Mining method selection for extracting moderately deep ore body using analytical hierarchy process at mindola sub-vertical shaft, Zambia

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Abstract: Mindola mine ore formation in Zambia comprises an interbedded sequence of argillites thinly banded to laminated dolomite and argillite. As a result of varying ore body characteristics, the mine has previously used different mining methods leading to increased mining cost. This study applies the Analytic Hierarchy Process (AHP) to determine a production method that fulfills the applicability requirement for mining a section of an ore-body below 4370 ft with the following characteristics: tabular; 45–90° of plunge; 10–20 m of ore thickness; intermediate grade; with moderate-to-strong ore and moderate side rocks. The mining method selected had to meet the following requirements: high recovery and lower powder factor. The AHP was applied because it can detect inconsistent judgements and provide a remedy for correction when dealing with complex decision making. The pairwise comparison matrix for criteria and weights was determined, followed by comparison of mining methods against each criterion. Synthesis of results for selecting a mining method was then done. Based on the assessed criteria, rock mass rating (RMR) ranked highest with

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PUBLIC INTEREST STATEMENT
Mining entities face a daunting task of selecting an appropriate mining method due to many factors required for evaluation such as the geological and rock mechanic properties of the ore-body and surrounding rock medium; environmental; engineering and economic factors. To date, there are many mining method section tools used for selecting a mining method. In this study, the Analytic Hierarchy Process (AHP) was used to determine a technically applicable production method at Mindola mine in Zambia based on the ore body characteristics and the need for high ore recovery and low powder factor rather than a mining method that incorporates many factors such as the economic and engineering aspects. The AHP was applied due to its ability to simplify complex decision analyses and test for consistency of judgement of participants. When the criteria were evaluated with the alternatives, the technically applicable mining method with the highest score of 18 % was VCR, followed by sublevel open stoping with 16.62 %.
23.83%, thickness with 15.31% and powder factor with 15.11%. When the criteria were evaluated with the alternatives, the technically applicable mining method with the highest score of 18% was Vertical Crater Retreat (VCR), followed by sublevel open stoping with 16.62%. Sensitivity analysis revealed that as the variables were altered by 1 to 6% and 5 to 25%, VCR remained as the technically applicable method rather than the production method that meets both economic and engineering conditions.

Subjects: Mining, Mineral & Petroleum Engineering; Civil, Environmental and Geotechnical Engineering; Engineering Economics

Keywords: mining method selection; analytic hierarchy process; moderate deep ore-body

1. Introduction
Selecting a mining method for mining moderately deep ore bodies can be a complex process due to many factors required for evaluation. Such factors include but are not limited to the following: shape, dip, grade, depth and rock mechanic properties of the ore-body and surrounding rock medium. To date, there are many mining method section tools used for selecting a mining method in the mining industry. However, no single tool has been universally accepted as a standard tool for mining method selection. This is due to the inability of such tools to incorporate all factors in the application process. There are several factors that

| Progression of scale | Definition | Explanation |
|----------------------|------------|-------------|
| 1                    | Equal importance | Two elements contribute equally to the property |
| 3                    | Moderate Importance | Experience and judgment slightly favour one over the other |
| 5                    | Strong Importance | Experience and judgment strongly favour one over another |
| 7                    | Very strong or demonstrated importance | An element is strongly favoured and its dominance is demonstrated in Practice. |
| 9                    | Extreme importance | The evidence favouring one element over another is one of the highest possible order of affirmation |
| 2, 4, 6, 8           | Intermediate values | Comprise is needed between two Judgments |

| Matrix Size | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| R           | 0.00| 0.00| 0.52| 0.89| 1.11| 1.25| 1.35| 1.40| 1.45| 1.49|
influence the selection of a mining method: Physical, mechanical and chemical characteristics of an ore-body and its host rock (compressive strength, weak planes, groundwater, mineralogy etc.); the value of mineral and grade; geometry of the deposit (thickness, size, shape and depth); labor (skilled and un-skilled); technology; environmental considerations; markets; production rate and availability of finance and capital. Ozyurt and Karadogani (2020) developed six different Artificial Neural Networks (ANN) models to evaluate geometric and rock mass properties of an underground mine, environmental factors and ventilation conditions to determine mining methods that satisfy the safety conditions for an underground mine. Geometric shapes e.g., tabular, lenticular reflect changes along strike and dip (Laubscher, 2000). There are cases where due to selecting improper mining methods, mines had to close. While selecting a mining method, ground stability and nature of the ore and enclosing rocks must be thoroughly studied (Ratan, 2005). In practice, there are cases in which the mining and geological factors allow the application of a certain mining method, but its application is not justified from the aspect of economic effects. There are also cases in which a certain mining method considers the application of certain types of machinery, but it is not justified from mining-technical factors (Bogdanovic et al., 2012).

| No. | Parameter                | Value           |
|-----|--------------------------|-----------------|
| 1   | Ore strength             | Moderate to strong |
| 2   | Ore Shape                | Tabular         |
| 3   | Grade                    | Intermediate    |
| 4   | Ore Thickness (m)        | 10-20           |
| 5   | Depth (m)                | Moderate        |
| 6   | Ore Plunge (°)           | 45°-90°         |
| 7   | Ore RMR                  | 60              |
| 8   | Hanging wall RMR         | 43              |
| 9   | Footwall RMR             | 74              |
| 10  | Grade Distribution       | Gradational     |
According to Karadogan and Ozyurt (2020), many traditional approaches of mining method selection techniques consider input parameters that are important at a given mine deposit, for this reason they are far from being an applicable model to all type of deposits. Another drawback of the existing techniques for selecting optimal underground mining methods requires the presence or prediction of all relevant criteria, therefore, in situations where one or more criteria are unknown, the techniques fail to offer a solution. To overcome this, Karadogan and Ozyurt (2020) developed ANN models that can make predictions in the presence of a lack of information by following technological developments and new findings obtained in scientific/sectoral studies if learning is continuous.

