MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 622.271:681.5:546.47/.49/.815(045)=111
DOI: 10.5937/mmeb2101035K

Received: 05.05.2021.
Revised: 20.05.2021.
Accepted: 24.05.2021.

Original Scientific Paper
Environmental Field

Daniel Kržanović[*], *Radmilo Rajković*[*], *Nenad Vušović*[**], *Milenko Jovanović*[*]

SELECTION OF THE OPTIMAL CONTOUR OF THE OPEN PIT IN MINING THE LEAD AND ZINC ORE DEPOSIT WITH THE INCREASED MERCURY CONTENT[***]

Abstract

Mining processes are complex and complicated, with many different economic, technical, environmental and other parameters that must be planned before the project gets its practical value. Many of these parameters are evaluated independently of others, due to the expediency and difficulties in predictting values for variables under consideration. Costs, prices, reserves, mining and processing of ore, as well as many social aspects, such as issuing permits for works, are absolutely crucial for the project evaluation. Each ore body is different, but the main steps in the open pit planning, when the main goal is to maximize NPV, follow the same principle. These steps are presented as the linear for simplicity. The actual planning process is an iterative process, in which some steps or a combination of steps are repeated many times with the sensitivity analysis.

Keywords: *software deposit modeling, optimal open pit contour, net present value*

1 INTRODUCTION

The main driving objective of any mining activity is certainly making a profit, but apart from this, the exploitation of mineral resources may be also motivated by the other specific factors such as the maximum (or such higher) resource recovery and economic (industrial) development of the local community where the project is situated, etc.

The problem of the open pit optimization requires a complex analysis that includes a large number of important parameters. As a rule, the exact value of many parameters is unknown or uncertain. For these reasons, the optimization of the open pit boundaries is usually a lengthy and iterative process.

The basic, primary input in the process of planning and designing an open pit is a geological block model of the ore body. Geological models are created on the basis of exploratory drilling data, which is performed according to a certain network and drilling density. Each mini-block in a block model of the deposit is assigned a level of trust supported by the data of exploration works in that area. It is very important to accurately calculate the block value in the optimization, because the wrong calculation leads to a wrong optimal contour of the open pit [1].

The most commonly accepted objective, in such complex production systems, in optimizing the open pit boundary is to ma-

[*] *Mining and Metallurgy Institute Bor*
[**] *Technical Faculty Bor*
[***] *This work was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, Grant No. 451-03-9/2021-14/ 200052.*

ximize the net present value of future cash flows [2]. To achieve this objective, the spatial relationship of variables in the deposit (such as the geographical location of the deposit and its geological properties) as well as the temporal relationship of the variables (including the order in which the ore will be mined and processed) must be taken into account, and accordingly the resulting cash flow.

Variable quantities relevant for optimization and production planning at the open pit interact in a cyclical manner. Without knowing one variable, the value of next variable in the cycle cannot be determined, Figure 1. The time required to excavate all open pits in the sequence represents the open pit life, while the shape of the last open pit in the sequence determines the final boundary of the open pit. In order to make the division between ore and waste, it is necessary to determine the cut-off grade for processing, which is a function of the final price of manufactured goods, as well as the price of excavation and processing.

It can be seen in Figure 1 that it is first necessary to establish the costs and revenues and, based on that, the limit ore content, in order to further spatially define the ore body and calculate the economic value of blocks. Then, the final boundary of the open pit is defined which is then used to make a production plan that includes the annual production and excavation plan. Further, the selected annual production and excavation plan are used to revise the costs and revenues.

