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# Optimization of underground mine access layout and production scheduling

## Introduction

Optimization techniques have been applied in the mining industry since the 1960s (Musingwini and Metallurgy 2016; Krupiński 1963). A number of optimization models have been developed to solve different mine planning problems (Newman et al. 2010). Mine planning provides an effective method for evaluating mining operations (Alford et al. 2007). The objective of mine planning is to maximize profitability with a reasonable mining strategy. It is widely known that many algorithms (e.g., the Lerchs-Grossman, maximum flow and fundamental tree algorithms) have been used successfully to optimize boundary and production scheduling for open-pit mines (Ben-Awuah et al. 2016). These algorithms are packaged into mining software and utilized in mining projects, which improves the mining efficiency and benefits. However, underground mines are less extensively developed than open-pit mines due to the complicated situations in underground mining (MORIN 2002).

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Different underground mines apply different mining methods based on the orebody shape, rock mechanics and market.

Mine planning optimization for underground mines can be classified into three broad areas: the stope layout, access layout and production scheduling (Hou et al. 2019; Little et al. 2013, 2011). In general, planning is a continuous and sequential process, meaning that outputs from one phase provide inputs to the next phase. The general approach of stope layout optimization is to search for all possible combinations of blocks to maximize the profitability of the operation restricted by the predefined stope geometry and size. Numerous algorithms have been developed to optimize stope layout (Nhleko et al. 2018).

For access layout optimization, Brazil and coresearchers (Brazil and Grossman 2008; Brazil et al. 2003, 2004, 2008; Brazil and Thomas 2007) proposed several approaches to generate declines automatically with the constraints of gradient bounds and turning circle restrictions. The decline is modelled as a mathematical network using geometric techniques. Yardimci and Karpuz (Yardimci and Karpuz 2016, 2019) proposed heuristic algorithms to determine the shortest path of main haulage roads. Heuristic algorithms are efficient due to their computational advantages, which are useful in planning for large-scale underground mines. Previous studies focused on decline optimization, which assumes that production-level drives have been designed. However, there are few approaches available to optimize production-level layouts.

Production scheduling specifies the selection of stopes in an extraction sequence to maximize or minimize an objective while adhering to operational restrictions (Khodayari and Pourrahimian 2019; Martinez and Newman 2011; Nehring et al. 2010; O'Sullivan and Newman 2014; Terblanche and Bley 2015). In recent decades, Mixed Integer Programming (MIP) has been widely used in long-term production scheduling optimization to maximize NPV (Badiozamani et al. 2016; Little et al. 2008; Nehring et al. 2007). The methods of solving large mine scheduling problems have been advanced by heuristic algorithms to reduce the solution time (O'Sullivan and Newman 2015). An optimized schedule generates more profit than a manually generated schedule. However, most production scheduling optimization models do not consider access constraints. Access developments are mostly viewed as completed construction tasks that have no impact on the stope extraction sequence. Therefore, the optimization result would not be optimal due to ignoring the excavation sequence of access development.

This paper proposes approaches to optimize the access layout and production scheduling. A search algorithm for the shortest path to connect stopes is proposed to reduce the cost of production-level drive excavation. Moreover, a transportation path optimization model is used to decrease the cost of ore transportation. IP is utilized to establish a production scheduling optimization model considering the access constraints. The optimization model is validated in an application involving a hypothetical gold deposit, and the optimal design and production schedule are achieved. The results demonstrate that the optimization approach could automatically design production-level drives and formulate scheduling procedures for underground mines.

# 1. Access layout optimization

## 1.1. Access development design

The design of the access layout has a long-term impact on underground mines. Access development can be treated as a network that provides a pathway to access an orebody. Ore is mined and transported to the surface through access development. The cost of access development accounts for a large proportion of the capital expenditure in underground mines. Additionally, transportation and fuel costs are two major expenses in mining operations, and they are indirectly affected by access development.

Access layout optimization is not only a network flow problem but also a complex decision-making problem with multiple constraints. The optimization rules of an access network can be summarized as follows:

1. The access development scenario should be designed according to the orebody shape and surface topography conditions. The access layout includes the shaft, decline, cross-cut, and production-level drives. The shaft and decline are the main roads used to transport ore and materials between the surface and production levels. Cross-cut connects the main road to each production level. All the components of the access network should be reasonably linked.
2. An access network can be viewed as a large complex network model that provides the haul roads to transport ore to mills. The transportation capacity should be considered when the access layout is designed to avoid ore pile-up issues in the access network. The network model theory is commonly used to optimize the network flow and distance.
3. The objective of access network optimization is to minimize costs and expenses, which can be carried out from three aspects: shortening the road length, reducing the transportation distance, and avoiding turns and slopes. These aspects are described in detail below.
4. The construction and maintenance costs of shafts, cross-cuts and production levels are very high. Reductions in pathway length will result in lower capital expenditures.
5. Shortening the transportation distance can also reduce the fuel consumption and operation time of the transportation equipment to improve the ore transportation efficiency.
6. Turns and slopes not only affect the transportation efficiency but also increase fuel consumption and tire wear. Therefore, the numbers of sharp turns and slopes should be minimized in the design of routes. The turning angle should meet the requirements of the turning radius of equipment, and the slope of decline should be within a reasonable range.