According to Brady and Brown (2005), differences between mining methods involve different techniques of performing the unit operations. The different operating techniques employed in the various methods result from the different geometric, geomechanical and geologic properties of the ore-body and the host rock medium.

Because of the large data involved, the mining method selection process can be complex. In the past, the various mining method selection techniques qualitative (profile, checklist and numerical ranking) have been applied: (Boshkov & Wright, 1973), (Morrison, 1976), (Laubscher, 1981), (Nicholas, 1981), (Hartman,1987) and Multi-Criteria Decision Models (MCDM): (Yagar,

| Criteria       | Ore Shape | Ore Thickness | Ore Plunge | RMR  | Depth | Ore Recovery | Powder Factor |
|----------------|-----------|---------------|------------|------|-------|--------------|---------------|
| Ore Shape      | 1         | 1/3           | 1/2        | 1/7  | 1     | 1            | 1             |
| Ore Thickness  | 3         | 1             | 1          | 1    | 1     | 1            | 1             |
| Ore Plunge     | 2         | 1             | 1          | 1/3  | 1     | 1            | 1             |
| RMR            | 7         | 1             | 3          | 1    | 2     | 1            | 1             |
| Depth          | 1         | 1             | 1          | 1/2  | 1     | 1            | 1/2           |
| Ore Recovery   | 1         | 1             | 1          | 1    | 1     | 1            | 1             |
| Powder Factor  | 1         | 1             | 1          | 1    | 2     | 1            | 1             |

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Table 6. Normalised elements of the comparison matrix and priority vector

| Criteria          | Ore Shape    | Ore Thickness | Ore Plunge | RMR | Depth | Ore Recovery | Powder Factor | Priority average |
|-------------------|--------------|---------------|------------|-----|-------|--------------|---------------|-----------------|
| Ore Shape         | 0.0625       | 0.0526        | 0.0588     | 0.0280 | 0.1111 | 0.1428       | 0.1538        | 0.08709         |
| Ore Thickness     | 0.1875       | 0.1580        | 0.1176     | 0.2012 | 0.1111 | 0.1428       | 0.1538        | 0.15314         |
| Ore Plunge        | 0.1250       | 0.1580        | 0.1176     | 0.0671 | 0.1111 | 0.1428       | 0.1538        | 0.12506         |
| RMR               | 0.4375       | 0.1580        | 0.3529     | 0.2012 | 0.2222 | 0.1428       | 0.1538        | 0.23834         |
| Depth             | 0.0625       | 0.1580        | 0.1176     | 0.1006 | 0.1111 | 0.1428       | 0.0769        | 0.10993         |
| Ore Recovery      | 0.0625       | 0.1580        | 0.1176     | 0.2012 | 0.1111 | 0.1428       | 0.1538        | 0.13529         |
| Powder Factor     | 0.0625       | 0.1580        | 0.1176     | 0.2012 | 0.2222 | 0.1428       | 0.1538        | 0.15116         |
| **SUM**           | 1            | 1             | 1          | 1     | 1      | 1            | 1             | 1               |

1978), AHP (T. L Saaty, 1980), FAHP, (Zadeh, 1975), PROMETHEE (Brans & Vincke, 1985), TOPSIS (Yoon and Hwang, 1995), MAHP (Ataei et al., 2013), Modified Nicolas Technique (Azadeh et al., 2010), Intergrated AHP and PROMETHEE (Bogdanovic D., 2012), FAHP—Guided Decision Model (Azadeh et al., 2015), Grey and TODIM methods (Denghani et al., 2017), Multiple Criteria Analysis (Gelvez & Aldana, 2014), AHP—Guided Decision Model (Gupta & Udaim, 2012), AHP-Vikor (Jiang et al., 2015), FAHP (Kazemi & Bagloo, 2015), Artificial Neural Networks and Game Theory, (Ozyurt & Karadogani, 2020), Integrated fuzzy cognitive map and fuzzy analytical hierarchy process (Kazemi et al., 2019), Multimodal Decomposition and HMM-based refinement HMM (Jiang et al., 2019). A comprehensive survey of literature on qualitative techniques can be found in Namin et al. (2009).The shortcomings of the qualitative approaches for evaluating appropriate mining methods are that they do not take into account criteria weights that impact the selection of the mining method (Sitoris et al., 2019), which is something that MCDM methods do. The application of AHP for selecting mining method has been used by different authors such as (Ataei et al., 2008), (Musingwini & Minnitt, 2008) and (Kazemi & Bagloo, 2015). This paper applies the AHP to select a mining method for exploiting moderately deep

Table 7. Comparison of mining methods against ore shape

| Shape                | Room and Pillar | Sublevel open stopping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel caving | Block caving |
|----------------------|-----------------|------------------------|-------------------------|--------------|-----------|----------------|--------------|
| Room and Pillar      | 1               | 3                      | 1                       | 1            | 1         | 3              | 3            |
| Sublevel open stopping | 1/3            | 1                      | 1                       | 1/3          | 1/3       | 1/3            | 1/3          |
| Vertical Crater Retreat | 1              | 1                      | 1                       | 3            | 3         | 1              | 1            |
| Cut and Fill         | 1               | 1/3                    | 1/3                     | 1/3          | 1/3       | 1/3            | 1/3          |
| Shrinkage            | 1               | 3                      | 1/3                     | 1            | 1/3       | 1              | 1            |
| Sublevel caving      | 1/3             | 3                      | 1/3                     | 3            | 3         | 1              | 1            |
| Block caving         | 1/3             | 3                      | 1/3                     | 3            | 3         | 1              | 1            |
| **SUM**              | 5               | 15                     | 5.7                     | 13           | 12.33     | 7              | 7            |
ore body at Mindola Sub-vertical Shaft. The AHP, introduced by Thomas Saaty (T. L. Saaty, 1980), is being applied because it is an effective tool for dealing with complex decision making. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of the decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker’s evaluations, thus reducing the bias in the decision making process.