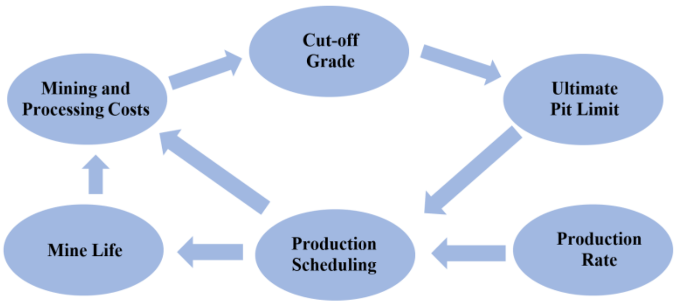


Figure 1 *Circular flow of production optimization at the open pit [3]*

2 SOFTWARE MODELING OF THE DEPOSIT

Block model of the deposit, created by the geostatistical modeling, with separate areas of useful ore blocks and non-profit waste blocks, allows engineers to choose the appropriate excavation methods and to plan the necessary equipment and infrastructure facilities necessary for the ore exploitation process. The block model of a deposit represents the main input in the process of open pit optimization.

Interpretation of the deposit and its immediate surroundings through the appropriate block model, implies their division into blocks of regular dimensions. The size of block depends on numerous factors of the mathematical and statistical character, degree of complexity of the geological structure of the deposit, etc. Blocks in general should not be too small, because in this way the error of calculation of the total volume of minefield ("assessment") increases, but not too large, because they must be adjusted to the characteristics of planned exploitation method.

3 ECONOMIC MODEL FOR OPTIMIZATION THE OPEN PIT BOUNDARY

Developing an economic model for optimizing the open pit boundary is the basis for generating an economic block model. The economic block model aims to calculate for each block model the expected net value of a block, which would arise in the event of its excavation. The economic block model was created in Whittle software, which is specialized for the open pit exploitation analysis and optimization of design solutions.

The economic model is based on the following economic and technological parameters:

- Operating costs
- Waste excavation costs
- Ore mining costs
- Total mineral processing costs (including crushing, sorting, grinding, flotation and other general and administrative costs)
- Costs of metal sales (smelter, refining, concentrate transport and fees for use of mineral resources/ore rent)
- Metal prices
- Discount rate
- Capital investments
- Ore mining capacity
- Recovery and depletion at excavation
- Recovery of metals (on sorting, flotation, metallurgical + payability of metals)

Modern planning procedures imply the possibility of considering the variant solutions and selection the optimal solution. The standard economic measure for optimization the open pit boundary is the Net Present Value (NPV).

Net Present Value (NPV) is calculated by discounting the estimated annual cash flows to the present time using a discount rate, which represents the investment risk.

$$Net\ Present\ Value\ (NPV) = \sum_{t=0}^{N} \frac{Cash\ Flow\ (CF)}{(1+k)^t} \quad (1)$$

where: k – discount rate
t – number of years

4 DEFINING THE OPTIMAL CONTOURS OF THE PHASE DEVELOPMENT OF THE OPEN PITS

In the optimization process, the results are generated for individual boundaries of the open pit, i.e. the calculated profit is shown as the Present Value (PV) for three variants of analysis - *"best case", "worst case"* and *"specified case"* which define the way of spatial development of the open pit [4].

The "best case" means a phase excavation where each of the generated boundaries of the open pit within a particular mine represents one phase of excavation, i.e. the working angle of the open pit is the maximum possible. This case has the most favorable NPV, but in practice it is very rarely possible, among other things due to the inadequate distance between successive pushbacks.

The "worst case" means excavation in depth successively floor by floor, where each floor is excavated to the final boundary of the open pit, i.e. the working angle of the open pit slopes is approximately equal to zero. The NPV for this case is the lowest possible.

The “*specified case*“ is a combination of the previous two scenarios.

Optimization involves a software analysis in order to determine the final open pit and adequate pushbacks based on the following criteria [5]:

- Maximum possible profit (NPV),
- Optimal service life,
- Optimal overburden ratio,
- Maximum possible utilization of deposits (balance reserves)

In practice, the mentioned criteria are interdependent and the final result implies their optimal relationship.

