often optimized due to mining constraints and modification factors related to the aspects of technical, social, environmental, geometry, costs, metal prices and gold content limitations usually referred to as cut-off grades (CoGs). Resource optimization is a process used to produce optimal reserves, and thus resulting in optimal benefits, which is typically measured by the net present value (NPV). This paper focuses on the optimization of gold resources in the smallest mining unit (SMU) blocks and CoG variations. More specifically, the paper explores how to determine the smallest mining decision unit (SMDU) that contains SMU blocks under certain CoG variations to obtain the optimal level of gold resources in the SMDU.

Selective mining is predominantly based on CoGs, meaning that not all materials are extracted – only those in the zone of high grade. Conversely, the geometry of the SMDU also depends on the CoG. The
optimization of the CoG is essential to maximize the NPV [1], which was initially developed by [2] and [3], who limited every operation that affected the profits made from mining, processing and refining. Lane’s theory in [2] and [3] focused on the CoG optimization of mining, not on the optimization of mining against SMDU. Thus far, Lane’s theory in [2], [3] has been predominantly applied to open-pit mining. However, the application of Lane’s method to UG mining was conducted by [1], [4] and [5], who applied the method to CoG-based sublevel stope mine optimization.

The objective of this paper is to explore the development of an optimized model of gold resources to accommodate long-term planning based on dynamic CoGs, which comprise the preliminary method for optimizing gold resources in this study. The case study was conducted at Pongkor Gold Mine Business Unit (UBPE Pongkor) in the Kubang Cicau gold vein mineralization zone. The optimization of gold resources was carried out in the presence of mining constraints using the cut and fill mining method and variations in the number of SMU blocks and CoGs.

2. Methods
Gold resources within orebodies are defined as the ore tonnage or quantity of gold mass in blocks that are limited by the grade of the gold as well as physical boundaries of geology, hydrogeology, hydrology, geomorphology, etc. The blocks were designed according to the SMU using geometry that is limited by the size of the mining equipment used, and the geometry of the orebody and various geotechnical constraints. In this paper, gold resources within the orebody were optimized subject to these constraints to obtain optimal ore tonnage and, or gold mass. The optimal number of blocks in the SMDU were selected according to the CoGs within the range stated. To support a long-term UG plan, the UG process was optimized using the cut and fill technique by proceeding downwards using CoG variations. The data and the method used will now be explained.

2.1. Smallest Mining Unit (SMU)
The modeling of spatial gold grade distribution was conducted using ordinary kriging for block sizes that were designed as SMUs. Geometrical variables were used in the direction of dip with adjustments for the geometry of the orebody, and geotechnical factors as well as the mining equipment used. The number of blocks needed to be limited based on the zone / body of the mineralization domain and according to the mining target. This limitation resulted in variations in the dimensions of the block. However, reducing the dimensions of the SMU blocks affected the resources, as each block had a different value. The criteria of the resources that can be converted into reserves were measured and indicated, based on the Australian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC), which comprised the base model used in this study.

2.2. Panel and Level
The spatial distribution of the SMU blocks was then arranged according to the short-term plan, which was based on the weekly production capacity referred to as the panel. The panel is a cumulation of SMU blocks along the strike of the orebody, while the level accommodates those panels at each elevation interval that fit the height of the SMU blocks. The dimension of the panel used in this study indirectly provided the quantity and gold grade per panel. Thus, the panel can be considered the most short-term SMDU in terms of weekly production. These determinants were closely related to the operating costs. Its size in each level varied due to variations in the configuration and dimension of the SMU blocks.

2.3. Optimization and Decision Model
Concerning the main objective of this study, the number of SMU blocks and the variations in the CoG represented the parameters to be determined. These parameters are expressed by chromosomes in the optimization procedure using a genetic algorithm (GA) scheme. The panel is considered as the basis of optimization, i.e., the mining decision unit. The goal was to optimize the quantity of ore tonnage and,
or the quantity of gold mass in the total number of considered levels. This quantity was then formulated into the maximization of the objective function, which is expressed as follows:

\[
Z_t = \sum_{i=nL}^{i=nP} \sum_{j=nL}^{j=nP} \sum_{k=nB}^{k=nB} \left( B_{ix}^j \cdot B_{iy}^j \cdot B_{iz}^j \right) \cdot (RD)
\]

\[
Z_g = \sum_{i=nL}^{i=nP} \sum_{j=nL}^{j=nP} \sum_{k=nB}^{k=nB} \left( B_{ix}^j \cdot B_{iy}^j \cdot B_{iz}^j \right) \cdot (RD) \cdot \left( \gamma_{ijk} \right)
\]