This study investigates the technically applicable production method for mining the deposit at moderate depth below the 4370 ft at Mindola mine. The objectives of this study are, (1) To investigate the geology and geotechnical properties of the ore body, (2) To evaluate the feasible ore-body characteristics, geomechanical parameters, and ore recovery and powder factor, and (3) To establish the technically applicable mining method based on given criteria and minimal time required to reach a decision rather than the mining method that meets both economic, engineering and environmental factors to mine the deposit at moderate depth.

| Ore Shape         | Room and Pillar | Sublevel Open Stopping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving | Priority Vector |
|-------------------|-----------------|------------------------|-------------------------|--------------|-----------|-----------------|--------------|-----------------|
| Room and Pillar   | 0.2000          | 0.2000                 | 0.1754                  | 0.0769       | 0.0811    | 0.0426          | 0.4286       | 0.2272          |
| Sublevel Open Stopping | 0.0667      | 0.0600                 | 0.1754                  | 0.0769       | 0.0270    | 0.0476          | 0.0476       | 0.0716          |
| Vertical Crater Retreat | 0.2000     | 0.0600                 | 0.1754                  | 0.2308       | 0.2433    | 0.1428          | 0.1428       | 0.1707          |
| Cut and Fill      | 0.2000          | 0.0600                 | 0.0585                  | 0.0769       | 0.0811    | 0.0476          | 0.0476       | 0.0817          |
| Shrinkage         | 0.2000          | 0.2000                 | 0.0585                  | 0.0769       | 0.0811    | 0.0476          | 0.0476       | 0.1017          |
| Sublevel Caving   | 0.0667          | 0.2000                 | 0.1754                  | 0.2308       | 0.2433    | 0.1428          | 0.1428       | 0.1717          |
| Block caving      | 0.0667          | 0.2000                 | 0.1754                  | 0.2308       | 0.2433    | 0.1428          | 0.1428       | 0.1717          |
| SUM               | 1               | 1                      | 1                       | 1            | 1         | 1               | 1             | 1               |

| Thickness         | Room and Pillar | Sublevel Open Stopping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving |
|-------------------|-----------------|------------------------|-------------------------|--------------|-----------|-----------------|--------------|
| Room and Pillar   | 1               | 1                      | 1                       | 3            | 3         | 1               | 1            |
| Sublevel Open Stopping | 1            | 1                      | 1                       | 2            | 3         | 1               | 1            |
| Vertical Crater Retreat | 1             | 1                      | 1                       | 3            | 3         | 1               | 1            |
| Cut and Fill      | 1/3             | 1/2                    | 1/3                     | 1            | 1         | 1/9             | 1/9          |
| Shrinkage         | 1/3             | 1/3                    | 1/3                     | 1            | 1         | 1/9             | 1/9          |
| Sublevel Caving   | 1               | 1                      | 1                       | 9            | 9         | 1               | 1            |
| Block Caving      | 1               | 1                      | 1                       | 9            | 9         | 1               | 1            |
| SUM               | 5.7             | 5.8                    | 5.7                     | 28           | 29        | 5.22            | 5.22         |
below the 4370 level using AHP. Detailed evaluation of the economic, engineering and environmental factors can be conducted at a later stage.

2. AHP model
The AHP is a general theory of measurement. It is used to derive ratio scales from both discrete and continuous paired comparisons. These comparisons may be taken from actual measurements or from a fundamental scale that reflects the relative strength of preferences and feelings (R. W. Saaty, 1987). The AHP has proven to simplify complex decision analyses because it allows for quantifying subjective criteria to be synthesized together with qualitative criteria in a simple, powerful and structured manner (Yavuz, 2015). The ultimate scope of the AHP is that of using pairwise comparisons between alternatives as inputs, to produce a rating of alternatives, compatibly with the theory of relative measurement (Brunelli, 2015). The AHP method looks at the problem in three parts or levels. It begins by clearly defining the problem/objective that needs to be resolved. The second step includes the provision of

