GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT
2014 Volume 30 Issue 2 Pages 173–186
DOI 10.2478/gospo-2014-0020

EHSAN MOOSAVI*, JAVAD GHOLAMNEJAD**, MAJID ATAEE-POUR***,
ESMAILE KHORRAM****

Optimal extraction sequence modeling for open pit mining operation considering the dynamic cutoff grade

Introduction

In mineral resource industries, considerable economic gains can be achieved by calculation of the optimal cutoff grades in each period, which maximizes the net present value (NPV) of a mining project. Choosing the cutoff grades is one of the most complicated problems relating to the extraction sequence of mining blocks in open pit mining operations. The cutoff grade directly affects the economic feasibility of mining operations during a project's life. The cutoff grade strategy, which results in higher overall NPV for a given project, starts with high cutoff grades. Higher cutoff grades lead to higher average grades per ton of ore in the initial periods of the mining sequence. Consequently, higher average grades are realized depending upon the grade distribution of the deposit (Dagdelen 1993). In each mining sequence, the cutoff grade indicates the quantity mined, processed, and, finally, the product produced in the refinery for marketing (Lane 1988; Mohammad 2002). The success of the project is significantly dependent on the selection of the cutoff grade. Therefore, cutoff grade optimization is essential in terms of the life of a mine.

* Department of Mining Engineering, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran; e-mail: Se.Moosavi@yahoo.com
** Department of Mining and Metallurgical Engineering, Yazd University, Yazd, Iran.
*** Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran.
**** Department of Applied Mathematical and Computer Science, Amirkabir University of Technology, Tehran, Iran.

Studies have dealt with the concept of cutoff grade development methods and algorithms with different focuses and merits. As a result of these studies, a number of cutoff grade algorithms address a given, constant cutoff grade with a long mine life. Based on the optimum cutoff grade algorithms, several variable cutoff grade procedures have also been elaborated. At first, the economic cutoff grade parameter was defined by Mortimer (1950). However, this parameter is in fact equivalent to the breakeven grade criteria, which does not lead to NPV maximization. One of the best observations for optimization of cutoff grade is Lane's theory (1964, 1988). This theory led to the construction of a function of the maximization of the NPV of cash flow, but is also able to include various constraints on the capacities (mine, mill, and refinery) in the mining operation. Other researchers have proceeded in this direction, such as Shinkuma and Nishiyama (2000), Cairns and Shinkuma (2003), Ataee and Osanloo (2003, 2004), Rashidinejad et al. (2008), as well as Gholamnejad (2009). Halls and John (1969) defined dual cutoff grades as a minimum grade that covers all estimated costs (mining, processing, refining, and marketing) and has a reasonable profit. In the following decade, Taylor (1972) suggested a differentiation between the planning and operational cutoff grades, indicating that they may not always be the same. He states that, "maximum present value and constant cutoff grades are incompatible". Taylor (1985) also highlighted the need for establishment of a stockpile through a real example. The results of these studies indicate that the optimization of the cutoff grade is due to limits on the capacities of any mining, milling, and refining stages but not the mining sequence. These methods have assumed the mining sequence to be known in advance, yet the mining sequence is certainly influenced by the cutoff grade choice. Therefore, various attempts have been made to develop a computerized procedure for optimization of cutoff grade, considering the mining sequence, such as relying on Penalization (Dantzig-Wolf) (Johnson 1968, 1969), Lagrangian Relaxation (Dagdelen 1985; Dagdelen and Johnson 1986; Kawahata 2007), 4D-Network Relaxation (Akaike and Dagdelen 1999; Mogi et al. 2001), and Dynamic Programming (Wang et al. 2008). Unfortunately, none of these attempts appears to enjoy widespread acceptance. The common theme among these methods is the large size and inherent difficulty of the model.

