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Simultaneous integrated optimization for underground mine planning: application and risk analysis of geological uncertainty in a gold deposit

Introduction

A large number of open pits enter are currently becoming deep mining, which not only causes the land occupation and the destruction of the ecological environment but also causes the increase of production cost and risk. Therefore, underground mining has become an inevitable trend in mineral resource development. Compared with open pits, underground mines are subject to many more conditions, such as geometallurgical and geotechnical characteristics, which greatly affects mining efficiency. So optimizing the production scheduling is a reasonable way to stabilize the mining operations and maximize the economic benefits.

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For underground mines, it takes a lot of time to do the mining design and production scheduling manually, which hardly achieve the optimal and repeatable result. The design modification cannot be completed in a short time when the mining conditions change. The designing engineers have to spend lots of time revising or recreating the plan. Many researchers have put forward optimization methods to implement the automatic mine design and planning with the aid of Operations Research since 1960s, which have successfully been applied in mining companies to establish and develop a cost-effective solution for the extraction of minerals at optimal quality and quantities in a reasonable time (Newman et al. 2010; Osanloo et al. 2008). The application fields could almost be divided into three components; including the stope layout, access network, and production scheduling (Bastante et al. 2004). In addition, mining projects are unique because of the inherent uncertainty associated with the nature variability of orebody geometry and grade, and rock properties, which indicates that risk management requires a more rigorous technical and economic assessment than other industries (Dowd et al. 2016).

The shape of the mining space required for extraction in an open pit is approximately an inverted cone. In underground mining, the acceptable zone of the stope is the mining target, which plays the most significant role for its optimization. The selection of the best combination of available stope boundaries will directly affect the profitability of the operation. Over the years, a number of algorithms have been developed to solve the problem (Ataee-Pour 2005). Ovanic and Young (1999) use a mixed integer programming (IP) model to identify the optimal start and end points for mining within the stope. Alford (1996) demonstrates a floating stope concept to search for the optimal stope layout. Ataee-Pour proposes a heuristic method based on the maximum value neighborhood (MVN) approach (Ataee-Pour 2000, 2004). Topal et al. (2010) and Sandanayake et al. (2015) contribute heuristic approaches for stope layout optimization in three-dimensions.

The connected system will create the opening space to access the stope and transport the ore to the surface. The construction cost of tunnels and the ore transportation cost account for a great proportion of the capital expenditure and operation cost respectively. Hence optimizing the access layout to minimize the cost have a major impact on the economic benefits. Brazil describes some methods to find an efficient layout for the access network connecting the access points at each production level (Brazil and Grossman 2008; Brazil et al. 2003; Brazil and Thomas 2007).

Based on the mining design, optimal production scheduling could be developed to undertake the project evaluation and determine the mining strategy. Little et al. (2008), Kuchta et al. (2004) and Nehring et al. (2010) demonstrate that the mixed integer programming has the good ability to generate an optimal production schedule. O'Sullivan and Newman (2015) propose a heuristic approach to reduce the model size to obtain the solution in an acceptable time. The uncertainty inherited in mining activity is the main issue for the mine planning. The geological uncertainty is a significant factor which could lead to a big loss if it is ignored. Dimitrakopoulos, Godoy and Ramzan present methods to quantify the influence of in-situ grade variability on the mine planning (Dimitrakopoulos et al. 2002, 2007;

Dimitrakopoulos and Ramazan 2004; Dimitrakopoulos and Environment 1998; Godoy and Dimitrakopoulos 2011; Ramazan and Dimitrakopoulos 2004).

It is common practice for mine plans to be optimized sequentially, where results from one planning process form the input data for the other. However, the globally optimal solution can be achieved when integrating the planning phases. Nehring et al. (2012) present a model to integrate the short- and medium-term production scheduling while Martinez and Newman (2011) propose a solution approach for optimizing long- and short-term production scheduling simultaneously. Little et al. (2013) demonstrates an IP to integrate the stope layout and production scheduling into an optimization model. Carlyle and Eaves (2001) describe the interaction of the development system and production. The integrated optimization model will provide a more profitable result than the independent optimization model.

This paper reviews some basic methods and strategies that have been implemented in underground mining optimization. The interaction and relationship between stope layout, access layout, and production scheduling are analyzed in detail (Ding et al. 2004), based on which the integrated optimization strategy is proposed to optimize these three components simultaneously to maximize the NPV. An IP formulation is presented to relate the stope extraction and access excavation sequence. The optimization model is validated in a gold deposit in China. The optimal design and production schedules are achieved and the key performance indicators are discussed demonstrating the performance of the model. The conditional simulation method is utilized to generate equally probable representations of in-situ orebody variability to evaluate the grade uncertainty. The framework not only obtains a globally optimal solution but also assesses the potential risk of the mine planning.

1. Optimization method and strategy

Underground mine optimization is a multi-phase and serial process; the components include: cut-off grade, stope layout, access network, and production scheduling optimization.

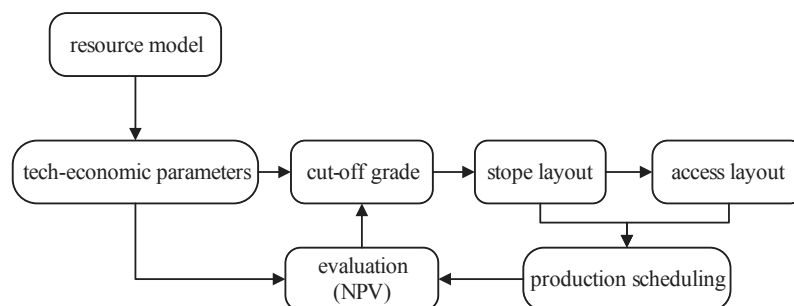


Fig. 1. Underground mine optimization procedure

Rys. 1. Procedura optymalizacji podziemnej kopalni

Figure 1 demonstrates the details about the optimization procedure. The relationship between different optimization phases is independent and orderly, which means the output of one optimization step becomes the input for the next step.