| Ore Thickness | Room and Pillar | Sublevel Open Stoping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving | Priority Vector |
|---------------|----------------|-----------------------|-------------------------|--------------|-----------|----------------|--------------|-----------------|
| Room and Pillar | 0.1754 | 0.1792 | 0.1754 | 0.1071 | 0.1034 | 0.1916 | 0.1916 | 0.1605 |
| Sublevel Open Stoping | 0.1754 | 0.1792 | 0.1754 | 0.0800 | 0.1034 | 0.1916 | 0.1916 | 0.1566 |
| Vertical Crater Retreat | 0.1754 | 0.1792 | 0.1754 | 0.1071 | 0.1034 | 0.1916 | 0.1916 | 0.1605 |
| Cut and Fill | 0.0585 | 0.0862 | 0.0585 | 0.0357 | 0.0344 | 0.0213 | 0.0213 | 0.0451 |
| Shrinkage | 0.0585 | 0.0575 | 0.0585 | 0.0357 | 0.0344 | 0.0213 | 0.0213 | 0.0410 |
| Sublevel Caving | 0.1754 | 0.1792 | 0.1754 | 0.3600 | 0.3103 | 0.1916 | 0.1916 | 0.2262 |
| Block Caving | 0.1754 | 0.1792 | 0.1754 | 0.3600 | 0.3103 | 0.1916 | 0.1916 | 0.2262 |
| SUM | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| Ore Plunge | Room and Pillar | Sublevel Open Stoping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving |
|------------|----------------|-----------------------|-------------------------|--------------|-----------|----------------|--------------|
| Room and Pillar | 1 | 1/3 | 1/3 | 1 | 1/3 | 1/5 | 1/2 |
| Sublevel Open Stoping | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| Vertical Crater Retreat | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| Cut and Fill | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Shrinkage | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sublevel Caving | 5 | 1 | 1 | 1 | 1 | 1 | 1 |
| Block Caving | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| SUM | 18 | 6.33 | 6.33 | 7 | 6.33 | 6.20 | 6.5 |
| Ore Plunge         | Room and Pillar | Sublevel Open Stopping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving | Priority Vector |
|--------------------|-----------------|------------------------|-------------------------|--------------|-----------|----------------|--------------|-----------------|
| Room and Pillar    | 0.0556          | 0.0526                 | 0.0526                  | 0.1428       | 0.0526    | 0.0322         | 0.0769       | 0.0665          |
| Sublevel Open Stopping | 0.1667        | 0.1580                 | 0.1580                  | 0.1428       | 0.1580    | 0.1613         | 0.1538       | 0.15694         |
| Vertical Crater Retreat | 0.1667    | 0.1580                 | 0.1580                  | 0.1428       | 0.1580    | 0.1613         | 0.1538       | 0.15694         |
| Cut and Fill       | 0.0556          | 0.1580                 | 0.1580                  | 0.1428       | 0.1580    | 0.1613         | 0.1538       | 0.14107         |
| Shrinkage          | 0.1667          | 0.1580                 | 0.1580                  | 0.1428       | 0.1580    | 0.1613         | 0.1538       | 0.15694         |
| Sublevel Caving    | 0.2778          | 0.1580                 | 0.1580                  | 0.1428       | 0.1580    | 0.1613         | 0.1538       | 0.17281         |
| Block Caving       | 0.1111          | 0.1580                 | 0.1580                  | 0.1428       | 0.1580    | 0.1613         | 0.1538       | 0.14900         |
| SUM                | 1               | 1                      | 1                       | 1            | 1         | 1               | 1             | 1               |
alternate solutions that are available to solve the problem. The third and the most important part is concerned with the application of the criteria that must be used to evaluate the alternative solutions. The information is then arranged in a hierarchical tree starting with the objective statement, followed by criteria to be applied and picking the alternatives available (Haas & Meixner, 2000). Implementation of the AHP is then done in the following order: computing the vector of criteria weights; computing the matrix of option scores, ranking of the options and Checking Consistency. The final stage in AHP is concerned with synthesizing of the results in order to obtain the ranking of the results. The pairwise comparison developed by SAATY (2012) is based on a scale of 1 to 9 according to weights shown in (Table 1). The

| RMR          | Room and Pillar | Sublevel Open Stoping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving | Priority Vector |
|--------------|-----------------|-----------------------|-------------------------|--------------|-----------|-----------------|---------------|-----------------|
| Room and Pillar | 1               | 1                     | 1                       | 3            | 2         | 3               | 3             | 0.21399         |
| Sublevel Open Stoping | 1           | 1                     | 1                       | 3            | 3         | 3               | 3             | 0.22739         |
| Vertical Crater Retreat | 1          | 1                     | 1                       | 3            | 3         | 3               | 3             | 0.22739         |
| Cut and Fill | 1/3             | 1/3                   | 1/3                     | 1            | 1         | 2               | 3             | 0.07990         |
| Shrinkage    | 1/2             | 1/3                   | 1/3                     | 1            | 1         | 3               | 3             | 0.07990         |
| Sublevel Caving | 1/3           | 1/3                   | 1/3                     | 1/2          | 1/3       | 1               | 3             | 0.07990         |
| BLC          | 1/3             | 1/3                   | 1/3                     | 1/3          | 1/3       | 1               | 1             | 0.07990         |
| SUM          | 4.5             | 4.3                   | 4.3                     | 11.83        | 10.66     | 15.33           | 19            |                 |

Table 13. Comparison of mining methods against RMR (Hanging wall & ore- Fair)

Table 14. Normalised elements of the comparison matrix and priority vector

| RMR          | Room and Pillar | Sublevel Open Stoping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving | Priority Vector |
|--------------|-----------------|-----------------------|-------------------------|--------------|-----------|-----------------|---------------|-----------------|
| Room and Pillar | 0.2381          | 0.2325                | 0.2325                  | 0.2536       | 0.1876    | 0.1957          | 0.1579        | 0.21399         |
| Sublevel Open Stoping | 0.2381      | 0.2325                | 0.2325                  | 0.2536       | 0.2814    | 0.1957          | 0.1579        | 0.22739         |
| Vertical Crater Retreat | 0.2381    | 0.2325                | 0.2325                  | 0.2536       | 0.2814    | 0.1957          | 0.1579        | 0.22739         |
| Cut and Fill | 0.0740          | 0.0775                | 0.0775                  | 0.0845       | 0.0938    | 0.1305          | 0.1579        | 0.09939         |
| Shrinkage    | 0.1111          | 0.0775                | 0.0775                  | 0.0845       | 0.0938    | 0.1957          | 0.1579        | 0.11400         |
| Sublevel Caving | 0.0740        | 0.0775                | 0.0775                  | 0.0422       | 0.0313    | 0.0667          | 0.1579        | 0.07530         |
| Block Caving | 0.0740          | 0.0775                | 0.0775                  | 0.0282       | 0.0313    | 0.0217          | 0.0526        | 0.05183         |
| SUM          | 1               | 1                     | 1                       | 1            | 1         | 1               | 1             |                 |
The pairwise comparison process is quite simple but often leads to errors because it is very easy to confuse the logic and assign the incorrect value (K. D. Balt, 2015).