To overcome this shortcoming, Zhang (2006) proposed a methodology based on a combination of Genetic Algorithm and Topological Sort to reduce the problem size, but the quality of the final solution is not guaranteed. Boland et al. (2009) used several strategies to reduce the computational time. Gleixner (2008) extended the work of Boland et al. (2009) by developing a type of aggregation, and also presented ideas for applying Lagrangian Relaxation. They did not, however, take the grade blending constraint into account. None of these models guarantee qualitative satisfaction of the grade blending in each period. Extensive surveys of different operational research techniques and modeling issues were provided by Sattarvand and Niemann-Delius (2008) as well as Newman et al. (2010).

The metal recovery, mining, and processing costs depend on processing decisions. Those decisions, in turn, determine the block's classification (waste, heap leach, dump leach, mill, etc.) and, therefore, the block's economic value during the life of the mine. Ignoring the effect of these changes in the mining sequence on the optimum cutoff grades would lead to unrealistic mine design analysis. The study presented in the following text applied a new binary integer programming model for solving the extraction sequence problem. This paper presents the effect of the cutoff grade strategy on the mining sequence. The formulation is based on an economic loss assessment of a block considering each of the alternative processing decisions and the probabilities distribution of the ore body grades. Economic loss assessment of a block and probabilities are integrated with physical constraints in a binary integer programming model. The ultimate goal of the presented model is setting the best mining sequence while optimizing cutoff grades in each period of mine life simultaneously.

1. Necessity of cutoff grade optimization in open pit mines

The cutoff grade analysis, as usual, replies to the following questions:

- What material in a deposit is worth mining and processing (and if none it should be considered waste)
- How should that material be processed once it is mined

One cutoff grade, dictated by management, fails to allow the flexibility needed to maximize profits in different situations (Gershon 1983). In fact, the cutoff grade is calculated for the purposes of managing materials that are extracted from the mine. Figure 1 shows the decision criteria based on the cutoff grade.

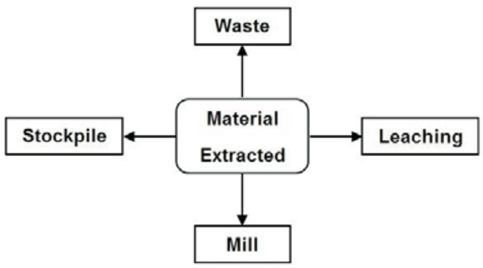

Fig. 1. Decision criteria based on the cutoff grade

Rys. 1. Kryteria decyzyjne na podstawie zawartości brzeżnej

Cutoff grade optimization is an interactive process, including considerations such as metal price, mining, milling cost, the capacity of the processing plant, mining capacity in the mining operation, mining sequence, grade distribution of the deposit, and resulting cash flow. Processing decisions for the block play a principal role in changes to the mining sequence. The effect of these changes will be enormous on the cutoff grade's mining operations, which change due to the declining effect of net present value during the mine's life. This is despite the fact that optimization of cutoff grades should be simultaneously considered in the mining sequence (Johnson 1968). Cutoff grade optimization is therefore one of the most important topics in mining operations, because:

- Cutoff grade optimization is used for the decision of processing material types (mill/leaching/stockpile/waste) to determine which decision dictates the maximum economic profit
- Cutoff grade optimization can improve the mining sequence during the life of the mine

2. Formulation of mining sequence considering a dynamic cutoff grade

2.1. Definitions and assumptions

With respect to the mining sequence, the extraction of each block in each period is dependent upon the definition of the cutoff grade. The cutoff grade dictates the block's classification. Obviously, choosing among the different types of processing is directly related to the selection of the block's classification in the mining sequence, and is effected by special recovery costs and special block economic value. Consequently, the misclassification of a block results in incorrect calculation of a block's economic value. In this regard, Richmond (2001) defines the function "economic loss", which is used to distinguish between ore and waste block. The actual economic loss associated with each type of processing d ($d = 1, 2, \ldots, D$ ordered from lowest grade to highest grade) is the potential value less than the recovered value, which can be calculated using the following equation:

$$L_{ijk}^{d} = [(P - C_{sel}) \cdot \overline{\alpha}_{ijk} \cdot R^{d} - C_{p}^{d} - C_{m}^{d}] - [(P - C_{sel}) \cdot \overline{\alpha}_{ijk} \cdot R^{d'} - C_{p}^{d'} - C_{m}^{d'}] \tag{1}$$

where:

P	–	Unit selling price of the metal
C_{sel}	–	Unit selling cost of the metal
ijk	–	The block identification number
$\overline{\alpha}_{ijk}$	–	The average grade of block ijk
R^{d}	–	Total metal recovery of material if processed as type d
C_{p}^{d}	–	Unit processing cost of the material if processed as type d
C_{m}^{d}	–	Unit mining cost of the material if processed as type d
d	–	Correct processing type for block ijk
d'	–	Chosen processing type for block ijk

Based on Equation 1, if the correct processing type for block ijk is chosen, then economic loss is zero. In practice, the ore block is unknown and it will be represented by a cumulative distribution function. A more realistic method is to use conditional simulation techniques, which allows the generation of a number of equally probable realizations of block grades. Taking this into consideration, the expected economic loss (EEL) for each alternative d is calculated using the probabilities distribution and average grade for each type of processing generated from independent realization as described in the following equation:

$$EEL_{ijk}^{d} = \sum_{d=1}^{D} \left[P_{ijk}^{d} \middle| O \right] \cdot L_{ijk}^{d} \tag{2}$$

where:

$(P_{ijk}^{d} | O)$ – Probabilities distribution of block ijk if processed as type d

The optimal processing type for block ijk is that d for which the EEL is minimized, i.e.:

$$L(opt)_{ijk} = Min \qquad [EEL_{ijk}^{d}] \tag{3}$$

The mathematical programming method is defined as follows:

- The implementation of the model begins with a three dimensional block model.
- The ultimate pit limits and pushback design is completed.
- The parameters including mining and processing stages' capacities, mining costs and processing type costs, and current metal price through entire extraction periods are known at the beginning of each extraction period.
- The generation of a number of equally probable realizations of the block model were obtained using sequential Gaussian simulation.
- Providing the economic loss matrix of each block for each processing type and, subsequently, calculating the EEL for each alternative d.
- Developing a mixed integer programming model for optimal selection of the blocks in each period on the specified criteria.

2.2. Formulation as an integer problem

In light of the definitions and assumptions described above, the mathematical programming model of the mining sequence in terms of integer decision variables governs in which period the particular block is extracted, correctly determining its destination. In fact, this model can simultaneously optimize the block extraction sequence and cutoff grades strategy. As mentioned earlier, the objective function of the model can be represented mathematically as the following:

$$Minimize \quad Z = \sum_{ijk \in \Gamma} \sum_{t}^{T} \frac{L(opt)_{ijk}^{t} \cdot b_{ijk}^{t}}{(1+r)^{t}} \tag{4}$$

The objective function in Equation 4 does not explicitly maximize NPV, but rather optimizes feasible extraction sequencing and ensures a desired cutoff grade. Subsequently, the destination of the block extracted is quite straightforward. The reason is that feasible extraction sequences and the amount of ore having the desired quality to be sent to the mill need to be prioritized. Therefore, the mentioned objective function indirectly leads to a maximum NPV that is optimal. Otherwise, the generated NPV would only be optimal in theory but not in mining practice. However, economic loss for the suitable ore block which has the desired properties has been integrated in the present model, maximizing the chances of delivering to the mill the amount and quality of ore required during mining operation. EEL minimization and feasible sequences result in maximum NPV. On the other hand, the model suggests a unique cutoff grade policy and looks into the risk of maintaining the cash flows to maximize NPV based on the possible variations in production from the mine processes during the life of operation. The proposed model in Equation 4 contains a series of constraints as follows:

$$\sum_{ijk \in \Gamma} (\overline{\alpha}_{ijk} - U_{\alpha}^{t}) \cdot Q_{ijk}^{o} \cdot b_{ijk}^{t} \leq 0 \qquad \text{for all } t \tag{5}$$