5 CASE STUDY

Selection of the optimal contour in planning the open pits was considered on the example of lead and zinc ore deposits Žuta Prla-Višnjica and Brskovo, which are located about 6 km east of Mojkovac and belong to the municipality of Mojkovac. The characteristic of these deposits is the increased mercury content in the ore. In the Žuta Prla-Višnjica deposit, the average mercury content in the ore is 54.427 g/t, and in the Brskovo deposit 26.719 g/t.

Block models for the lead-zinc ore deposits Žuta Prla-Višnjica and Brskovo were made in the Geovia Gems software package and represent the block models with regular blocks, size 10x10x5. The economic value of the deposit is determined on the basis of the value of metals present in the ore, i.e. lead, zinc, copper and silver. The economic effects of ore exploitation are calculated on the basis of the selling price of payable metals in the ore, i.e. lead, zinc, copper and silver. Based on this, the cut-off grade of the equivalent metal lead and zinc (Pb + Zn) in the ore was determined, which is 0.6% Pb + Zn. Blocks with content for Pb + Zn below the cut-off grade are treated as waste.

A block model was formed for the Brskovo deposit with:

- 160 rows
- 115 columns
- 110 levels
  (+1300/+1295 to +510/505).

A block model was formed for the Višnjica-Žuta Prla-Razvršje:

- 125 rows
- 150 columns
- 110 levels
  (+1300/+1295 to +510/505).

By creating a block model, the following values were defined for each block:

- Rock type;
- Volume mass;
- Content of useful components: Pb (%), Zn (%), Zn+Pb (%), Au (g/t), Ag (g/t), Cu (%) and harmful components: Hg (g/t), As (g/t), Sb (g/t), Bi (g/t) and Cd (g/t).

Determining the content of these components in blocks, began with development of variograms, which are the basis for calculation ("assessment") of the content.

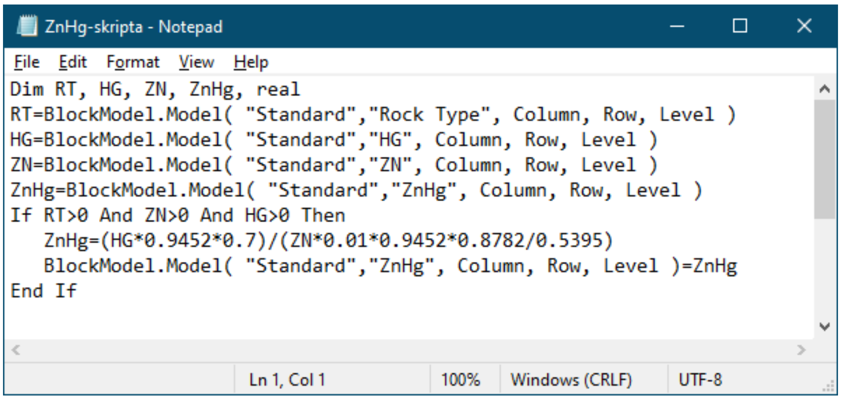
Variograms can be made from all or selected individual or composite samples. For the deposits Brskovo and Višnjica-Žuta Prla-Razvršje, the "extract files" were made, which contain data on the exact location of data in space, as well as values on the quality of mineral raw materials and type of hydrothermal alteration. The extract files were made for composite tests (Pb, Zn, Au, Ag, Cu, Hg, As, Sb, Bi and Cd), for the Brskovo deposit, as well as separately for the Žuta Prla-Višnjica deposit, in order to determine the distribution of useful components in each alteration. The sample centers were taken as the reference points of all extract files, either individual or composite samples in order to perform the three-dimensional interpretation of the subject mineralized spaces as correctly as possible.