In pairwise comparison, the general understanding is that if attribute A is extremely important than attribute B and is rated at 9, then B must be absolutely less important than A and is valued at 1/9. This understanding, therefore, applies to all scales.

### 3. Checking consistency of judgements

For a comparison matrix to be consistent, it must fulfil the reciprocity and transitivity, According to Saaty (2012), the consistency index (CI) is determined as follows:

![Table 15. Comparison of mining method against depth](image)

![Table 16. Normalised elements of the comparison matrix and priority vector](image)
\[ CI = \frac{(\lambda_{\text{max}} - n)}{(n - 1)} \quad (1) \]

Where \( \lambda_{\text{max}} \) is the matrix maximal eigenvalue, which is obtained by establishing the products of the sums of the columns of the comparison matrix and the elements of the priority vectors.

n-principal eigenvalue in the matrix

The consistency ratio (CR) is defined as:

| Table 17. Comparison of mining method against Ore recovery |
|-----------------------------------------------------------|
| **Ore Recovery**                                           |
| **Room and Pillar**                                       |
| **Sublevel Open Stoping**                                 |
| **Vertical Crater Retreat**                               |
| **Cut and Fill**                                          |
| **Shrinkage**                                             |
| **Sublevel Caving**                                       |
| **Block Caving**                                          |
| Room and Pillar                                           |
| Sublevel open Stoping                                     |
| Vertical Crater Retreat                                   |
| Cut and Fill                                              |
| Shrinkage                                                 |
| Sublevel Caving                                           |
| Block Caving                                              |
| SUM                                                       |
| 1                                                         |
| 1                                                         |
| 1                                                         |
| 1                                                         |
| 1                                                         |
| 1                                                         |
| 3                                                         |
| 7                                                         |
| 7                                                         |
| 7                                                         |
| 21                                                        |

| Table 18. Normalised elements of the comparison matrix and priority vector |
|--------------------------------------------------------------------------|
| **Ore Recovery**                                                         |
| **Room and Pillar**                                                      |
| **Sublevel Open Stoping**                                                |
| **Vertical Crater Retreat**                                              |
| **Cut and Fill**                                                         |
| **Shrinkage**                                                            |
| **Sublevel Caving**                                                      |
| **Block Caving**                                                         |
| **Priority Vector**                                                      |
| Room and Pillar                                                          |
| Sublevel Open Stoping                                                    |
| Vertical Crater Retreat                                                  |
| Cut and Fill                                                             |
| Shrinkage                                                                |
| Sublevel Caving                                                          |
| Block Caving                                                             |
| Priority Vector                                                          |
| 0.1428                                                                  |
| 0.1587                                                                  |
| 0.1629                                                                  |
| 0.1629                                                                  |
| 0.0862                                                                  |
| 0.0862                                                                  |
| 0.0476                                                                  |
| 0.1210                                                                  |
| 0.1428                                                                  |
| 0.1587                                                                  |
| 0.1629                                                                  |
| 0.1629                                                                  |
| 0.1724                                                                  |
| 0.1724                                                                  |
| 0.1429                                                                  |
| 0.1593                                                                  |
| 0.1428                                                                  |
| 0.1587                                                                  |
| 0.1629                                                                  |
| 0.1629                                                                  |
| 0.1724                                                                  |
| 0.1724                                                                  |
| 0.1429                                                                  |
| 0.1593                                                                  |
| 0.1428                                                                  |
| 0.1587                                                                  |
| 0.1629                                                                  |
| 0.1629                                                                  |
| 0.1724                                                                  |
| 0.1724                                                                  |
| 0.1429                                                                  |
| 0.1593                                                                  |
| 0.1428                                                                  |
| 0.0529                                                                  |
| 0.1428                                                                  |
| 0.1428                                                                  |
| 0.0575                                                                  |
| 0.0575                                                                  |
| 0.0476                                                                  |
| 0.0920                                                                  |
| 1                                                                       |
| 1                                                                       |
| 1                                                                       |
| 1                                                                       |
| 1                                                                       |
| 1                                                                       |
| 1                                                                       |
| SUM                                                                     |
\[ Cr = \frac{CI}{RI} \] (2)

\( R \)—Random consistency index. \( R \) is determined from (Table 2).

According to Saaty, the Consistency ratio should not be more than 0.10 or 10 per cent. \( Cr \) values of 0.1 or below constitute acceptable consistency and indicates that priorities weights for criteria comparison matrix can be calculated.