$$\sum_{ijk \in \Gamma} (\overline{\alpha}_{ijk} - L_{\alpha}^{t}) \cdot Q_{ijk}^{o} \cdot b_{ijk}^{t} \geq 0 \qquad \text{for all } t \tag{6}$$

$$\sum_{t=1}^{T} b_{ijk}^{t} = 1 \qquad \text{for all } ijk \in \Gamma \tag{7}$$

$$\sum_{ijk \in \Gamma} (Q_{ijk}^{o} \cdot b_{ijk}^{t}) \leq U_{o}^{t} \qquad \text{for all } t \tag{8}$$

$$\sum_{ijk \in \Gamma} (Q_{ijk}^{o} \cdot b_{ijk}^{t}) \geq L_{o}^{t} \qquad \text{for all } t \tag{9}$$

$$\sum_{ijk \in \Gamma} (Q_{ijk}^{o} + Q_{ijk}^{w}) \cdot b_{ijk}^{t} \leq U_{w\&o}^{t} \qquad \text{for all } t \tag{10}$$

$$\sum_{ijk \in \Gamma} (Q_{ijk}^{o} + Q_{ijk}^{w}) \cdot b_{ijk}^{t} \geq L_{w\&o}^{t} \qquad \text{for all } t \tag{11}$$

$$b_k^t - \sum_{y}^{Y} \sum_{r=1}^{t} b_y^r \leq 0 \qquad \text{for all } t, k \tag{12}$$

where:

- $L(opt)_{ijk}^t$ – The optimal processing type for block ijk in period t
- T – The total number of scheduling periods
- t – The scheduling periods index, $t = 1, 2, \ldots, T$
- Γ – The total number of blocks to be scheduled
- r – The discount rate in each period
- b_{ijk}^t – The binary variable equal to $= \begin{cases} 1 & \text{if block } ijk \text{ is extractedat period } t \\ 0 & \text{Otherwise} \end{cases}$
- Q_{ijk}^o – The ore tonnage in block ijk
- Q_{ijk}^w – The waste tonnage in block ijk
- $\overline{\alpha}_{ijk}$ – The average grade of block ijk
- U_{α}^t – The upper bound average grade of material sent to the mill in period t
- L_{α}^t – The lower bound average grade of material sent to the mill in period t
- U_o^t – The upper bound total tons of ore processed in period t
- L_o^t – The lower bound total tons of ore processed in period t
- $U_{w\&o}^t$ – The upper bound total amount of material (waste and ore) to be mined in period t
- $L_{w\&o}^t$ – The lower bound total amount of material (waste and ore) to be mined in period t
- Y – The total number of blocks overlaying block k
- K – The index of a block considered for extraction in period t
- y – The counter for the Y overlaying blocks

Constraints 5 and 6 limit the average grade of the material sent to the mill to a certain value. Constraint 7 enforces that a block is removed in one period only. Constraints 8 and 9 ensure that the milling capacities hold. These upper and lower bounds are necessary to secure a smooth feed of ore. Constraints 10 and 11 relate the actual available equipment capacity for each period. These upper and lower bounds are the total amount of material (ore and waste) to be mined in period. Constraint 12 is the wall slope restriction on the basis of Y constraints for each block per period.

The proposed model provides a tool for evaluating alternative policies as a part of feasibility studies at the long-term production scheduling stage. Consequently, the resultant cutoff grade policy facilitates a risk-quantified decision making process involving major investments for sustainable utilization of mineral resources.

3. Application of proposed model in a gold ore deposit

This section demonstrates the implementation and testing of the proposed model on a real mine block to ensure optimization of the block's extraction sequence and the cutoff grade strategy. A gold mine sends its mineralized products to four destinations: waste dump, dump leach, heap leach, or mill. The characteristics of these four classes are listed in Table 1.