### 1.2. Access network graph

There are a large number of stopes distributed over a wide range for large-scale underground mines. As a result, it is very difficult for mining engineers to design access layouts. The traditional design method mainly relies on experienced engineers for manual design. Many design scenarios have been established to compare the best solution. These manual methods depend on the experience of engineers, and different engineers often propose different designs. In addition numerous feasible scenarios may be present, and it may be impossible to enumerate them all. Therefore, manual design methods may face challenges in finding the optimal solution. With the development of operations research and computing technology, computer-aided methods have provided the ability to solve access layout optimization problems.

Figure 1 demonstrates a scenario of production-level drives for the stopes. Drives are connected to access each stope and transport ore to ore passes or declines, which can be viewed as a complex network. Therefore, a network flow model is created to optimize access layouts.

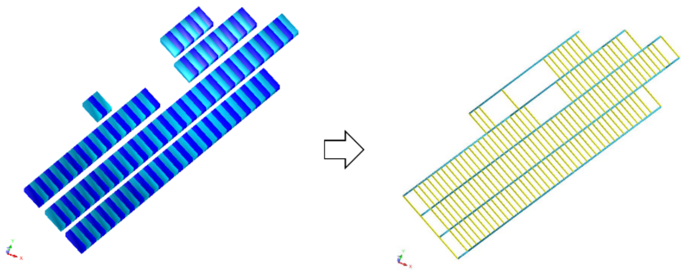


Fig. 1. Production-level drive planning

Rys. 1. Planowanie wybierania poziomu produkcyjnego

Only the access developments related to ore transportation are considered in the access network. The stope is the starting point of the access network. Each transportation path corresponds to one edge in the network. The cross-cut is the end of the access network. The steps involved in drawing the network are as follows:

1. Nodes. Stopes are the nodes in the layout of the network. In reality, the access network needs to be built outside the stopes. However, the location of each stope can be treated as a node for optimization modeling in the feasibility study to estimate the cost.
2. Edges. The shortest distance between two nodes is the straight line that connects them. This layout not only ensures the interconnection and intercommunication between stopes but also realizes the shortest path length. This approach provides a basic method of estimating excavation quantities.

### 1.3. Shortest-path optimization

Suppose that Figure 2 illustrates the top view of stopes distributed in the same production level, in which the average grade of gray stopes is lower than the cut-off grade. The average grade of stopes shown in white is higher than the cut-off grade, which could benefit the mining company.

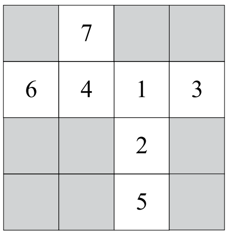



Fig. 2. Top view of stopes in one production level

Rys. 2. Widok z góry wyrobisk górniczych jednego poziomu produkcyjnego

The objective of the shortest-path planning is to ensure that the shortest path is being used under the premise that all stopes are connected by access drives. The path does not need to form a closed loop to reduce the construction of redundant paths. A search algorithm for the shortest path of stope connections is designed to avoid closed-loop issues.

The algorithm is described as follows.

1. The seven stopes in Figure 2 are treated as nodes that are connected by straight edges. The straight-line distance between adjacent stopes is assumed as the unit length. The distances between all the stopes are computed, and the results are shown in Table 1.

Table 1. Distance between each stope

Tabela 1. Odległość między każdym wyrobiskiem górniczym

| Stope | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 | – | 1 | 1 | 1 | 2 | 2 | $\sqrt{2}$ |
| 2 | 1 | – | $\sqrt{2}$ | $\sqrt{2}$ | 1 | $\sqrt{5}$ | $\sqrt{5}$ |
| 3 | 1 | $\sqrt{2}$ | – | 2 | $\sqrt{5}$ | 3 | $\sqrt{5}$ |
| 4 | 1 | $\sqrt{2}$ | 2 | – | $\sqrt{5}$ | 1 | 1 |
| 5 | 2 | 1 | $\sqrt{5}$ | $\sqrt{5}$ | – | $\sqrt{8}$ | $\sqrt{10}$ |
| 6 | 2 | $\sqrt{5}$ | 3 | 1 | $\sqrt{8}$ | – | $\sqrt{2}$ |
| 7 | $\sqrt{2}$ | $\sqrt{5}$ | $\sqrt{5}$ | 1 | $\sqrt{5}$ | $\sqrt{2}$ | – |

2. Suppose that the start point is stope 1. Stopes 2, 3 and 4 are the nearest stopes. There are three scenarios because any of the three stopes could be chosen randomly to extend the drive. If the edge extends from stope 1 to 2, it is expressed as 1→2. Searching for the stope closest to stope 2 indicates that stopes 1 and 5 are located the same distance from stope 2. The previously extended node (stope 1) is excluded to avoid a closed loop. Therefore, the path is extended to stope 5, which is denoted as 1→2→5. Searching will stop when all the nearest ore blocks are the previously extended ore blocks.
3. Search for the external node closest to the extended path. Stopes 3 and 4 have the shortest distances to stope 1. If the shortest path is extended to stope 3, expressed as 1→3, the node closest to stope 3 will then be determined. The closest node is stope 1 in this case, which results in the stop condition.
4. Paths 1→4→6 and 1→4→7 can also be identified based on the search algorithm.