One of the key factors in creating an economic model for the Žuta Prla-Višnjica and Brskovo deposits is the evaluation of mercury content in concentrate, i.e. the value limit to 900 ppm. To estimate the mercury content in concentrate, the following formula was developed, based on the conducted experimental investigations:

$$Hg_{\_CON} = \left(\frac{Hg[ppm]}{Zn[\%]\cdot 0.01}\right)\cdot 0.406 \quad [ppm] \tag{2}$$

The formula is based on the mean contents of mercury (Hg, ppm) and zinc (Zn,%) in the run-of-mine ore. The next step is to create a new attribute of mercury content called ZnHg, which contains ≤900 ppm Hg. Using a scripting language, a script is written defining the ore with mercury content of ≤900 ppm.

The panel in Figure 2 shows a script that uses Gems software to separate the ore with mercury content ≤900 ppm and the ore with mercury content >900 ppm.



```
Dim RT, HG, ZN, ZnHg, real
RT=BlockModel.Model( "Standard","Rock Type", Column, Row, Level )
HG=BlockModel.Model( "Standard","HG", Column, Row, Level )
ZN=BlockModel.Model( "Standard","ZN", Column, Row, Level )
ZnHg=BlockModel.Model( "Standard","ZnHg", Column, Row, Level )
If RT>0 And ZN>0 And HG>0 Then
   ZnHg=(HG*0.9452*0.7)/(ZN*0.01*0.9452*0.8782/0.5395)
   BlockModel.Model( "Standard","ZnHg", Column, Row, Level )=ZnHg
End If
```

Figure 2 *Script used by Gems software to separate defined ore types*

Optimization of the open pits at the Brskovo site was performed on the basis of two block models of deposits and defined the input techno-economic parameters.

Optimization of the open pits was performed on the balance reserves using Whittle software, which is the industry standard for this area. The Whittle software package uses a modified *Lerch Grosmman* algorithm in the optimization process, according to which the optimal contour of the mine is obtained based on the economic value of individual mini-blocks in the deposit. The software has the ability to apply the *Revenue Factor* to metal prices to change the size of revenue and thus generate more possible contours of the open pits [6].

Taking into account the amount of exploitation reserves affected by the open pit with a coefficient (factor) of income of 1, which corresponds to the optimal open pit based on undiscounted profit, ore excavation capacity, minimum width between intermediate excavation of 50 m, the decision was made to determine the final boundary of the optimal open pit for discounted profit based on excavation the final open pit in two intermediate excavations.

Based on this solution, an analysis of potential contours of the first pushback and optimal final contour of the open pit Žuta Prla-Višnjica was performed. The results of performed analysis are shown graphically in Figure 3.

The analysis of optimal development of the open pit Žuta Prla-Višnjica, for the case of phase development with one intermediate excavation (open pit 12 in the analysis), gave the result that the optimal final contour of the open pit Žuta Prla-

Višnjica, the open pit under ordinal number 30, income coefficient = 0.94). The open pit 30 provides the maximum discounted cash flow (NPV for the *"Specified case")* for the analyzed phase development. The optimal contour of the Žuta prla-Višnjica open pit covered 57.90% of the balance reserves.

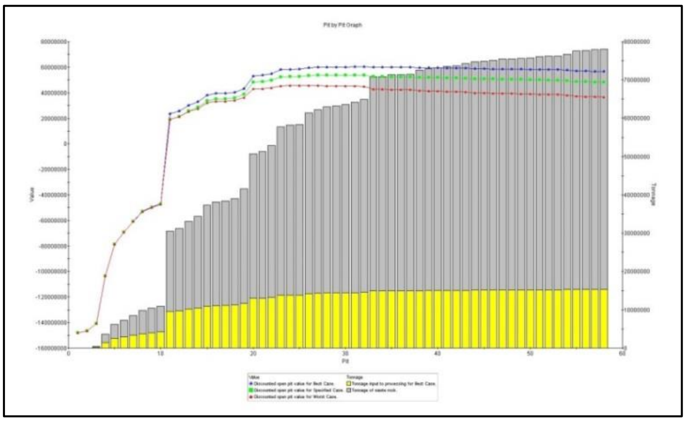


Figure 3 *Graph of the NPV analysis for the optimal boundaries of the open pit ZPV*