\[
K = \frac{Z_t}{Z_g}
\]

where \(i, j, k\) are the summation indexes; \(nL, nP, nB\) are the number of levels, the number of panels, and the number of SMU blocks within each panel, respectively; \(B_x, B_y, B_z, RD\), \(\gamma\) are the width of the SMU blocks in the dip direction, the length of the SMU blocks in the strike direction, the height of the SMU blocks, and the rock density and variable CoG, respectively; \(Z_t, Z_g, K\) are the ore production (tonnage), quantity of gold mass, and average quantity of gold mass in the considered number of levels, respectively. The objective function expressed by Eq. (1) was calculated based on the assumption that there were no geological losses. Eq. (1) defines the equation of ore tonnage, while Eq. (2) quantifies the gold mass in the considered number of levels.

Eq. (1) and (2) are limited by two constraints – namely, the range of SMU blocks within the panel and the range of CoG variations. Concerning the summary of the decision model given above, some constraints were noted and are presented below:

a. The number of SMU blocks was set within the range of \(nB_{\text{min}} = 2\) blocks to \(nB_{\text{max}} = 8\) blocks. The constraint related to the range of SMU blocks can be expressed as:

\[
nB = \text{integer}\left[ nB_{\text{min}}, nB_{\text{max}} \right].
\]

b. The CoG variation was set within the range of \(\gamma_{\text{min}} = 2.00\) g/ton to \(\gamma_{\text{max}} = 12.58\) g/ton. The constraint related to the range of CoG variation can be expressed as:

\[
\gamma = \left[ \gamma_{\text{min}}, \gamma_{\text{max}} \right].
\]

The minimum CoG for the resources model (i.e., the economic threshold that may be converted into reserves) was placed at 2 g/ton of gold grade in each block following [6]. This reduce the weight, as 33.5% of blocks contained a grade lower than 2.00 g/ton of gold content. The maximum gold grade used in this paper for the optimization of gold resources was set at 12.58 g/ton. The dimension of the SMU blocks in the direction of the strike \((B_x)\), the height of the SMU blocks \((B_z)\), and the rock density comprised the constants. Concerning the number of SMU blocks, the integer constraint was used to facilitate the simplified optimization process.

2.4. Optimization Process for the Optimization of Gold Resources

The following steps explain the optimization process, which used the GA scheme.

- **Step 1**: The CoG value was determined within the range of CoG variations. The determination of said value was based on an economic analysis that served as the basis for the optimization calculations.

- **Step 2**: The dimension of the SMU blocks, the rock density, the range of CoG variations, and the number of levels. Panels were given and SMU blocks were then calculated.
- **Step 3**: The ore tonnage and gold mass were calculated by completing the objective functions in Eq. (1) and (2) for the number of SMU blocks within the range of SMU blocks ($k = nB_{\text{min}} \ldots \ldots \ldots \ldots nB_{\text{max}}$), for the number of panels on a certain level within the range of panels ($j = 1, \ldots \ldots \ldots \ldots nP$), and for the number of levels ($i = 1, \ldots \ldots \ldots \ldots nL$).

- **Step 4**: The ore tonnage and gold mass were optimized using the GA scheme by selecting the maximum ore tonnage and maximum gold mass obtained on the particular number of SMU blocks and CoG values.

- **Step 5**: Step 1 was repeated for the other CoG values within the range of CoG variations.

Optimization using the GA scheme shows its effectiveness and efficiency for a wide range of SMU blocks in large-scale mining production. For small-scale weekly production, the range of number of SMU blocks is not so large, so optimization can be conducted manually.

### 3. Case Study

UG mining in the Kubang Cicau gold vein mineralization zone was chosen as the case study, as some of the requirements for the implementation of the proposed method were met, including: (1) having a wide-range grade distribution and (2) having a medium-sized average grade.