Table 1. The characteristics of each mineralized block class for gold ore deposit

Tabela 1. Charakterystyka poszczególnych klas bloków z mineralizacją dla złoża rud złota

Explanation	Unit	Waste	Dump leach	Heap leach	Mill
Processing type (destination)	No.	1	2	3	4
Grade range	g/ton	0–0.49	0.5–0.99	1–1.99	2
Average grade	g/ton	0.4	0.7	1.5	4.5
Metal recovery	%	0	45	70	95
Selling cost	USD/g of gold	0.5	0.5	0.5	0.5
Mining and processing costs	USD/ton of ore	1.5	3.5	5.7	10.5
Gold price	USD/g of gold	10			

At first, one hundred equally probable realizations of the ore body gold grades were generated using Sequential Gaussian Simulation. The results of the simulation for a given block are shown in Table 2.

Table 2. The results of the simulation for a given block of gold ore deposit

Tabela 2. Wyniki symulacji dla danego bloku w złożu rud złota

Grade range	0–0.49	0.5–0.99	1–1.99	≥2
Number of realization	35	28	20	17
Corresponding probability [%]	35	28	20	17

For example, assume that a correct mining destination for block *ijk* is the dump leach ($d = 3$), but it is incorrectly sent to the waste dump ($d' = 2$), then the economic loss assessment due to this misclassification can be calculated from Equation 1 in the following way:

$$L_{ijk}^{3} = [10 - 0.5) \cdot 1.5 \cdot 0.7 - 5.7] - [10 - 0.5) \cdot 1.5 \cdot 0.45 - 3.5] = 1.362 \qquad (13)$$

Table 3 shows the results of the economic loss for the other values of d and d'. If the chosen class of block *ijk* is $d = 2$, then the expected economic loss due to its misclassification can be achieved from Equation 2 as follows:

$$EEL_{ijk}^{2} = 0.29 \cdot 0.35 + 0 \cdot 0.28 + 1.362 \cdot 0.2 + 14.375 \cdot 0.17 = 2.81 \quad (14)$$

Table 3. The results of the economic loss of the block classification

Tabela 3. Wartości strat ekonomicznych dla klasyfikacji blokowej

Chosen mining destination	Correct mining destination				Expected economic loss
	1	2	3	4	
1	0	1	5.775	31.612	6.8
2	0.29	0	1.362	14.375	2.81
3	1.54	0.538	0	5.887	1.69
4	5.39	3.68	1.237	0	3.16

According to Table 3, the optimum expected economic loss is 1.69; therefore, the optimum destination of this block is $d = 3$, meaning that it is better to send this block to the heap leach.

In the extraction sequence problem, the extraction of each block in each period depends on its economic value in that period. On the other hand, due to changes in price and costs during this time, the block's economic value varies with time. It may therefore be possible that the optimum block classification in a period can be different from the optimum block classification in the other periods. Accordingly, the loss function for block *ijk* in period *t* can be calculated as in Equation 4. Due to the operational requirements, the minimization of the objective function is subjected to the available constraints as in Equations 5 through 12.

Since the iterative steps of optimization are boring and time consuming, an Excel spreadsheet was developed to facilitate performing the calculations. For solving the presented model in the gold mine, an input file for the block model using Excel software was provided, including characteristics of the counters for each block, tonnage, grade and ore content of each block, and the expected economic loss of each block. Decision variables and available constraints related to the type of block in the model are considered. The goal here was to generate a schedule for a 12 year mine life by maintaining the discount rate at 8%.

Knowing the input information, the steps for the model presented in the previous section are implemented to develop the optimal cutoff grade policy along with a portfolio of production rates and net present values. Table 4 demonstrates the cutoff grades policy generated by simultaneously utilizing mining sequences.

As shown in Table 4, during year 1 the heap leach processes ore carrying a metal content between 1.96% and 2.36%. This dictates that material below 1.96% be treated as waste and transported to the waste dumps. However, it generates a portfolio of optimal net present value.