The analysis of optimal development of the open pit Brskovo, for the case of phase development with one intermediate excavation (open pit 16 in the analysis), gave the result that the optimal final contour of the open pit Brskovo, the open pit under ordinal number 33 (income coefficient = 0.96), Figure 4. The open pit 33 provides the maximum NPV *("Specified case")* for the analyzed phase development. Also, the analysis results of the Brskovo open pit showed a low sensitivity to NPV in the selection of potential intermediate excavation, which is evident in a small difference in NPV values between the *"Best case"* and *"Worst case"* analysis. The reason for the small difference in NPV values between the analyzed variants is a short service life for the Brskovo open pit. The optimal contour of the Brskovo open pit covers 75.13% of the balance reserves.

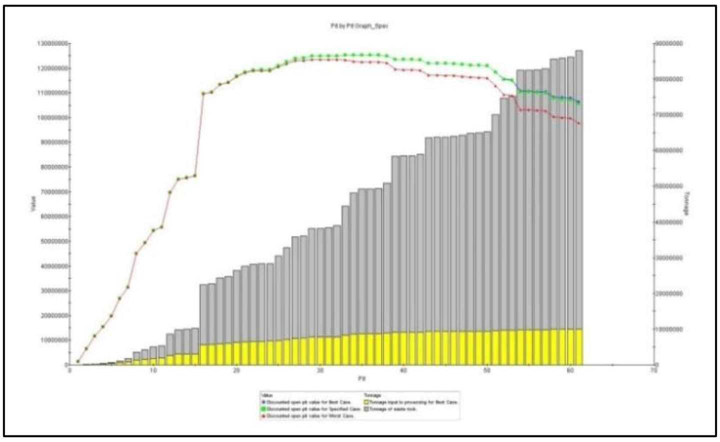


Figure 4 *Graph of the NPV analysis for the optimal boundaries of the open pit Brskovo*

Construction of the open pit Žuta Prla-Višnjica, i.e. Brskovo, according to the defined phases of development, was performed in the Gems software. Contours of the open pits (final open pits and pushbacks), obtained in the process of deposit optimization in the Whittle software, were used as the starting point for construction.

The appearance of the open pit Žuta Prla-Višnjica at the end of exploitation is shown in Figure 5.

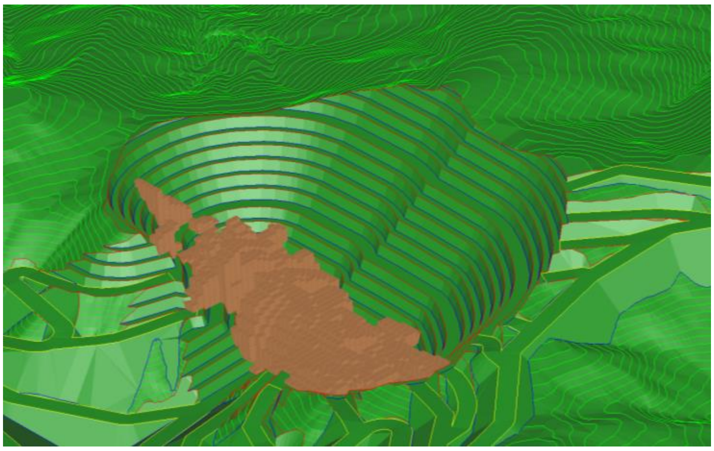


Figure 5 *The appearance of the final contour of the open pit with a presentation of the block model for the Višnjica-Žuta Prla-Razvršje deposit (Gems software)*

The appearance of the open pit Brskovo at the end of exploitation is shown in Figure 6.