The optimal extension layout of access development is shown in Figure 3.

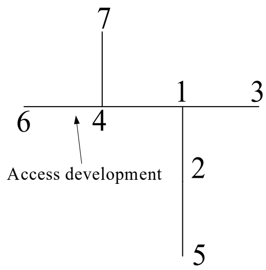



Fig. 3. Optimal result of production-level drives

Rys. 3. Optymalny wynik wybierania poziomu produkcyjnego

The logic of the shortest-path search algorithm for stope connection is shown in Figure 4. The detailed steps of the shortest-path search algorithm are explained as follows.

- Step 1: Set all the stopes as alternative nodes to the feasible region. From this set, the start point is randomly selected, and this node is added to the forbidden area set.
- Step 2: Calculate the distance between each stope and the chosen node. Select the nearest node and determine whether the node exists in the forbidden area set. Go to step 3 if the node does not exist in the forbidden area set; otherwise, go to step 4.
- Step 3: Add the chosen node to the forbidden area set. This node is then treated as the chosen node, and the algorithm returns to step 2.
- Step 4: If there is no node in the feasible region, the program ends. Otherwise, go to step 5.
- Step 5: Map each node in the forbidden area set to calculate the distance from the node in the feasible region set. The nearest node in the feasible region set is chosen as a new node. Then, the algorithm returns to step 2.

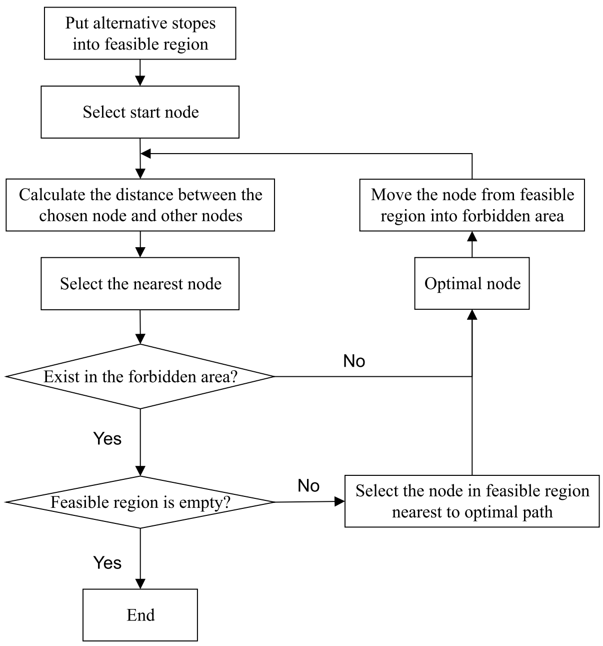



Fig. 4. Shortest-path search algorithm

Rys. 4. Algorytm wyszukiwania najkrótszej ścieżki

The optimal path is extended in a node-by-node process through the above algorithm. Different starting nodes may have different paths. Therefore, it is necessary to enumerate each stope based on the starting point to obtain the corresponding optimal path, but the path length of each scenario should be the same.

### 1.4. Transportation path optimization

One of the key parameters in access layout optimization is the transportation cost, which is equal to the transportation distance multiplied by the unit transportation cost. The unit transportation cost is directly related to the commodity price of fuel, which does change often. Therefore, the transportation distance is the leading factor that affects transportation costs.

Figure 3 shows the optimal path used to connect each node. Ore is mined and transported through production-level drives to the decline. The volume of each stope is the same. The ore transportation distance can be used to replace the transport work indicator to evaluate each scenario. The decline location will affect the transportation distance directly; thus, optimizing the location of the main haulage road is very important for reducing the transportation cost.

The stope location is used to represent the decline location in the model and make the distance calculation easier, but a location outside the vein should be selected in reality. The location of the stope is approximately chosen as the optimal decline location in the model to compute the distance between each stope and the optimal decline location. The decline location can be changed to produce different scenarios. The transportation distance of each scenario is compared to find the optimal location with the shortest total transportation distance.

Figure 5 shows the tree diagram of the ore transportation path when the decline location is changed from stope 1 to stope 7 in sequence, as shown in Figure 3. The extracted ore from each stope will be transported to the decline according to the planned path. The transport distance result for each scenario is shown in Table 2.