1.1. Stope layout optimization

Stope is the minimum mining unit of underground mines, and it can be regarded as the combination of blocks. The attributes of a stope could be calculated by the contained blocks. When the finance parameters are taken into account, the economic value generated by each stope can be computed. Therefore, searching for the stope boundary to find the maximum benefit is the optimization target. The optimization of the stope layout could be treated as a three-dimensional problem to determine the size and spatial position of each stope. The size of the stope can be set to multiple options in reality. The upper bound stope size is the maximum size that meets the requirements of geotechnical conditions, and the lower bound stope size is the minimum size that meets the requirements of various access constraints (e.g., equipment).

Figure 2 shows a two-dimensional stope searching diagram. The combination possibility is diversity due to the variable size and position of the stope. For example, the red, blue and green frames are the assumed stope boundaries. The red frame is the combination of 3×2 blocks, the blue frame is the combination of 3×3 blocks and the green frame is the combination of 2×2 blocks.

Figure 3 shows a situation in which two stopes are overlapping. One block is shared by two stopes at the same time, which will cause the economic value of the block to be double-counted. Therefore, it is necessary to consider the constraints in the optimization model to ensure the independence between the stopes to avoid overlapping.

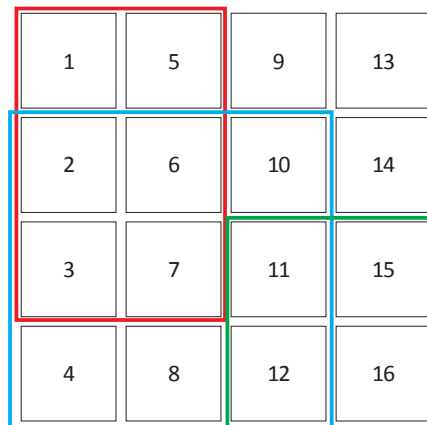


Fig. 2. Stope searching diagram

Rys. 2. Schemat wyszukiwania przodka wybierkowego

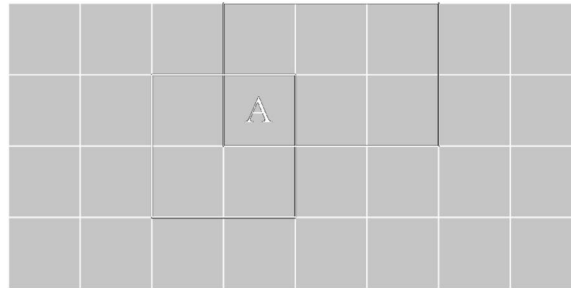


Fig. 3. Stope overlapping

Rys. 3. Nakładanie się przodków wybierkowych

1.2. Access network optimization

In the open pit, the exposed space is the operating place for the next bench when the rock is stripped. Whereas the underground minerals need to be exploited when the access network is constructed to connect the stopes with the surface. The establishment of a series of tunnels provides the path to transport equipment, materials, and ore between the surface and the stopes.

The construction of the access network accounts for a large proportion of the investment. Moreover, the scenario of access network design directly affects the transportation efficiency, construction cost, safety and ventilation, which is a general arrangement that has a far-reaching impact on the mining process. The strategy of optimizing access network is to reduce the accumulated transportation distance.

1.3. Mining sequence optimization

Due to the time value effect of the money, the mining sequence has a significant impact on the NPV. As the construction of new mines requires a lot of infrastructure investment and the mine will produce profit after several years, which means that future funds need to be discounted to the initial stage to calculate the NPV of the project. In fact, a large number of studies show that in addition to the mine life and annual production rate, the choice of the cut-off grade also affects benefits. If the lower cut-off grade is selected, the range of exploitable mineral resources is more extensive. On the contrary, the range is smaller. Under different production rate, a series of cut-off grades can be used to obtain a series of economic value as shown in Figure 4. Therefore, it is necessary to repeat the estimation and compare the value of each scenario to find the optimal production rate and cut-off grade to get the maximum NPV.

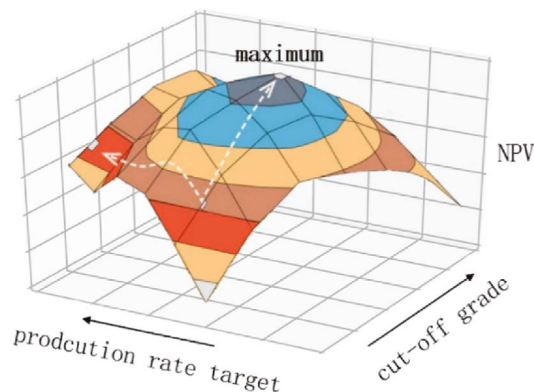


Fig. 4. Hill of NPV with changing parameters

Rys. 4. NPV ze zmieniającymi się parametrami

1.4. Integrated optimization strategy

For each optimization topic, researchers have developed many techniques, strategies, and algorithms which have been applied in the underground mining operation. Due to the complicated interaction between the various steps of underground mining operations, it is difficult to find a globally optimal solution based on the independent and sequential optimization method. This inter-dependency must be incorporated into the optimization process to generate more realistic results.

A simultaneous integrated optimization model could optimize the stope boundary, access layout and production scheduling at the same time. The stope and access development are generated by gathering blocks and drive units respectively. The sequence between access drilling and stope mining is taken into account in the optimization model, which means the stope could not be mined until all the excavations are finished. The excavation of tunnels is the premise of the extraction of minerals. The time of excavation has a great impact on the stope mining time which also influences the profit obtained by the mining company, because the amount of excavation consumes money while the ore extraction produces value. Therefore, the drilling time of each access unit is regarded as another decision variable in the optimization model. The amount of excavation for each stope could be computed by length multiplying area. In addition, the extension sequence of the main shaft, drift, and tunnel are considered as the constraints in the model.

2. Formulation of the simultaneous integrated optimization model

2.1. Resource estimation

The Sanshandao gold deposit is located in the special industrial zone in the north of Laizhou City, Shandong Province. A new orebody named Xinli is currently being founded next to the original orebody. The Sanshandao Gold Mining Company intends to develop the orebody to increase the production capacity from 1500 t/day to 8000 t/day.