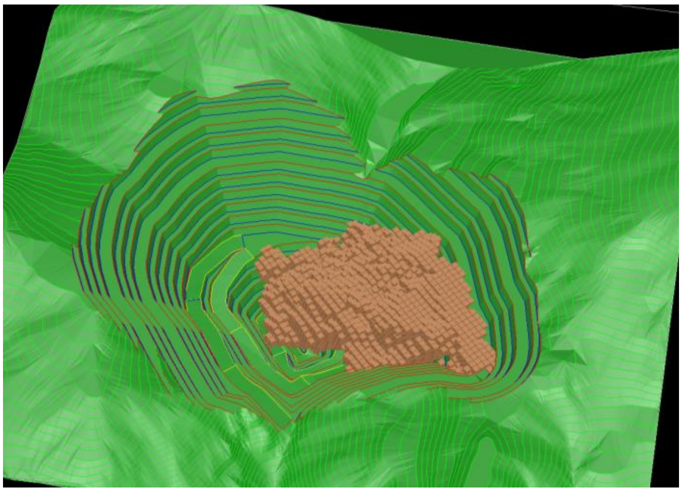


Figure 6 *The appearance of the final contour of the open pit with a presentation of the block model for the Brskovo deposit (Gems software)*

CONCLUSION

The main objective of every mining operation is to make a profit. Basically, the mining processes are complex and complicated, with many different economic, technical, environmental and other parameters that must be planned before the project gets its practical value. Therefore, the costs, prices, reserves, as well as many restrictions on the content of useful and harmful minerals in the ore, which affect the possibility of its processing, i.e. the realization of economic profit, are of the key importance for the project evaluation.

On a real example, for the lead and zinc ore deposits, with increased mercury content, using Whittle software, the analysis was performed based on two block models of deposits and defined the input techno-economic parameters and optimal contours of the open pits Žuta Prla - Višnjica and Brskovo were selected. One of the key limitations in the optimization process is to limit the value of mercury content in concentrate to 900 ppm. As a result, the utilization of the balance quantities of ore in the deposits are as follows:

- Žuta prla - Višnjica 57.90 %
- Brskovo 75.13 %.

REFERENCES

[1] D. Kržanović, M. Ljubojev, I. Jovanović, N. Vušović, An Analysis the Effects of Changes in Price of Metal and Operating Costs to the Profit in Exploitation the Copper Ore Deposits, A Case Study: Copper Mine Majdanpek, Serbia, Mining & Metallurgy Engineering Bor, No. 3-4 2017, pp. 51-58.

[2] D. Kržanović, N. Vušović, M. Ljubojev, R. Rajković, Importance of Planning the Open Pits in the Conditions of Contemporary Mining - A Case Study: The Open Pit South Mining District Majdanpek, Mining & Metallurgy Engineering Bor, No. 1-2 2017, pp. 15-22.

[3] Sevim H, Lei D.D., 1998, Problem of Production Planning in Open Pit Mines. INFOR J. Vol. 36, pp. 1–12

[4] Kržanović D., Vušović N., Ljubojev M., Selection of the Optimum Pushbacks in a Long-Term Planning Process of the Open Pit – A Condition for Maximization the Net Present Value: Case Study: The Open Pit Veliki Krivelj, Serbia, Mining Engineering, Mining and Metallurgy Institute Bor, No. 1-2/2018, pp.37-44.

[5] D. Kržanović, N. Vušović, M. Ljubojev, R. Rajković, Analysis the Profitability of the Copper Ore Exploitation on the Cerovo Primarno-Drenova Deposit for the Capacities of Flotation Ore Processing of 6.0 and 12.0 Million Tons Annually, Mining & Metallurgy Engineering Bor, No. 3-4/2018, pp. 9-18.

[6] J. Whittle, Open Pit Optimization, Surface Mining, 2nd Edition, Editor Bruce A. Kennedy, Society for Mining, Metallurgy, and Exploration, Inc, Littleton, Colorado, 1990, pp. 470-475;