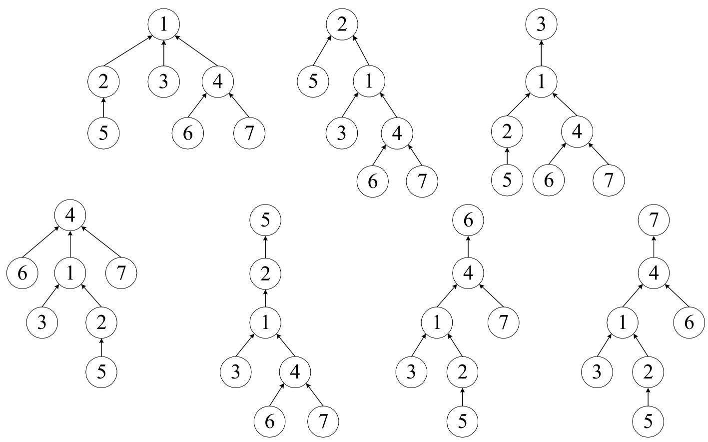


Fig. 5. Ore transportation path

Rys. 5. Ścieżka transportu rudy

Table 2. Transport path of each scenario

Tabela 2. Ścieżka transportu dla każdego scenariusza

| Scenario | Transportation path | Distance |
|---|---|---|
| 1 | 2→1; 3→1; 4→1; 5→2→1; 6→4→1; 7→4→1 | 9 |
| 2 | 1→2; 3→1→2; 4→1→2; 5→2; 6→4→1→2; 7→4→1→2 | 12 |
| 3 | 1→3; 2→1→3; 4→1→3; 5→2→1→3; 6→4→1→3; 7→4→1→3 | 14 |
| 4 | 1→4; 2→1→4; 3→1→4; 5→2→1→4; 6→4; 7→4 | 10 |
| 5 | 1→2→5; 2→5; 3→1→2→5; 4→1→2→5; 6→4→1→2→5; 7→4→1→2→5 | 17 |
| 6 | 1→4→6; 2→1→4→6; 3→1→4→6; 4→6; 5→2→1→4→6; 7→4→6 | 15 |
| 7 | 1→4→7; 2→1→4→7; 3→1→4→7; 4→7; 5→2→1→4→7; 6→4→7 | 15 |

The total transportation distances are 9, 12, 14, 10, 17, 15 and 15 unit lengths based on the calculation of the transportation distance of each scheme. Although the path design is the same, the total transportation distance is quite different due to the different decline locations.

Choosing an optimal decline location will reduce transportation costs and improve the transportation efficiency for the mining operation of large-scale mines. The number of alternative locations to be searched is reduced because the decline is generally located at the edge of the ore body. The optimal location at different production levels can be linked by the decline.

## 2. Production scheduling optimization

Production scheduling optimization is a comprehensive consideration of various factors, such as the ore output, grade requirements, mining time and location. The objective of production scheduling optimization for a mining company is to obtain the maximum NPV. High-grade ores should be mined prior to shortening the payback period, and the ore grade should be stable to ensure an acceptable processing recovery rate.

The production schedule should meet a series of mining conditions as follows.

1. The ore tonnage and grade of ore supplied to the processing plant should be stable in each period.
2. The output of ore and waste tonnage should match the production capacity of the mining equipment.
3. The production capacity and average ore grade in each year should be balanced during the mine's life.
4. According to the characteristics of the mining method used at an underground mine, a stope cannot be excavated if the access roads do not reach it. The spatial and time relationships between stopes and access drives should be obeyed.

The IP is utilized to build the optimization model. Maximizing the NPV is the objective, and the constraints include the restriction relationship between the extension sequence of the access network and the mining sequence of stopes, the mining capacity, the lifting capacity, the transportation capacity and the feeding grade in each period. Stopes and access networks are decomposed into units that are the decision variables of the optimization model.

- Subscript notation
  - $j$ – stope indicator,
  - $k$ – drive indicator,
  - $t$ – scheduling time period: $t = 1, 2, ..., T$.
- Parameters
  - $r$ – discounted rate,
  - $R$ – recovery rate of minerals,

$k_j$ – unit drive access to stope *j*,
$f_k$ – drive unit should be extracted before drilling in drive unit *k*,
$G_t$ – ore grade target of the mineral in period *t*,
$PR_t$, $DR_t$ – target of ore extraction and drive excavation in period *t*,
$v_j$ – volume of stope *j*,
$g_j$ – grade of stope *j*,
$d_j$ – material density of stope *j*,
$P$ – commodity price of the mineral,
$MC$ – mining cost,
$PC$ – processing and refining cost,
$DC$ – unit excavation cost of a drive,
$DCL$ – length of a unit drive,
$c_{pr}$, $c_{dr}$, $c_g$ – unit costs of the ore tonnage, drive excavation and ore grade deviating from the target in each period,
$d^+_{pr,t}$, $d^+_{dr,t}$, $d^+_{g,t}$ – excess amounts of ore tonnage, drive excavation and ore grade produced above a target in period *t*,
$d^-_{pr,t}$, $d^-_{dr,t}$, $d^-_{g,t}$ – deficient amounts of ore tonnage, drive excavation and ore grade produced below a target in period *t*.

- Decision variables

$a_{j,t}$ – 1 if stope *j* is to be mined during period *t*
0 otherwise,

$b_{k,t}$ – 1 if drive *k* is developed during period *t*
0 otherwise.