The Xinli orebody extends from about 40 meters to 700 meters under the sea level and the strike of the orebody is NE 60 to 70 degree with a dip angle of 40 to 50 degree. The shape of the Xinli orebody is generally stratiform. A two-dimensional block model is used to do the resource estimation for the stratiform orebody with the clear geological boundaries on the hanging wall and foot wall. The thickness and accumulation (thickness \times grade) are treated as the variables for the OK interpolation. Figure 5 shows the estimation result of thickness and accumulation. The average grade of the block is obtained by dividing the accumulation by the thickness. The ore tonnage and metal content of each block could be calculated by the estimated result.

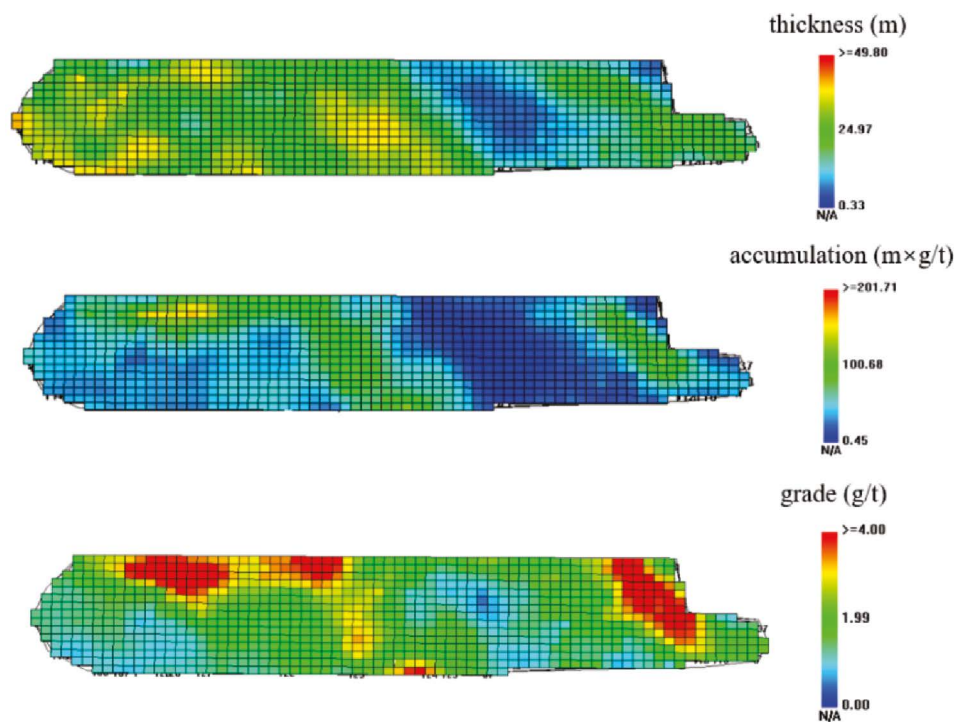


Fig. 5. Resource estimation result

Rys. 5. Wynik szacowania zasobów

The economic and technical parameters are estimated analogous to the orebody mined previously. With the parameters listed in Table 1 and grade and thickness of each block, revenue and cost for each stope could be computed. The currency utilized is Chinese RMB (¥). The exchange rate of the US dollar against RMB is 1:6.6 as is used in this paper.

Table 1. Estimated economic and technical parameters

Tabela 1. Szacowane parametry ekonomiczne i technologiczne

Items	Unit	Amount
Metal price	¥/g	258
Density	t/m ³	2.8
Tunneling cost	¥/m	19,800
Mining cost	¥/t	250
Processing cost	¥/t	70
Mining recovery	%	90
Processing recovery	%	90
Shaft construction cost	¥/m	198,000

2.2. Mathematical formulation

Although the mining process has multiple steps in terms of drilling, charging, blasting, extraction and backfilling, the mining process is continuous. Therefore, the mining process of each stope could be regarded as one unit. The mining state of each stope is the decision variable. The integer programming (IP) is employed to construct the production planning optimization model.

Subscript notation

- i – block indicator,
- l – production level indicator $l = 1, 2, \dots, L$,
- o – orientation indicator of the stopes at level,
- k – drive unit indicator,
- t – time period $t = 1, 2, \dots, T$,
- j – stope indicator. Each stope is named by level, orientation, start and end block indicator shown in Figure 6, loi_{start}^{end} .

Sets

- S_j – set of all stopes overlapping with stope j ,
- Z_j – set of horizontal drives should be extracted before mining stope j ,
- U_j – set of horizontal drives at level l .

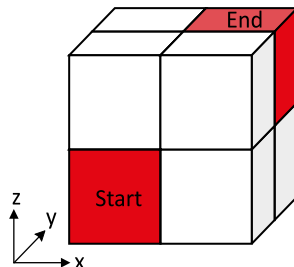


Fig. 6. Demonstration of slope indicator represented by blocks

Rys. 6. Demonstracja wskaźnika przodków wybierkowych w formie bloku

Parameters

r	– discounted rate (%)
x_i, y_i, z_i	– location coordinates (x, y, z) of block i ,
v_j	– volume of stope j ,
g_j	– average grade of stope j ,
d_j	– average material density of stope j ,
R	– recovery rate (%)
o_j	– ore tonnage of stope j , $o_j = v_j \cdot d_j \cdot R$,
w_j	– metal weight of stope j , $w_j = v_j \cdot d_j \cdot g_j \cdot R$,
h_j	– segment of drive corresponding to stope j ,
f_k	– segment of drives should be developed before the development of drive segment k ,
P	– commodity price of metal,
MC	– mining cost per unit,
PC	– processing and refining cost per unit,
DC_k	– drilling cost of drive k ,
SC_l	– shaft cost from the surface to level l ,
G_t^{\min}, G_t^{\max}	– target minimum and maximum ore grade at time period t ,
PR_t, DR_t, SR_t	– maximum capacity of production, drive development and shaft development at time period t ,
M_t^{\min}	– target minimum contained metal tonnage for mineral type m at time period t .

Decision variables

$a_{j,t}$	– 1 if stope j is valuable to be mined at the time period t , 0 otherwise,
$b_{k,t}$	– 1 if drive k is to be developed at time period t , 0 otherwise,
$c_{l,t}$	– 1 if shaft l is to be developed at time period t , 0 otherwise.