**Table 19. Comparison of mining method against powder factor**

| Powder factor          | Room and Pillar | Sublevel Open Stoping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving |
|------------------------|-----------------|-----------------------|-------------------------|--------------|------------|-----------------|--------------|
| Room and Pillar        | 1               | 1                     | 1                       | 1            | 1          | 1               | 3            |
| Sublevel Open Stoping  | 1               | 1                     | 1                       | 1            | 1          | 1               | 3            |
| Vertical Crater Retreat| 1               | 1                     | 1                       | 1            | 1          | 1               | 5            |
| Cut and Fill           | 1               | 1                     | 1                       | 1            | 1          | 1               | 5            |
| Shrinkage              | 1               | 1                     | 1                       | 1            | 1          | 1               | 3            |
| Sublevel Caving        | 1               | 1                     | 1                       | 1            | 1          | 1               | 3            |
| Block Caving           | 1/3             | 1/3                   | 1/5                     | 1/5          | 1/3        | 1/3             | 1            |
| **SUM**                | **6.3**         | **6.3**               | **6.2**                 | **6.2**      | **6.3**    | **6.3**         | **23**       |

**Table 20. Normalised elements of the comparison matrix and priority vector**

| Powder factor          | Room and Pillar | Sublevel Open Stoping | Vertical Crater Retreat | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving | Priority Vector |
|------------------------|-----------------|-----------------------|-------------------------|--------------|------------|-----------------|--------------|-----------------|
| Room and Pillar        | 0.1667          | 0.1667                | 0.1613                  | 0.1613       | 0.1667    | 0.1667          | 0.1304       | 0.1600          |
| Sublevel Open Stoping  | 0.1667          | 0.1667                | 0.1613                  | 0.1613       | 0.1667    | 0.1667          | 0.1304       | 0.1600          |
| Vertical Crater Retreat| 0.1667          | 0.1667                | 0.1613                  | 0.1613       | 0.1667    | 0.1667          | 0.2174       | 0.1724          |
| Cut and Fill           | 0.1667          | 0.1667                | 0.1613                  | 0.1613       | 0.1667    | 0.1667          | 0.2174       | 0.1724          |
| Shrinkage              | 0.1667          | 0.1667                | 0.1613                  | 0.1613       | 0.1667    | 0.1667          | 0.1304       | 0.1600          |
| Sublevel Caving        | 0.1667          | 0.1667                | 0.1613                  | 0.1613       | 0.1667    | 0.1667          | 0.1304       | 0.1600          |
| Block Caving           | 0.0529          | 0.0529                | 0.0322                  | 0.0322       | 0.0529    | 0.0529          | 0.0435       | 0.0456          |
| **SUM**                | **1**           | **1**                 | **1**                   | **1**        | **1**     | **1**           | **1**        |                  |
Table 21. Determination of final score for the mining methods

| Criteria          | Ore Shape | Ore Thickness | Ore Plunge | RMR | Depth | Ore Recovery | Powder Factor | Room and Pillar | Sublevel open stoping | VCR | Cut and Fill | Shrinkage | Sublevel Caving | Block Caving |
|-------------------|-----------|---------------|------------|-----|-------|--------------|---------------|------------------|----------------------|-----|--------------|------------|------------------|--------------|
|                   | 8.71%     | 15.31%        | 12.51%     | 23.83% | 10.99% | 13.53%       | 15.11%        | 22.72            | 7.16                  | 17.07| 8.17         | 10.17      | 17.17           | 17.17        |
| Ore Shape         | 16.05     | 15.66         | 16.05      | 4.51 | 4.10  | 22.62        | 22.62         |                  |                      |
| Ore Thickness     | 6.65      | 15.69         | 15.69      | 14.10 | 15.69 | 17.28        | 14.90         |                  |                      |
| Ore Plunge        | 21.40     | 22.74         | 22.74      | 9.94 | 11.40 | 7.53         | 5.18          |                  |                      |
| RMR               | 12.74     | 14.94         | 14.94      | 14.94 | 14.94 | 13.75        | 13.75         |                  |                      |
| Depth             | 12.10     | 15.93         | 18.65      | 18.65 | 14.57 | 14.57        | 9.20          |                  |                      |
| Ore Recovery      | 16.0      | 16.0          | 17.24      | 17.24 | 16.0  | 16.0         | 4.56          |                  |                      |
| Powder Factor     | 15.82     | 16.62         | 18.00      | 12.30 | 12.22 | 14.82        | 11.55         |                  |                      |

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Figure 2. Overall score of each mining method.

Table 22. Room and Pillar

| % Change in | 15.82 | 5   | 10  | 15  | 20  | 25  |
|---|---|---|---|---|---|---|
| Ore Shape criterion | 1 | 14.75 | 19.75 | 24.75 | 29.75 | 34.75 |
| criterion | 2 | 15.75 | 20.75 | 25.75 | 30.75 | 35.75 |
| criterion | 3 | 16.75 | 21.75 | 26.75 | 31.75 | 36.75 |
| criterion | 4 | 17.75 | 22.75 | 27.75 | 32.75 | 37.75 |
| criterion | 5 | 18.75 | 23.75 | 28.75 | 33.75 | **38.75** |
| criterion | 6 | 19.75 | 24.75 | 29.75 | 34.75 | 39.75 |

Table 23. Sublevel open stoping

| % Change in Sublevel open Stoping RMR | 16.62 | 5   | 10  | 15  | 20  | 25  |
|---|---|---|---|---|---|---|
| % change in ore shape | 1 | 16.58 | 21.58 | 26.58 | 31.58 | 36.58 |
| criterion | 2 | 17.58 | 22.58 | 27.58 | 32.58 | 37.58 |
| criterion | 3 | 18.58 | 23.58 | 28.58 | 33.58 | 38.58 |
| criterion | 4 | 19.58 | 24.58 | 29.58 | **34.58** | 39.58 |
| criterion | 5 | 20.58 | 25.58 | 30.58 | 35.58 | **40.58** |
| criterion | 6 | 21.58 | 26.58 | 31.58 | 36.58 | 41.58 |
4. Synthesis of results
This is the final step in AHP which is meant to synthesise the results in order to obtain the overall ranking of alternatives based on the goal. The final score for each alternative is arrived at by multiplying the criterion in percentage by the value in percentage (Mn) obtained by each alternative for each criterion and summing the products using the following expression.

\[ FS = \sum (C_1M_1) + (C_2M_2) + (C_3M_3) + \ldots (C_nM_n) \]  \hspace{1cm} (3)

Where—FS is the final score

\( C_n \)—Value of criterion

\( M_n \)—Value in percentage obtained by each alternative.