- Objective function
  - Maximize:

$$P \cdot R \cdot \sum_{j,t} \frac{v_j \cdot d_j \cdot g_j \cdot a_{j,t}}{(1+r)^t} - (MC + PC) \cdot \sum_{j,t} \frac{v_j \cdot d_j \cdot a_{j,t}}{(1+r)^t} - DC \cdot \sum_{k,t} \frac{b_{k,t}}{(1+r)^t} - \tag{1}$$

$$-c_{pr} \cdot \sum_t \frac{d^-_{pr,t} + d^+_{pr,t}}{(1+r)^t} - c_{dr} \cdot \sum_t \frac{d^-_{dr,t} + d^+_{dr,t}}{(1+r)^t} - c_g \cdot \sum_t \frac{d^-_{g,t} + d^+_{g,t}}{(1+r)^t}$$

  - Constraints

$$\sum_t a_{j,t} \le \sum_t b_{k,t} \quad \forall j \mid k \in k_j \tag{2}$$

$$\sum_t a_{j,t} \le 1 \quad \forall j \tag{3}$$

$$\sum_{t} b_{k,t} \leq 1 \quad \forall k \tag{4}$$

$$b_{k,t} \leq \sum_{t'} b_{k',t'} \quad \forall k,t \mid t' \leq t, k' \in f_k \tag{5}$$

$$\sum_{j} v_j \cdot d_j \cdot R \cdot a_{j,t} + d_{pr,t}^{-} - d_{pr,t}^{+} = PR_t \quad \forall t \tag{6}$$

$$\sum_{k} DCL \cdot b_{k,t} + d_{dr,t}^{-} - d_{dr,t}^{+} = DR_t \quad \forall t \tag{7}$$

$$\sum_{j,m} (v_j \cdot d_j \cdot g_j \cdot R \cdot a_{j,t}) \Big/ \sum_{j} (v_j \cdot d_j \cdot R \cdot a_{j,t}) + d_{g,t}^{-} - d_{g,t}^{+} = G_t \quad \forall t \tag{8}$$

Equation (1) is the objective function, which maximizes the discounted cash flow to determine the mining sequence of drives and stopes considering access constraints. The violation of constraints will be penalized in the objective function to reduce the NPV. Equation (2) ensures that materials can be extracted from the stope after the corresponding drive is developed. Equations (3) and (4) ensure that stopes and drives are worked on only once during the life of the mine. Equation (5) ensures that drive development is continuously performed and that subsequent drives can only be constructed after all the previous drives are developed. Equations (6) and (7) ensure that the production rates of the stopes and drives are approximately equal to the annual production targets. Equation (8) ensures that the ore grade reaches the target in all relevant time periods, thus reducing the grade fluctuations of ore fed to the processing plant.

## 4. Model application

### 4.1. Access development optimization

A hypothetical gold deposit is used to verify the access layout optimization model. The stopes with economic value for mining at a production level are delineated based on the cut-off grade, as shown in Figure 6. There are 88 stopes in the model, which are numbered 0 to 87 in sequence. The size of the stope is 6 × 6 m, so the distance between two adjacent stopes is 6 m. The shortest-path search algorithm is used to generate the shortest path, and then the optimal decline location is selected from the location of alternative stopes at the edge of the orebody. The optimization model is programmed in Python and solved on an

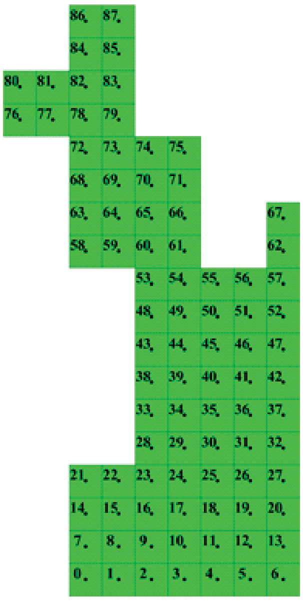



Fig. 6. Tope view of stopes

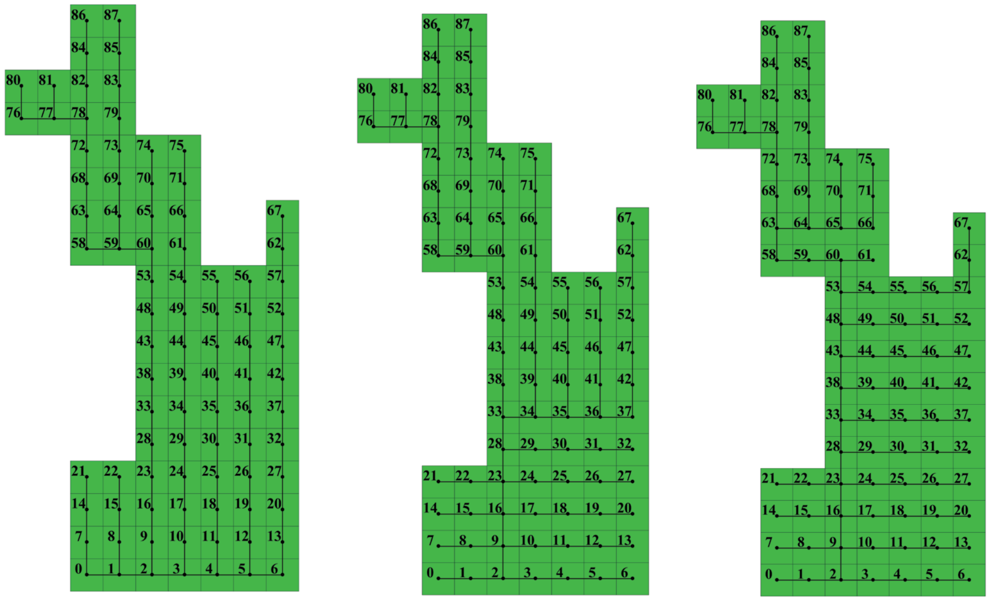
Rys. 6. Widok wyrobisk górniczych z góry