Objective function

Maximize:

$$\sum_{j,t} \frac{P \cdot w_j \cdot a_{j,t}}{(1+r)^t} - \sum_{j,t} \frac{(MC+PC) \cdot o_j \cdot a_{j,t}}{(1+r)^t} - \sum_{k,t} \frac{DC_k \cdot b_{k,t}}{(1+r)^t} - \sum_{l,t} \frac{SC_l \cdot c_{l,t}}{(1+r)^t} \quad (1)$$

Constraints

$$a_{j,t} \leq \sum_{t'} b_{k,t'} \quad \forall j | t' \leq t, k \in h_j \quad (2)$$

$$b_{k,t} \leq \sum_{t'} c_{l,t'} \quad \forall k | t' \leq t, k \in U_l \quad (3)$$

$$b_{k,t} \leq \sum_{t'} b_{k',t'} \quad \forall k, t | t' \leq t, k' \in f_k \quad (4)$$

$$\sum_t a_{j,t} \leq 1 \quad \forall j \quad (5)$$

$$\sum_t b_{k,t} \leq 1 \quad \forall k \quad (6)$$

$$\sum_t c_{l,t} \leq 1 \quad \forall l \quad (7)$$

$$\sum_t a_{j,t} + \sum_t a_{j',t} \leq 1 \quad \forall j | j' \in s_j \quad (8)$$

$$\sum_j o_j \cdot a_{j,t} \leq PR_t \quad \forall t \quad (9)$$

$$\sum_k DC_k \cdot b_{k,t} \leq DR_t \quad \forall t \quad (10)$$

$$\sum_l SC_l \cdot c_{l,t} \leq SR_t \quad \forall t \quad (11)$$

$$G_t^{\min} \leq \frac{\sum_j w_j \cdot a_{j,t}}{\sum_j o_j \cdot a_{j,t}} \leq G_t^{\max} \quad \forall t \quad (12)$$

$$M_t^{\min} \leq \sum_j w_j \cdot a_{j,t} \quad \forall t \quad (13)$$

Equation (1) is the objective function, maximizes the discounted cash flow to determine the best stope size and location with access constraints whilst generating a corresponding production schedule. Equation (2) ensures that only the accessible stopes can be extracted in the mine life. If the drives are not developed, there will be no possibility to mine the stopes. Equation (3) limits the horizontal tunnels drilling until the shaft is extended to that level. Equation (4) ensures the tunnels are drilled continuously. It also restricts the creation of subsequent drives when all the previous drives are constructed. Equations (5), (6) and (7) limit stopes, shafts and tunnels can be produced only once in the entire mine life. Equation (8) ensures that only one stope, from all stopes sharing at least one block, is allowed to be produced. Equations (9), (10) and (11) ensure the stopes extraction amount, tunnels and shafts excavation amount cannot exceed the annual maximum capacities. Equation (12) restricts ore grade lying between an upper and lower limit in any time period. It reduces the grade fluctuations of ore transferred to the processing plant. Equation (13) limits the contained minimum ore tonnage in any period. It ensures the mineral yield can be kept at a stable rate at the end of mine life.

2.3. Optimization result analysis

A simultaneous integrated approach is where stope layouts, access network, and a production schedule are optimized at the same time by applying all the constraints to the dataset of Xinli orebody. All the tech-economic parameters used can be referred to Table 1. In addition, relevant mining parameters are shown in Table 2 which are estimated based on the size and scale of operation within the Chinese mining context.

Table 2. Mining parameters

Tabela 2. Parametry wydobywania

Items	Unit	Value
Maximum production capacity	t/a	1,300,000
Grade scale limitation	g/t	2.2~2.8
Minimum metal yield each year	g	2,000,000
Tunnel drilling capacity	m/a	700
Shaft drilling capacity	m/a	400
Discounted rate	%	10
Mine life	year	15

Figure 7 shows the block model with the assumed access network in terms of shaft and production level tunnel. The optimization result is expressed in Figure 8. The production period is represented by a different color. The NPV obtained is $2,023.99 \times 10^6$ ¥, and the ore tonnage is 15,812,245 tons, and the average grade is 2.50 g/t.

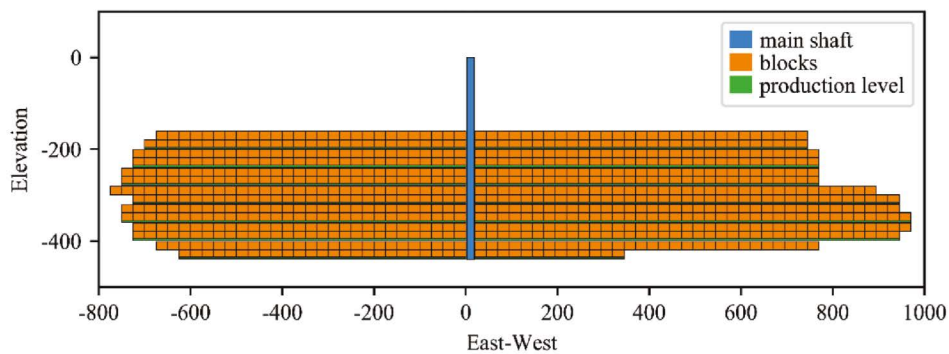


Fig. 7. Access network attached to the block model

Rys. 7. Infrastruktura udostępniająca w modelu blokowym

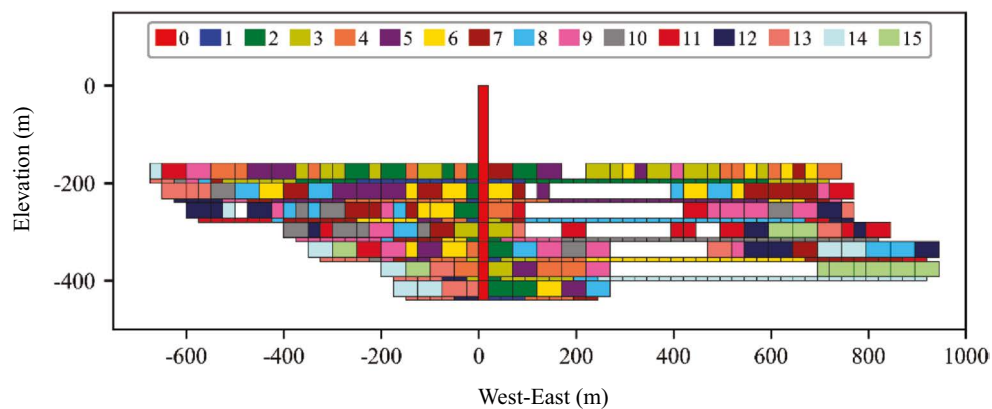


Fig. 8. Optimal stope layout, access network, and production scheduling

Rys. 8. Optymalne parametry przodka wybierkowego, infrastruktury udostępniającej i planowanie robót górniczych