Table 4. The optimal cutoff grade policy and corresponding production rates, and NPV of the gold mine

Tabela 4. Optymalna zawartość brzeżna i związana z nim wielkość produkcji oraz NPV dla kopalni złota

Year	Mill		Heap leach		NPV [USD M]
	Cutoff grade [%]	Quantity of ore processed [MT]	Cutoff grade [%]	Quantity of ore processed [MT]	
1.	2.36	0.073	1.96	0.054	1.794
2.	1.97	0.073	1.61	0.064	0.985
3.	1.83	0.073	1.52	0.077	0.745
4.	1.75	0.073	1.47	0.071	0.581
5.	1.63	0.073	1.43	0.070	0.745
6.	1.58	0.073	1.37	0.074	0.454
7.	1.47	0.073	1.31	0.078	0.376
8.	1.42	0.073	1.26	0.086	0.371
9.	1.35	0.073	1.24	0.050	0.319
10.	1.28	0.073	1.17	0.028	0.253
11.	1.19	0.073	1.04	0.017	0.228
12.	1.06	0.046	0.99	0.011	0.110

Conclusion

This paper has presented a mathematical model based on binary integer programming for open pit mines, which can combine reasonable mining operations and cutoff grades strategy into one. The proposed procedure develops a model that generates a practical and feasible schedule considering processing types while satisfying system constraints and minimizing expected economic loss. Although the proposed model is not set up to directly maximize NPV, it provides a realized NPV, which is optimum given the mining sequencing and cutoff grade strategy considerations. As a matter of fact, that NPV can be increased by determining the probabilities distribution of the blocks, because the suggested model tends to minimize the EEL. This leads to more high-grade blocks being mined in earlier periods. This study used economic loss as the objective function. Clearly, the economic loss function method is an efficient technique to determine the optimum processing type of the material in each period. This model overcomes the limitation of conventional methods, and includes certain innovations such as the following:

- Reducing the required number of variables and, subsequently, managing the available variables and constraints in a short time.
- The capability of taking various types of processing in to account.

The proposed model was applied to a gold ore deposit. The results of the case study indicate that the proposed model provides flexibility at the mine planning stage for evaluation of various alternatives, and ensures the optimum resource utilization coupled with accurate economic decisions with respect to major mining investments.

REFRENCES

Akaike, A. and Dagdelen, K. 1999. A strategic production scheduling method for an open pit mine. *In proceedings of the 28th Application of Computers and Operation Research in the Mineral Industry*, pp. 729–738.

Ataei, M. and Osanloo, M. 2003. Methods for calculation of optimal cutoff grade in complex ore deposits. *Journal of Mining Science* 39, pp. 499–507.

Ataei, M. and Osanloo, M. 2004. Using a combination of genetic algorithm and the grid search method to determine optimum cutoff grades of multiple metal deposits. *International Journal of Surface Mining, Reclamation and Environment* 18(1), pp. 60–78.

Boland et al. 2009 – Boland, N., Dumitrescu, I., Froyland, G. and Gleixner, A.M. 2009. LP- based disaggregation approaches to solving the open pit mining production scheduling problem with block processing selectivity *Computer Operation Research* 36(4), pp. 1064–1089.

Cairns, R.D. and Shinkuma, T. 2003. The choice of cutoff grade in mining. *Resource Policy* 29, pp. 75–81.

Dagdelen, K. 1985. Optimum multi-period open pit mine production scheduling. *Ph.D thesis*, Colorado School of Mines, Golden, Colorado.

Dagdelen, K. and Johnson, T.B. 1986. Optimum open pit mine production scheduling by lagrangian parameterization. *19th International Symposium on the Application of Computers and Operations Research in the Mineral Industry* (*APCOM)* Ch. 13, PP. 127–142.

Dagdelen, K. 1993. An optimization algorithm for open pit mine design. *24th International Symposium on the Application of Computers and Operations Research in the Mineral Industry (APCOM)*. Canada: Montral, Quebec, pp. 157–165.