5. Brief geology
Mindola Sub-Vertical Shaft (MSV) is one of the four underground shafts of the Nkana mine. The geology is comprised of the late Precambrian Katanga system draped around the franks of a major northwest-trending late tectonic structural feature, the Kafue anticline. As a result of the Lufillian
Oregon, the Katanga rocks have been thrown into a series of long narrow echelon folds and late-tectonic dome and basin-line structure (Crooker, 2011).

The Chambishi-Nkana basin lies about midway on the southern flanks of the Kafue anticline and is elongated in a northwesterly to southwesterly direction. The Nkana mining area covers the northwesterly plunging Nkana syncline, forming the southeastward prolongation to the Chambishi-Nkana basin.

The basement complex is divisible into an assemblage of metasediments assigned to the Lufubu system. At Mindola the Lufubu rocks consist predominantly of impure quartzite phyllite and semi-pelitic schist, with meta-arkose also present.

The Katanga system comprises of the Lower Roan group, the upper Roan group, Mweshi and the lower Kundelungu group. The Lower Roan group has the footwall formation consisting of six members; although not all these are present everywhere. Much of the underground workings are developed in the upper part of the footwall formation. The six members are

basal member conglomerate, 0–4 m thick;

the basal quartzite member which attains a maximum thickness of 150 m;

the lower overlying footwall sandstone member, which is between 15–20 m and

the footwall conglomerate.

The ore formation extends from the top of the footwall conglomerate to the base of the hanging quartzite. The ore formation type comprises of an interbedded sequence of argillites and thinly banded to laminated dolomite and argillite. The hanging wall formation consists of four members: the hanging wall quartzite member, the near water sediments member, the upper quartzite member and the dolomite argillite sequence (Muchez et al., 2009).

The copper ore minerals are chalcopyrite and bornite, which subordinate chalcocite. The minerals typically occur as fine dissemination, commonly aggregated into clots and blebs in the richer units. The sulphide minerals at Mindola mine are zoned stratigraphically and regionally. The lower members, the schistose ore and lower grade argillite carry low-grade Bornite and chalcopyrite. In the higher succession, the banded ore and cherty ore contain Bornite of higher grade with chalcopyrite becoming more predominant over bornite. At higher levels, porous sandstone and mineralized argillite contain almost exclusively chalcopyrite minerals with minor pyrite.

In summary, the mineral zones are; bornite, mixed bornite-chalcopyrite-carrollite and lastly chalcopyrite-pyrite in that order from lower levels to higher levels. A post-Katanga intrusive dyke crosscuts through the basement complex, the footwall rocks, the ore formation and finally losing itself in the hanging rocks. The dyke, which is a greenish-grey fine-grained biotite rich rock of uniform texture was identified as a kersantite class lamprophyre. The continuation of the dyke to below 5660 ft has been confirmed by drilling carried out on 5660 ft in the CSV Shaft area, which also indicates that the dip is irregularly varying from 56–78 ESE between 4440 ft and 5360 L to around 47 ESE below 5660 L. On 4440 ft, the dyke has been intersected by the haulage in the south, at the triangle's base and the water drive south. Pilot drilling carried out for the dyke on this level shows the dyke thinning rapidly towards the ore formation, attaining a thickness of 2 m in the upper parts of the footwall.
sandstone. The dyke contacts are generally sharp in the footwall sand stones and quartzites but not as distinct in the ore formation. No signs of displacements or fracture zones have been noted in contact zone areas. The average in situ rock mass strength for the dyke (120mPa) and other rock formation including the contact zone at Mindola indicate that the difference in strength is insignificant. Field observation on dyke intersected locations on 3920 fl and 4180 fl positions in the north curve areas of the base of the triangle show no major stress or ground problems despite the facts that these excavations have been standing for a long time.

The ore-body characteristics commonly applied for mining method selection have been described by various authors: Hustrulid and Bullock (2001), Brady and Brown (2006), Nicholas (1981), and Karadogan and Ozyurt (2020). In selecting the appropriate mining method, its attributes are matched with the ore body characteristics. However, many parameters affect the choice of the mining method. Only as a result of evaluation of these parameters can only technically applicable production methods be obtained. This explains why over the years many researchers have studied on the implementation of the different decision making methods to underground mining method selection process (Karadogan & Ozyurt, 2020). Ozyurt (2018) has undertaken and presented a comprehensive review on the underground mining methods selection and criteria. The ore-body characteristics for MSV are presented in (Table 3).

The rock mass rating for the foot wall is good while for the hanging wall and ore-body is fair. The ground water condition for both the hanging and footwall wall is dry. The mine does not emit dangerous gases from the rock strata. The dust from blasting and loading works below 4370 fl will be directed to existing return airways on the upper level. Therefore, the effects of water, gases and dust as significant factors on the selection process of the technically applicable mining method are less significant.