Figure 9 shows the key performance indicators in all mine life based on the optimization result. Figure 9(a) indicates that more effort is spent on development such as shafts, cross-cut and production level at the initial stage of mine construction. After the ore production

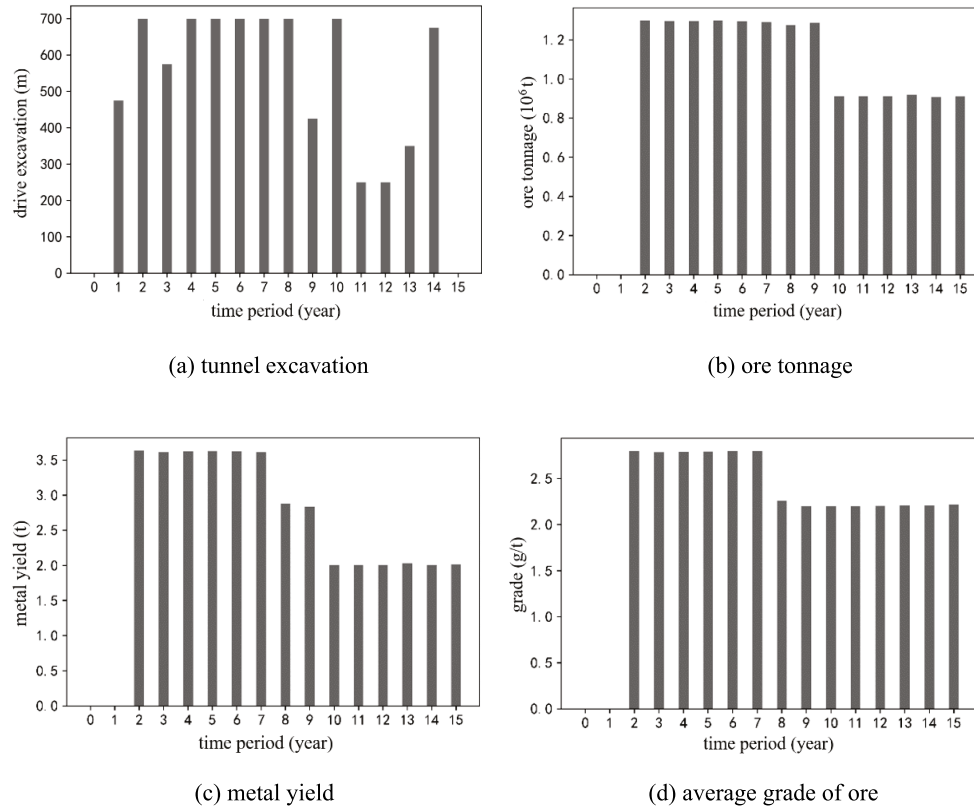


Fig. 9. Key performance indicators in all mine life

Rys. 9. Kluczowe wskaźniki wydajności w trakcie eksploatacji kopalni

starts, the access development is still an on-going process to keep a stable production rate. The ore production starts in the second year, and the optimal production rate fluctuates at approximately 1,300,000 t/a as shown in Figure 9(b). The optimal production rate decreases at the 10th year to keep a fixed mine life of 15 years. However, metal production and grade decrease at the 8th year shown in Figure 9(c) and 9(d). The cause for the decrease is that more high-grade stopes are mined at an early stage in order to obtain a higher NPV.

Figure 10(a) shows the discounted present value (PV) of net cash flow for each year of the operation. The corresponding accumulated PV is shown in Figure 10(b). Note the sum of all PV shown in Figure 10(a) is the NPV of the project, which is the accumulated PV at the 15th year as shown in Figure 10(b). Note a significant drop in PV is experienced in this operation in year 8 due to the decline in overall metal production.

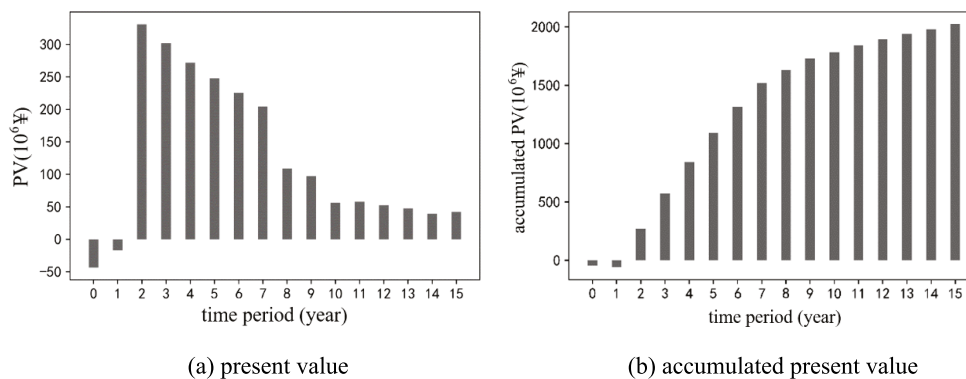


Fig. 10. Financial indicators in all mine life

Rys. 10. Wskaźniki finansowe w trakcie eksploatacji kopalni

3. Risk assessment based on grade uncertainty

In the past few decades, geostatistics has been widely used to estimate the grade distribution of the deposit. The most important method of geostatistics is the Kriging interpolation method. However, its major drawback is that the grade tends to be smooth. The dispersion and volatility of the spatial distribution of the grade cannot be performed, which leads to the inaccuracy of mining design and production scheduling. The grade uncertainty is the main risk for the mining company to get the expected profit from the considerable investment. Therefore, the evaluation of the impact of grade uncertainty on mine planning becomes an important task. The Conditional Simulation method ensures the correlation of all samples and the local variation simultaneously. The Sequential Gaussian Simulation (SGS) method is used to generate many models with equal probability, which can help the engineers to carry out the risk assessment related to the grade uncertainty shown in Figure 11.