Intel (R) Xeon (R) CPU with a 2.3 GHz processor and 64 GB RAM. The computation time is approximately 143 seconds.

The optimization process is described as follows.

1. Path planning. Different path results can be obtained when different stopes are treated as the starting node. Figure 7 shows the path results with stopes 0, 33 and 63 as the starting node. The path length of the three optimization results is the same, which verifies that starting node selection has no impact on the path length.
2. Selection of the optimal decline location. The purpose of selecting the optimal decline location is to achieve the shortest transportation distance. Although the path length with different stopes as the starting node is the same, the shortest total transportation distance in each situation is different. The optimal solution is finally obtained by comparing the shortest transportation distance in each scenario when each node is treated as the start node. The optimal decline location is set near stope 43, as shown in Figure 8. The path length is 522 m, and the shortest ore transportation distance is 3240 m. See Table 3 for the detailed path results.

The automatic design of the access layout can be realized through the optimization algorithm. Compared with the traditional manual design, the design method based on the optimization algorithm is faster and repeatable, which can help engineers complete work in a short time.



(a) Start from stope 0 (b) Start from stope 33 (c) Start from stope 63

Fig. 7. Optimal path starting from different nodes

Rys. 7. Optymalna ścieżka zaczynająca się od różnych węzłów

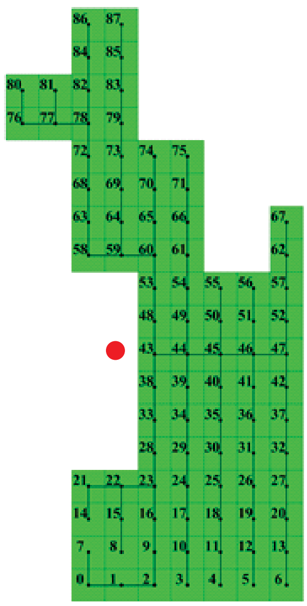


Fig. 8. Optimal decline location

Rys. 8. Optymalna lokalizacja upadowej

Table 3. Optimal transport path

Tabela 3. Optymalna ścieżka transportu

| Transport path | Distance (m) |
|---|---|
| 80→76→77→78→72→68→63→58→59→60→53→48→43 | 72 |
| 7→0→1→2→9→16→23→28→33→38→43 | 60 |
| 3→10→17→24→29→34→39→44→43 | 48 |
| 8→15→22→23 | 18 |
| 4→11→18→25→30→35→40→45→44 | 48 |
| 75→71→66→61→54→49→44 | 36 |
| 14→21→22 | 12 |
| 5→12→19→26→31→36→41→46→45 | 48 |
| 55→50→45 | 12 |
| 6→13→20→27→32→37→42→47→46 | 48 |
| 56→51→46 | 12 |
| 74→70→65→60 | 18 |
| 67→62→57→52→47 | 24 |
| 87→85→83→79→73→69→64→59 | 42 |
| 86→84→82→78 | 18 |
| 81→77 | 6 |

### 4.2. Production scheduling optimization

Figure 9 shows the grade of each stope. The parameters used in the production scheduling optimization model are listed in Table 4. The used currency is Chinese RMB (¥). The optimization model contains 700 variables and 875 constraints. The model was implemented in Python and solved using Gurobi optimization software running on an Intel (R) Xeon (R) CPU with a 2.3 GHz processor and 64 GB RAM. The computation time was approximately 1 second.

The optimization result is shown in Figure 10. The legend of Figure 10 reflects the mining period. Note that white stopes in Figure 10(b) are not mined in the mining period. The detailed optimization results are shown in Table 5.

The parameters used in the optimization model varied during mining period. Sensitive analysis is used to estimate the range of variation, see Figure 11.