6. Hierarchy, Application of criteria and mining alternatives
Figure 1, shows the hierarchy for selecting the mining method. The criteria selected and applied in the hierarchy were chosen based on consensus with experienced experts and judges (2 Mine planning engineers, Geologist, Mechanical engineer and Cost account) at Mindola mine. The selected mining method must satisfy the ore-body characteristics and geomechanical parameters existing at the mine below 4047 fl including achieving high economic indices of mining in terms of ore recovery and powder consumption. Since, the mine has previously used different mining methods in mining the upper ore body, the experts and the researchers agreed that only seven (7) mining methods out of 18 traditional mining methods be evaluated against the criteria as shown in Figure 1.

The mining methods evaluated with AHP are: room and pillar; sublevel open stoping; vertical crater retreat; cut and fill; shrinkage mining; sublevel caving and block caving. Mining methods can be classified based on the degree of support offered to generated excavation and magnitude of displacement (Brown, 2004). Room and pillar; sublevel open stoping and vertical crater retreat belong to a class of pillar supported mining methods, while cut and fill and shrinkage mining belong to artificially supported mining methods. Sublevel caving and block caving belong to unsupported mining methods.

Results and discussion
Using the approximate Solution (Saaty, 2012), the values in each column of the comparison matrix in (Table 4) are summed up (see, Table 5) and the judgements are normalised by
dividing each element of the comparison matrix by the sum obtained in the comparison matrix (Table 6). The normalised values are then entered into the corresponding grid in a new matrix where the average of the values in each row of the normalised matrix is calculated to derive the priority vector.

The consistency index and consistency ratio are calculated using equations 1 and 2,

\[ \lambda_{max} = 7.51; Ci = 0.08; Cr = 0.05 \]

7. Comparison of mining methods against each criteria

Formation of pairwise matrices for mining methods against criterion and determination of appropriate values is shown in (Tables 7,8,9,10,11,12,13,14,15,16,17,18,19,20), while the overall score of each mining method is shown in Figure 2.

\[ \lambda_{max} = 7.8; Ci = 0.133; Cr = 0.09850r0.1 \]

\[ \lambda_{max} = 7.56; Ci = 0.09; Cr = 0.06 \]

\[ \lambda_{max} = 6.3; Ci = -0.11; Cr = 0.08 \]

\[ \lambda_{max} = 7.1; Ci = 0.017; Cr = 0.01 \]

\[ \lambda_{max} = 6.707; Ci = 0; Cr = 0 \]

\[ \lambda_{max} = 8; Ci = 0.17; Cr = 0.12 \]

\[ \lambda_{max} = 7.23; Ci = 0.038; Cr = 0.03 \]

8. Synthesis of results for selecting a mining method

The final score for each mining method was calculated using equation 3 and is shown in (Table 21).

Based on the assessed criteria, RMR ranked high with 23.83%, followed by thickness with 15.31 % and powder factor with 15.11%. When the criteria are evaluated with the alternatives, the mining method with the highest score of 18% was Vertical Crater Retreat (VCR), followed by Sublevel open stoping with 16.62%. Vertical retreat mining, is an open stopping, bottom-up mining method that involves vertically drilling large-diameter holes into the ore-body from the top, and then blasting horizontal slices of the ore-body into an undercut using spherical charges, which has a length to diameter ratio of 6:1 or 4: 1. VCR is also referred to as the modern version of sublevel open stopping, which has done away with sublevels. The ore-body characteristics for the Mindola mine given in (Table 2) are favourable and in conformity with this mining method’s sphere of application.

9. Sensitivity Analysis

The top three mining methods determined in (Table 21), were subjected to sensitivity analysis using excel to establish the effects of percentage changes in two variables: ore shape and rock mass rating on valuation. The percentage changes on room and pillar, sublevel open stoping and VCR are shown in (Tables 22 and 24), respectively.

From the sensitivity analysis in Tables 22 and 24, rankings did not change as the variables were altered by 1 to 6% for change in ore shape and 5 to 25% for RMR. The Vertical crater mining method still remains a technically applicable production method. The ranking of the mining methods is shown in Table 25.
10. Conclusion
This study was aimed at determining a technically applicable production method rather than the production method that meets both the economic and engineering conditions for mining the deposit at moderate depth below the 4370 ft at Mindola mine using the AHP. This study evaluated seven (7) commonly used metallic mining methods out of the 18 traditionally used underground mining methods by using the AHP. The study investigated the geology and geotechnical properties of the ore body, evaluated the feasible ore-body characteristics, geomechanical parameters, high ore recovery and low powder factor necessary for achieving the highest economic indices in a mining method.

The AHP was chosen, because it can detect inconsistent judgements and provide remedy for correction when dealing with complex decision making. The AHP has inbuilt checks and balances that ensure getting the right decision when comparing the relative importance of the criteria in the process of assigning weights to them. In this study initially, the pairwise comparison matrix for criteria and weights were determined followed by a comparison of mining methods against each criterion. Synthesis of results for selecting a mining method was then done by determining the final score for each mining method by multiplying the criterion in percentage with the value obtained by each mining method for each criterion and summing the products.

Based on the assessed criteria, RMR ranked high with 23.83% followed by thickness 15.31% and Powder factor 15.11%. When the criteria are evaluated with the alternatives, the mining method with the highest score of 18% was found to be Vertical Crater Retreat (VCR) followed by Sublevel Open Stoping with 16.62%. From the sensitivity analysis, rankings did not change as the variables were altered by 1 to 6% and 5 to 25%. The vertical crater retreat still remains a technically applicable mining method.

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