Figure 11(a) and 11(b) show the 50 estimation results of the thickness and accumulation of the orebody respectively. It can be seen that the overall distributions are very similar, but there are subtle differences between each simulation result because of the random estimation sequence. The grade of each block is calculated by division calculation as shown in Figure 11(c).

A series of possible results could be obtained from the geological models estimated by SGS rather than the signal result using OK estimation. The distributions show all the possible situations in which the orebody is mined. The risk of the variability of geological parameters will lead to the mining company not being able to extract the expected ore quality, which will result in economic loss. Therefore, the possibility of not achieving the expected value should be quantized to measure the penitential risk in the assessment of the investment project.

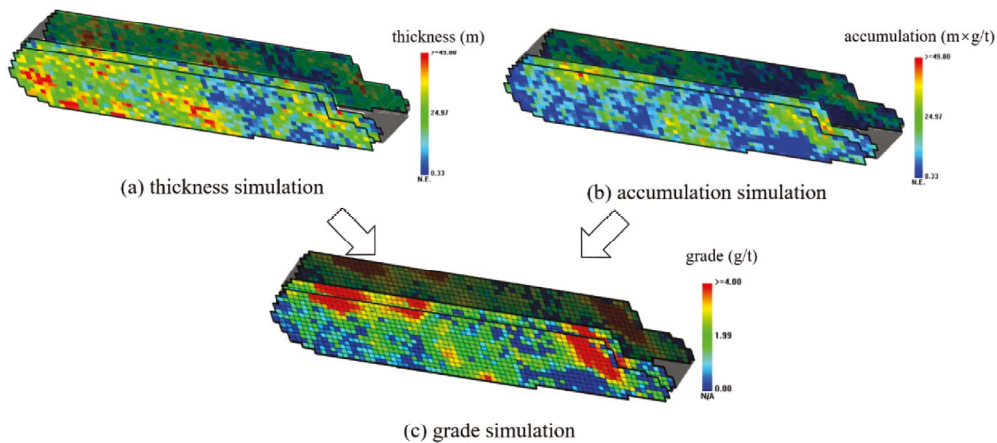


Fig. 11. Estimation results of SGS

Rys. 11. Wyniki estymacji SGS

The block models obtained by stochastic simulation will be used as the input data of the mine planning optimization model to analyze the influence of grade uncertainty on the optimal production scheduling computed by the simultaneous integrated optimization model. Figure 12 shows the key production indicators for each year based on the optimal production scheduling. The different estimated results lead to a different changing regulation of the indicators. The black line represents the annual key performance indicators based on the deposit estimated by OK, while the grey lines represent the annual key performance indicators based on the deposits estimated by SGS.

Figure 12(a) shows that the orebody model estimated by OK is more likely to produce more metal from the beginning to the 2nd year. From the 2nd to the 15th year, the metal yield produced by the deposit models estimated by SGS fluctuate on a large scale, which means the differences among the simulation results is obvious. However, the entire trend is similar to the metal tons of the deposit produced by OK.

Figure 12(b) shows the comparison of the ore tonnage produced in each year. The grey lines are significantly lower than the black line from the beginning to the 8th year, which indicates that there is a big possibility that the simulated orebody will not produce the expected amount of ore in the initial mining stage. The ore tonnage of orebody based on the SGS exceeds that of OK for 8th to 15th years except for the 10th and 14th year. The most different situation occurs in the 2nd, 9th, 11th, 14th and 15th years respectively. All of the grey lines have a low degree of dispersion and good overall performance, which indicates that there is a great possibility that the actual ore tonnage in each year is significantly different from the expected ore tonnage.

Figure 12(c) shows the average grade of ore produced in each year. The overall trend of the grey lines is more consistent from the beginning to 8th year, which are consistent with

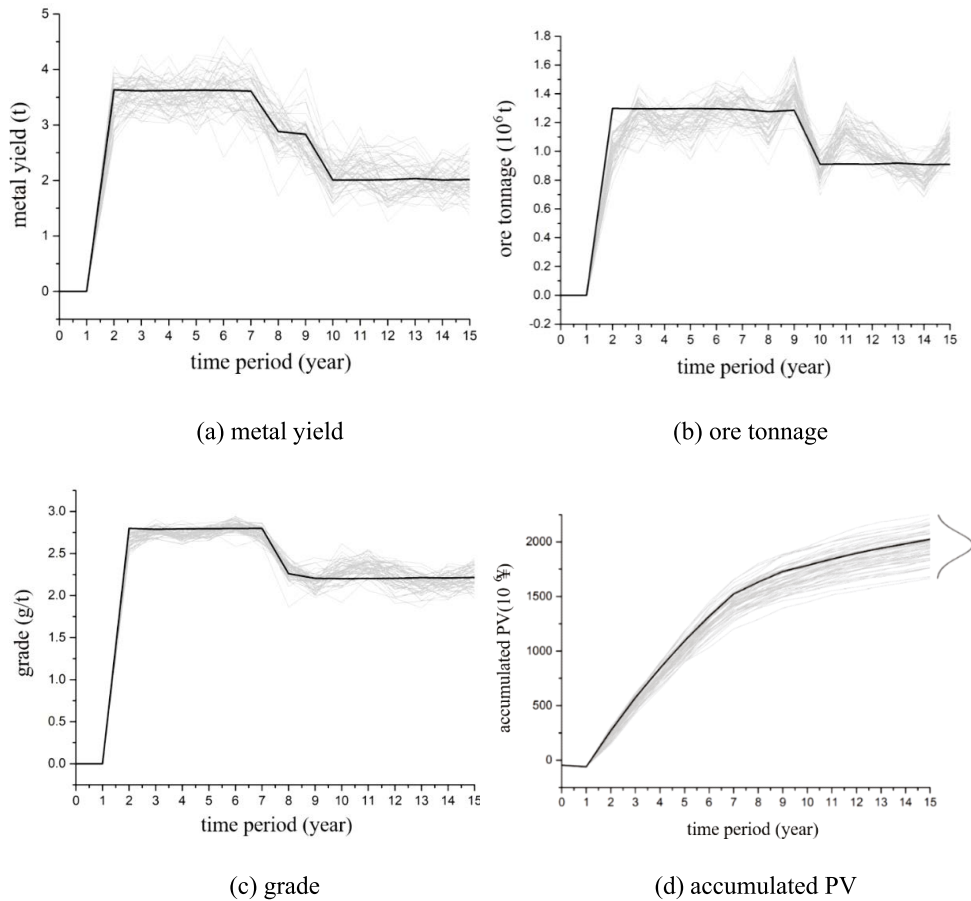


Fig. 12. Annual key production indicators based on OK and SGS results respectively