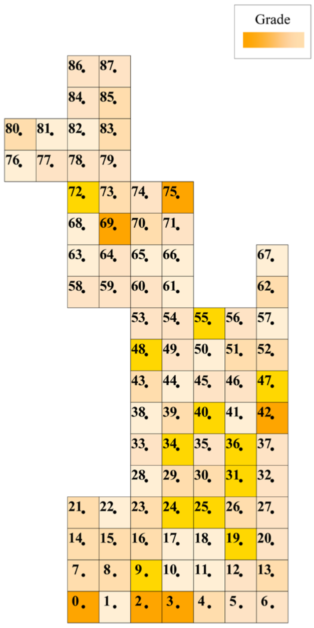


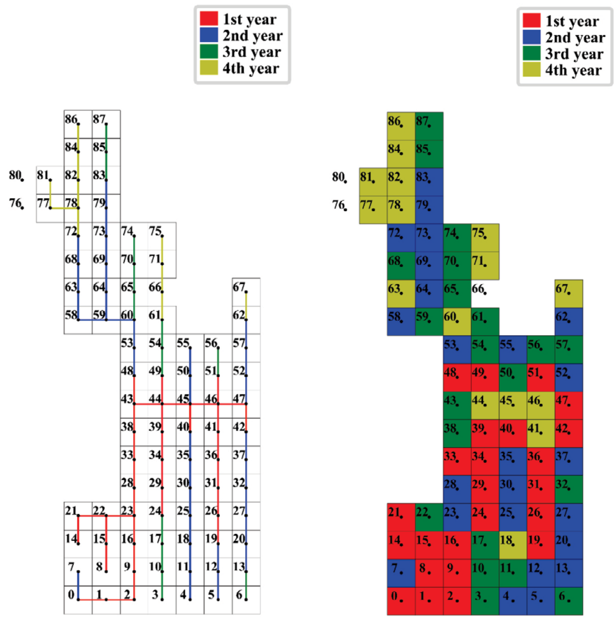

Fig. 9. Grade of each stope

Rys. 9. Ocena każdego wyrobiska górniczego

Table 4. Technical and economic parameters

Tabela 4. Parametry techniczne i ekonomiczne

| Parameters | Amount | Unit |
|---|---|---|
| Time | 4 | year |
| Target of annual production rate | 14 500 | t/a |
| Target of annual excavation rate | 300 | m/a |
| Mining recovery | 90 | % |
| Processing recovery | 90 | % |
| Average grade target | 2 | g/t |
| Gold price | 260 | ¥/g |
| Mining cost | 200 | ¥/t |
| Processing cost | 60 | ¥/t |
| Access development cost | 20 000 | ¥/m |
| Discounted rate | 10 | % |




(a) drive excavation scheduling (b) stope extraction scheduling

Fig. 10. Optimal production scheduling

Rys. 10. Optymalne planowanie produkcji

Table 5. Optimization result

Tabela 5. Wynik optymalizacji

| Time (year) | Number of stopes | Average grade (g/t) | Au (g) |
|---|---|---|---|
| 1 | 24 | 2.211 | 32 092 |
| 2 | 24 | 2.027 | 29 429 |
| 3 | 21 | 1.819 | 23 104 |
| 4 | 16 | 1.793 | 17 355 |

## 5. Discussion

Numerous studies on access layout optimization have focused on declines but ignored production-level drive optimization. Furthermore, most production scheduling optimization

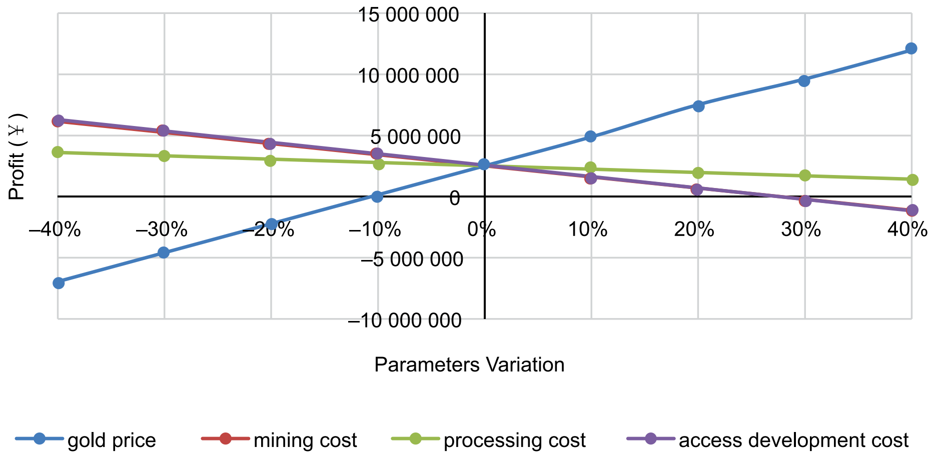



Fig. 11. Sensitive analysis

Rys. 11. Analiza wrażliwości

models treat access developments as having been excavated. The spatial and sequential relationships associated with stope extraction and access excavation were not taken into account in previous optimization models. In this paper, two optimization models were proposed to optimize the access layout and production scheduling process to maximize the NPV of the mining project, and a case study was conducted. This research enriches the optimization approach for underground mining operations.

The presented methodology is applicable to a hypothetical gold deposit. The production-level drives that achieve the shortest length for one mining level are obtained by the shortest-path search algorithm. The optimal transportation path is optimized to reduce the transport distance. The proposed production scheduling optimization model considers the interactions and effects among different optimization components to obtain a globally optimal solution. The amount of access development and stope mining in each year is balanced by the schedule to ensure that enough stopes can be accessed in the next production period. However, the research results have certain limitations. The model is only used for one level of mining to demonstrate the feasibility of the method. In further research, we need to improve the model to optimize the simultaneous production of multiple levels.