Gershon, M.E. 1983. Optimal mine production scheduling: evaluation of large scale mathematical programming approaches. *International Journal of Mining Engineering* 1(4), pp. 315–329.

Gholamnejad, J. 2009. Incorporation of rehabilitation cost into the optimum cut-off grade determination. *Journal South African Institute of Mining and Metallurgy* 108, pp. 89–94.

Gleixner, A. 2008. Solving large-scale open pit mining production scheduling problems by integer programming. *Master's thesis*, Technische Universität Berlin.

Halls, J.L. and John, L. 1969. Determination of optimum ore reserves and plant size by incremental financial analysis. *Transactions of the Institute of Mining and Metallurgy* London: 78, pp. A20–A26.

Johnson, T.B. 1968. Optimum open pit mine production scheduling. *Ph.D thesis*, Operations Research Department, University of California, Berkeley, pp. 539–562.

Johnson, T.B. 1969. Optimum production scheduling. *In Processing of the 8th International Symposium on Computers and Operations Research*, pp. 539–562.

Kawahata, K. 2007. A new algorithm to solve large scale mine production scheduling problems by using the lagrangian relaxation method. *Ph.D. thesis*, Colorado School of Mines.

Lane, K.F. 1964. Choosing the optimum cutoff grade. *Colorado School of Mines Quarterly* 59, pp. 485–492.

Lane, K. F. 1988. The economic definition of ore, cutoff grade in theory and practice. *Mining Journal Books Limited*, London.

Mogi et al. 2001 – Mogi, G. Adachi, T. Akaike, A. and Yamatomi J. 2001. Optimum production scale and scheduling of open pit mines using revised 4D network relaxation method. *In proceedings of the 17th International Symposium on Mine Planning and Equipment Selection*, pp. 337-344.

Mohammad, W.A. 2002. Development of generalized cutoff grade optimization algorithm for open pit mining operations. *Journal of Engineering & Applied Science* 21(2), pp. 119–127.

Mortimer, G.J. 1950. Grade Control, *Trans. Inst. Min. Metall* 59, pp. 357-99.

Newman et al. 2010 – Newman, A. Rubio, E. Caro, R. Weintraub, A. and Eurek, K. 2010. A review of operation research in mine planning. *Interface* 40(3), pp. 222–245.

Rashidinejad et al. 2008 – Rashidinejad, F. Osanloo, M. and Rezai, B. 2008. An environmental oriented model for optimum cut-off grades in open pit mining projects to minimize acid mine drainage. *Int. J. Environ. Sci. Tech* 5(2), pp. 183–194.

Richmond, A.J. 2001. Maximum profitability with minimum risk and effort. *Proceeding of Application of Computers and Operations Research in the Mineral Industry* pp. 45–50.

Sattarvand J. and Niemann-Delius, C. 2008. Perspective of Meta heuristic optimization methods in open pit production planning. *Mineral Resources Management* pp. 143–155.

Shinkuma, T. and Nishiyama, T. 2000. The grade selection rule of metal mines: An empirical study on copper mines. *Resource Policy* 26, pp. 31–38.

Taylor, H.K. 1972. General background theory of cutoff grade. *Transactions of the Institute of Mining and Metallurgy* 96, sect A, pp. A204–A216.

Taylor, H.K. 1985. Cutoff grades ? some further reflections. *Transactions of the Institute of Mining and Metallurgy* 81, sect A, pp. A160–A179.

Wang et al. 2008 – Wang, Q. Gu, X. and CHU, D. 2008. A dynamic optimization method for determining cutoff grades in underground mines. *Mineral Resources Management* pp. 133–142.

Zhang, M. 2006. Combination genetic algorithms and topological sort to optimize open-pit mine plans. *In 15th Mine Planning and Equipment Selection* Italy: Torino, pp1234–1239.