Rys. 12. Roczne kluczowe wskaźniki produkcji oparte na wynikach uzyskanych przez OK i SGS

the trend of the black line. The grey lines have an upward trend and then stabilizes from 8th to 15th year, which indicates that the average grade of ore has a low sensitivity to the uncertainty of the geological resource model. Figure 12(d) shows the annual accumulated PV curve. Both of the grey lines and the black line show an upward trend. The black line is always within the gray lines, which indicates that it is reliable to use the OK estimation result to do the production planning for the Xinli orebody. However, there is about 75% probability that the actual result is lower than the expected return, and there is a 25% probability that the actual result is higher than the expected return shown in Figure 13(a).

Figures 13(b), 13(c) and 13(d) show the amount of ore tonnage, metal yield, and grade that may be produced when the production scheduling is applied based on the estimated results of 50 random simulations. The lowest value of ore tonnage is about 14,654,243 tons,

and the highest value is about 16,919,594 tons. From the histogram of annual ore tonnage, there is about 53% probability that the ore tonnage is lower than the expected, which means that there is approximately 47% probability that the ore tonnage is higher than expected. The metal output is between approximately 35 tons and approximately 43 tons. The histogram of metal yield illustrates that there is about 55% probability that the metal tons are lower than the expected and there is 45% probability that the metal tons are higher than the expected. The lowest avg-grade is about 2.39 g/t and the highest avg-grade is about 2.56 g/t. The histogram of average grade means that there is about 55% probability that the ore grade is lower than the expected, meanwhile, there is 45% probability that the ore grade is higher than the expected.

All the key performance indicators show that the production scheduling optimized using the results of OK performs strong robustness under geological uncertainties. All indicators fluctuate within the normal range, which means that the Xinli deposit model has low geological uncertainty. When optimal production scheduling is applied, the probability that the ore production, metal volume, grade, and yield are lower than the expected is slightly higher than the probability of higher than the expected value.

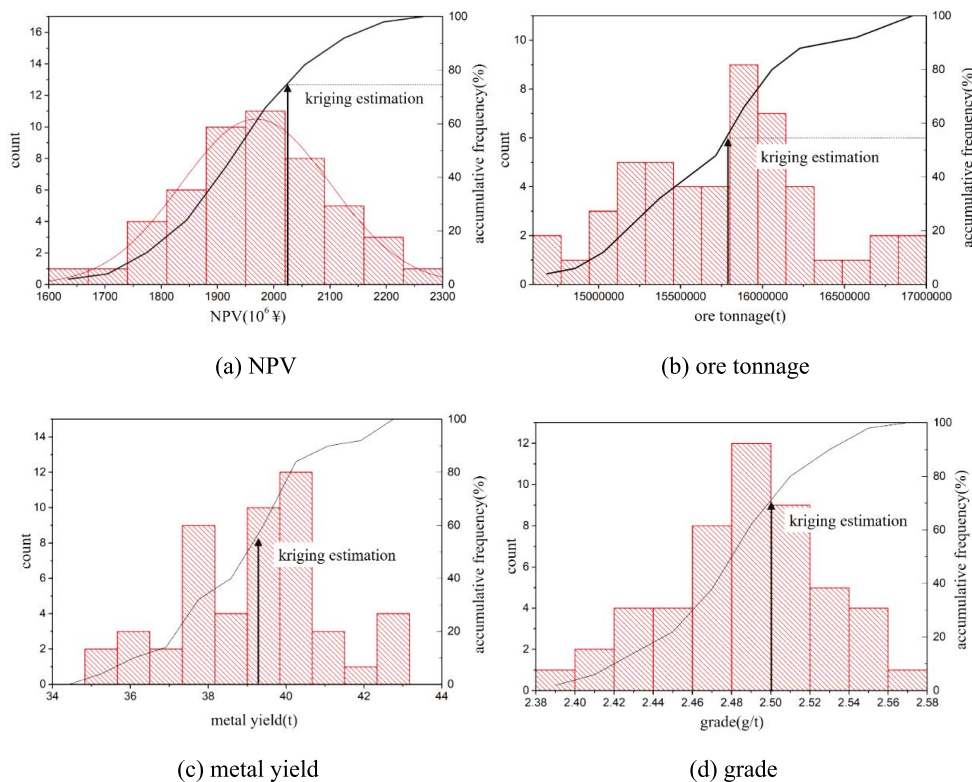


Fig. 13. Histogram of key performance indicators based on the orebodies produced by SGS

Rys. 13. Histogram kluczowych wskaźników wydajności na podstawie złóż rud wydobywanych przez SGS

4. Discussion

In this paper, a simultaneous integrated optimization model was proposed optimizing stope layout, access layout and production scheduling in a single model to maximize the NPV of the project. The spatial and sequence relationship of stope extraction and access excavation is taken into account in the optimization model, and a case study of a large gold mining enterprise in China was conducted. The research enriches the integrated optimization method for underground mining operations. Furthermore, the risk of geological uncertainty is evaluated by a series of orebodies simulated by SGS, which present a framework to assess the risk of grade variability.

The presented methodology is applicable to the stratiform orebody. Compared with the traditional independent and sequential optimization method, the simultaneous integrated optimization model considers the interaction and influence between different optimization components to get a globally optimal solution. The amount of access development and stope mining for each year is balanced by the schedule to promise that a sufficient amount of stopes could be accessed in the next production period. However, the research results also have certain limitations. The model is a two-dimensional based optimization model, and the disseminated deposit is not taken into account. The access design and mining method is complex for the disseminated deposit. During further research, we need to improve the model to solve the three-dimensional problem and integrate the grade uncertainty into the optimization model to get a more robust and profitable solution.