This study provides a theoretical basis for the optimization of underground mining operations and a new concept and basic optimization model for access layout and production scheduling. This approach is of great practical importance for increasing the profit of shareholders.

## Conclusions

Mine planning is the basis for investment and decision making in mining projects. The objective of mine planning optimization is to find a technically feasible scenario with the maximum benefit. At present, there are few optimization technologies and methods for underground mines because the underground mining process is complicated.

Access development provides a pathway to access orebodies at underground mines. The design of the access layout has a long-term impact on underground mines. The costs of access development and ore transportation account for large proportions of the capital expenditures and total mine operation cost. Access layout optimization is treated as a network flow problem. Stopes are viewed as nodes, and the roads between stopes are regarded as edges. Two steps are used to optimize the shortest path and the decline location. A shortest-path search algorithm is developed to automatically connect each stope at the same production level to achieve the shortest distance. The decline location is optimized to minimize transport work.

Production scheduling optimization considers numerous factors, such as the ore throughput, ore grade, and mining sequence. The objective of production scheduling optimization is to obtain the maximum NPV. The extension sequence of access excavation and stope extraction is taken into account in the optimization model to balance development and mining. The IP is utilized to develop the optimization model. Stopes and access networks are decomposed into units that are the decision variables of the optimization model. Gurobi software is used to find the optimal solution, which is more reasonable than the solution without considering the access layout and excavation sequence. The optimization model is applied to a hypothetical gold deposit to demonstrate its feasibility. The proposed approach could assist mining engineers in rapidly generating the access layout and production scheduling process to obtain an optimal mining plan.

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*The Gurobi optimization software package was used in this work to solve the IP equations.*

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## OPTIMIZATION OF UNDERGROUND MINE ACCESS LAYOUT AND PRODUCTION SCHEDULING

Keywords

access layout optimization, production schedule optimization, underground mine, integer programming

Abstract

Optimization in mine planning could improve the economic benefit for mining companies. The main optimization contents in an underground mine includes stope layout, access layout and production scheduling. It is common to optimize each part sequentially, where optimal results from one phase are treated as the input for the next phase. The production schedule is based on the mining design. Access layout plays an important role in determining the connection relationships between stopes. This paper proposes a shortest-path search algorithm to design a network that automatically connects each stope. Access layout optimization is treated as a network flow problem. Stopes are viewed as nodes, and the roads between the stopes are regarded as edges. Moreover, the decline location influences the ore transport paths and haul distances. Tree diagrams of the ore transportation path are analyzed when each stope location is treated as an alternative decline location. The optimal decline location is chosen by an enumeration method. Then, Integer Programming (IP) is used to optimize the production scheduling process and maximize the Net Present Value (NPV). The extension sequence of access excavation and stope extraction is taken into account in the optimization model to balance access development and stope mining. These optimization models are validated in an application involving a hypothetical gold deposit, and the results demonstrate that the new approach can provide a more realistic solution compared with those of traditional approaches.

## OPTYMALIZACJA UKŁADU DOSTĘPU DO KOPALNI PODZIEMNEJ I HARMONOGRAMU PRODUKCJI


Słowa kluczowe

optymalizacja układu dostępu, optymalizacja harmonogramu produkcji,
podziemna kopalnia, programowanie zintegrowane



Streszczenie

Optymalizacja w planowaniu kopalni może poprawić korzyści gospodarcze dla przedsiębiorstw górniczych. Główna część optymalizacji w kopalni podziemnej obejmuje układ wyrobisk eksploatacyjnych, schemat udostepnienia i harmonogram wydobycia. Zazwyczaj każdy etap optymalizowany jest sekwencyjnie, gdzie optymalne wyniki z jednej fazy są traktowane jako dane wejściowe do następnej fazy. Harmonogram produkcji opiera się na projekcie górniczym. Struktura udostępnienia odgrywa ważną rolę w określaniu połączeń pomiędzy przodkami eksploatacyjnymi. Ten artykuł proponuje algorytm wyszukiwania najkrótszej ścieżki, aby zaprojektować sieć, która automatycznie łączy każdy przodek. Optymalizacja struktury udostępnienia jest traktowana jako problem przepływu w sieci. Przodki są traktowane jako węzły, a drogi pomiędzy nimi jako krawędzie. Ponadto lokalizacja upadowej udostępniającej wpływa na drogi transportu rudy i odległości odstawy. Analiza ścieżek drzew zdarzeń odbywa się przy założeniu alternatywnych lokalizacji upadowych. Optymalna lokalizacja upadowej jest wybierana metodą wyliczania. Następnie, za pomocą programowania zintegrowanego (*Integer Programming* – IP) optymalizuje się proces planowania produkcji i maksymalizacji wartości bieżącej netto (NPV).Rozwinięty układ wyrobisk udostępniających i eksploatacyjnych jest uwzględniany w modelu optymalizacji do zbilansowania udostępnienia i eksploatacji złoża. Te modele optymalizacji są walidowane w aplikacji uwzględniającej hipotetyczne złoże rud złota, której wyniki pokazują, że nowe podejście może dostarczyć bardziej realistyczne rozwiązanie w porównaniu z tradycyjnymi metodami.