OPTYMALNE MODELOWANIE KOLEJNOŚCI EKSPLOATACJI DLA KOPALNI ODKRYWKOWEJ Z WYKORZYSTANIEM DYNAMICZNEJ ZAWARTOŚCI BRZEŻNEJ

S ł o w a k l u c z o w e

dynamiczna zawartość brzeżna, kopalnia odkrywkowa, binarne programowanie cyfrowe, decyzje procesowe, straty ekonomiczne

S t r e s z c z e n i e

Problem zawartości brzeżnej jest istotnym wyzwaniem badawczym i zadaniem optymalizacyjnym w rocznym planowaniu operacyjnym kopalń odkrywkowych w związku z jej naturą kombinatoryczną. Wynika to z faktu, że wpływa na nią szereg parametrów ekonomicznych, uwarunkowania poszczególnych etapów działalności górniczej, sekwencja eksploatacji górniczej oraz rozkład zawartości składnika użytecznego w złożu. W istocie ocenia się, że dynamiczna zawartość brzeżna podczas danego okresu jest funkcją dostępności rudy oraz potrzeb zakładu przeróbczego w tym okresie. W konsekwencji, strategia ustalania zawartości brzeżnej i kolejność eksploatacji złoża powinny być rozważane równocześnie. Biorąc to pod uwagę, przeprowadzono różne podejścia celem opracowania skomputeryzowanej procedury kolejności eksploatacji dla kopalni odkrywkowej. Żadne z otrzymanych podejść nie uzyskało powszechnej akceptacji z powodu dużej ilości zmiennych. W związku z tym zaproponowano nowy model celem pokonania tego problemu. Model ten rozwiązuje problem w trzech etapach:

- ustalana jest obecna strata ekonomiczna dla każdego rodzaju przeróbki dla każdego eksploatowanego bloku;

- rozkład prawdopodobieństwa i zawartość średnia dla każdego rodzaju przeróbki jest wyliczana niezależnie;
- każdy blok z jego przewidywaną stratą ekonomiczną jest rozwijany jako binarny cyfrowy model programowania.

Z użyciem tego modelu określana jest optymalna kolejność eksploatacji dla każdego okresu, na podstawie optymalnych decyzji przetwarzania. W artykule zaprezentowano studium przypadku celem ilustracji przydatności opracowanego modelu. Otrzymane rezultaty wykazują, że kolejność eksploatacji ustalona z wykorzystaniem sugerowanego modelu będzie realistyczna i przydatna. Model ten pozwala na rozwiązywanie poważnych problemów w odpowiednio krótkim czasie przy bardzo wysokiej jakości rozwiązań w kontekście określania optymalnej wartości bieżącej netto.

OPTIMAL EXTRACTION SEQUENCE MODELING FOR OPEN PIT MINING OPERATION CONSIDERING THE DYNAMIC CUTOFF GRADE

Key words

dynamic cutoff grade, open pit mine, binary integer programming, processing decisions, economic loss

Abstract

The cutoff grade problem is an important research challenge and vital optimization task in the yearly operational planning of open pit mines due to its combinatorial nature. This results from the fact that it is influenced by economic parameters, the capacities of stages in the mining operation, the mining sequence, and the grade distribution of the deposit. Essentially, it asserts that the dynamic cutoff grade during any given period is a function of the ore's availability and the needs of the mill in that period. Consequently, the cutoff grade strategy and extraction sequence should be considered simultaneously. With these factors in mind, various attempts have been made to develop a computerized procedure for the extraction sequence of open pit mines. None of the resulting approaches appear to enjoy widespread acceptance because of the numerous variables involved. A new model has therefore been proposed to overcome this shortcoming. This model solves the problem in three steps:

- the actual economic loss associated with each type of processing for each block is determined;
- the probabilities distribution and average grade for each type of processing is computed from independent realization;
- each block with its expected economic loss is developed as a binary integer programming model.

Using this model, the optimum extraction sequences in each period are identified based on the optimum processing decisions. A case study is presented in this article to illustrate the applicability of the model developed. The results show that the extraction sequences obtained using the suggested model will be realistic and practical. This model allows for the solution of very large problems in a reasonable time with very high solution quality in terms of optimal net present value.