**3.1. Kubang Cicau Vein B**

According to [7], Kubang Cicau is one of the four main veins of the Pongkor deposit. The three other veins are Pasir Jawa, Ciguha, and Ciurug. It is between 950–1,500m long and has an average thickness of 1.6–7.8m. The Kubang Cicau vein has a similar facies assemblage and mineral zone as the Ciguha vein, with dominant BOQ facies. The pitch of the ore shoots is steep to the south, meaning that it is parallel to the mineral zoning of the vein. The southern extension of the Kubang Cicau vein has an anastomosing calcitic stockwork bounded by a rim of chlorite and disseminated sulfides. The study will focus on the Kubang Cicau Vein B, which is 500 masl, between 375 and 475 masl, and possesses the following characteristics:

- $X_{\text{local}}$: 10,714–10,812 m
- $Y_{\text{local}}$: 7,914–8,136 m
- $Z_{\text{local}}$: 353–475 masl
- Strike: N 341° E
- Dip direction: N 79° E
- Dip: 72°

The local coordinates were set by the UBPE Pongkor, which is the primary mining operator in the area. Based on a statistical analysis of 1,474 drill samples, the following data were obtained: the gold grade averaged at 17.75 ppm, with a standard deviation of 9.77 ppm and a top cut of 90% probability at 29.47 ppm. The spherical semivariogram shows the correlation between data with a range of 15 m in the direction of 90°N, 70°E/ (N–S), and a range of 18 m in the direction of N0°E (E–W). The estimation of the block models was conducted using ordinary kriging with a configuration of a block size of 15m x 3m x 5m against the XYZ axis and then cut using sedimentary geometrical constraints. The dimension of the X-axis was variable, while the dimensions on the Y and Z axis were constant. The gold resources can be categorized as having been measured or indicated based on the kriging variance. The geometry of the block models used in this study was limited by the following boundary: 10,642–10,816 m on the local X-axis, 7,857–8,647 m on the local Y-axis and 350–475 masl on the Z-axis.
4. Results and Discussion

The resource models that may be converted to reserves based on long-term CoG planning comprise the blocks that have a CoG greater than 2.00 ppm and that are within the classification of the measured and indicated reserves that are economically mined from 475 masl to 350 masl along a strike length of 800m. The number of SMU blocks used for resource estimation in this study was 6,600 blocks. The information was then processed using MATLAB software.

Table 1 presents the results of probable gold reserve optimization for the panel with variations in the number of SMU blocks as well as CoG variations. As mentioned, when using the terminology of the reserve, no classification is needed. Conversely, if the terminology of resources is to be used, then the average total resource is used to combine several resource classifications. At a CoG lower than 6 g/ton, the panel, as the smallest decision unit, will contain four SMU blocks that produce an optimum probable reserve. At a CoG of 6 g/ton, the panel will contain two SMU blocks that provide an optimum probable reserve.

| No | Number of SMU blocks | CoG (g/ton) | Ore (ton) | Av. grade (g/ton) |
|----|----------------------|-------------|-----------|-------------------|
| 1  | 2                    | 2.00        | 449,677   | 4.37              |
|    | 3                    | 452,285     |           | 4.35              |
|    | 4                    | 462,234     |           | 4.29              |
|    | 6                    | 462,957     |           | 4.28              |
|    | 8                    | 459,292     |           | 4.28              |
| 2  | 2                    | 3.11        | 321.989   | 5.11              |
|    | 3                    | 322.303     |           | 5.11              |
|    | 4                    | 324.244     |           | 5.09              |
|    | 6                    | 322.025     |           | 5.08              |
|    | 8                    | 324.281     |           | 5.05              |
| 3  | 2                    | 4.05        | 228,580   | 5.72              |
|    | 3                    | 229,970     |           | 5.70              |
|    | 4                    | 233,800     |           | 5.67              |
|    | 6                    | 229,890     |           | 5.67              |
|    | 8                    | 235,210     |           | 5.60              |
| 4  | 2                    | 6.00        | 63.907    | 7.97              |
|    | 3                    | 61.848      |           | 8.02              |
|    | 4                    | 63.366      |           | 7.94              |
|    | 6                    | 59.286      |           | 8.01              |
|    | 8                    | 57.605      |           | 8.00              |

The results of the optimization of gold resources, as stated in Table 1, are necessary for panels as the SMDU, which is a collection of several SMU blocks. The panel is based on short-term planning, which, in this paper, was a weekly production level of between 7,000–8,000 tons. Based on specific CoG criteria, the number of SMU blocks can be established in order to achieve optimum production capacity. Because panels are SMDUs, different treatments can be applied in terms of the mining process.
Resource estimation using CoG provides a greater amount compared to resources with independent CoG. This is because the use of panels involving individual blocks that have not been economically mean-graded, but the distribution is close to high-grade blocks, meaning that when they are combined, they provide an average grade according to the expected CoG. Based on spatial distribution modeling, the use of decision units is more applicable.

5. Conclusion
The computation of probable reserves using a panel that considers the short-term mining process contributes to more gold recovery than the use of a single SMU block, and it is practically advantageous in the case of a high variation of block grades in close range. The optimization of resources for short-term production capacity will ensure the stability of supply to processing / milling units.

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