This study provides a theoretical basis for the integrated optimization for the underground mining operation. It provides a new idea and a basic optimization model for the integration of stope layout, access layout and production scheduling. It is of great practical implication to get more profit for shareholders, and decreasing the possibility of geological uncertainty leading to the big loss.

Conclusion

1. The optimization objects of underground mine planning could be classified into two aspects: design and production scheduling. The mining design includes the stope layout and access layout. The traditional optimization method considers these components as separate parts. Numerous algorithms and strategies are developed and implemented in underground mining operations to obtain additive profit for a mining company. However, the interaction between different optimization components is ignored, which could not find the globally optimal result. Hence, a simultaneous integrated optimization model is proposed to integrate the optimized objects into a single model to find the optimal solution.
2. The extension sequence of access excavation and stope extraction is taken into account in the optimization model to balance the development and mining. The time of mine

development could be arranged reasonably before the stopes will be mined to reduce the premature investment. The restrictive relationships between shaft and drift, drift and production level tunnel, production level tunnel and stope are discussed demonstrating the mining sequence. In addition, the mining capacity and ore quality requirement are considered in the model which is formulated by IP and calculated by Gurobi. The key performance indicators demonstrate the simultaneous integrated model gains the optimal mining design and production scheduling at the same time.

3. A series of geological resource models are established by SGS. The optimal mining design and production is carried out on the simulated resource models to validate the performance of the optimal solution under the grade uncertainty. The risk of geological uncertainty is assessed by the statistics of all the possible value of these indicators (NPV, metal yield, ore tonnage and grade). The comparisons of the results with the production scheduling optimized using the results of OK indicate that the possibility of less than the expected amount is much more than the possibility of the greater than the expected amount.

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**SIMULTANEOUS INTEGRATED OPTIMIZATION FOR UNDERGROUND MINE PLANNING:
APPLICATION AND RISK ANALYSIS OF GEOLOGICAL UNCERTAINTY IN A GOLD DEPOSIT****Key words**

underground mine, mine planning, integrated optimization,
geological uncertainty, integer programming

Abstract

The main optimized objects in underground mines include: stope layout, access layout and production scheduling. It is common to optimize each component sequentially, where optimal results from one phase are regarded as the input data for the next phase. Numerous methods have been developed and implemented to achieve the optimal solution for each component. In fact, the interaction between different phases is ignored in the tradition optimization models which only get the suboptimal solution compared to the integrated optimization model. This paper proposes a simultaneous integrated optimization model to optimize the three components at the same time. The model not only optimizes the mining layout to maximize the Net Present Value (NPV), but also considers the extension sequence of stope extraction and access excavation. The production capacity and ore quality requirement are also taken into account to keep the mining process stable in all mine life. The model is validated to a gold deposit in China. A two-dimensional block model is built to do the resource estimation due to the clear boundary of the hanging wall and footwall. The thickness and accumulation of each block is estimated by Ordinary Kriging (OK). In addition, the conditional simulation method is utilized to generate a series of orebodies with equal possibility. The optimal solution of optimization model is carried out on each simulated orebody to evaluate the influence of geological uncertainty on the optimal mining design and production scheduling. The risk of grade uncertainty is quantified by the possibility of obtaining the expected NPV. The results indicate that the optimization model has the ability to produce an optimal solution that has a good performance under the uncertainty of grade variability.

**ZINTEGROWANY MODEL OPTYMALIZACJI PLANOWANIA ROBÓT GÓRNICZYCH
W PODZIEMNYCH KOPALNIACH: ANALIZA RYZYKA I NIEPEWNOŚCI
GEOLOGICZNEJ W ZŁOŻACH ZŁOTA****Słowa kluczowe**

kopalnia podziemna, planowanie robót górniczych, zintegrowana optymalizacja,
niepewność geologiczna, programowanie całkowitoliczbowe

Streszczenie

Główne optymalizowane obiekty w kopalniach podziemnych to parametry struktury przodka wybiórkowego, optymalnego udostępnienia oraz planowanie robót górniczych. Powszechne jest

optymalizowanie każdego komponentu po kolei, przy czym optymalne wyniki jednej fazy są uważane za dane wejściowe dla następnej. Opracowano i wdrożono wiele metod w celu uzyskania optymalnego rozwiązania dla każdego komponentu. W rzeczywistości interakcja między różnymi fazami jest ignorowana w tradycyjnych modelach optymalizacji, które prowadzą do nieoptymalnych rozwiązań w porównaniu ze zintegrowanym modelem optymalizacji. Niniejszy artykuł przedstawia zintegrowany model optymalizacji optymalizujący trzy komponenty w tym samym czasie. Model nie tylko optymalizuje układ wydobywczy, aby zmaksymalizować wartość bieżącą netto (NPV), ale także uwzględnia parametry przodka wybierkowego oraz wkopu udostępniającego złoża. Aby utrzymać proces wydobywania na stałym poziomie przez cały czas trwania eksploatacji, pod uwagę brane są również zdolności produkcyjne oraz wymagania dotyczące jakości rudy. Omawiany model jest opracowany na potrzeby złoża złota w Chinach. Powstały dwuwymiarowy model blokowy do oszacowania zasobów ze względu na wyraźną granicę między skrzydłem wiszącym a spągowym. Grubość i akumulacja każdego bloku jest szacowana za pomocą krigingu zwyczajnego (OK). Dodatkowo wykorzystywana jest warunkowa symulacja w celu generowania szeregu złóż rudy. Optymalny model optymalizacji jest przeprowadzany na każdym symulowanym złożu w celu oceny wpływu niepewności geologicznej na optymalne planowanie robót górniczych i produkcji. Ryzyko odnośnie do niepewności jakości złoża jest kwantyfikowane przez możliwość uzyskania oczekiwanej wartości bieżącej netto (NPV). Wyniki wskazują, że model optymalizacji ma zdolność do tworzenia optymalnego rozwiązania w warunkach niepewności.