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AN ANOTHER WAY FOR OPEN PIT MINE DESIGN OPTIMIZATION – FLOATING SLOPES METHOD

NOVI NAČIN OPTIMALIZACIJE KONTURA POVRŠINSKIH KOPOVA – METODA POMIČNIH KOSINA

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Abstract

Authors of the work presents main principles of a new method of design the ultimate pit which is primarily applicable for bedded formations, but also can be acceptable for other types of deposits. On the basis of main criteria of optimum design (profitability and slope stability), the authors have tested theirs procedure and proposed a new method for optimum design of open pit mines, for which the most suitable name would be the Floating Slopes Method.

Sažetak

Autori u svom radu daju prikaz osnova nove metode projektiranja optimalnog kopa koja je prvenstveno namijenjena projektiranju u slojevitim ležištima, ali se može primijeniti i u drugim tipovima ležišta. Na temelju osnovnih mjerila optimalnog dizajna (profitabilnosti i stabilnosti kosina), autori su testirali svoju proceduru i predložili novu metodu optimalnog projektiranja površinskih kopova, za koju bi odgovarajući naziv bio metoda pomičnih kosina.

Introduction

In the last decades of the 20th century, growing processing power of computers has made possible to apply a number of methods for the determination of ultimate pits. These methods are: Lerchs-Grossmann method (Lerchs & Grossmann, 1965; Alford & Whittle, 1986), network or maximal flow techniques (Johnson & Barnes, 1988; Yegulalp & Arias, 1992), floating cone method (Berlanga et al., 1988; Lemieux, 1979), the Korobov algorithm (Korobov, 1974), the corrected form of the Korobov algorithm (Dowd & Onur, 1993), parameterization techniques (Matheron, 1975; François-Bongarçon & Guibal, 1982) and dynamic programming method (Johnson & Sharp, 1971; Koenigsberg, 1982; Wilke & Wright, 1984; Wright, 1987; Yamatomi et al., 1995), which assumptions and algorithms determine the today's direction of the design in open pit mining. The algorithms of above counted methods are the core of the programs which are used in the computer designing methods. The main goal of these methods, almost all of which are based on block models, is the optimal open pit outline with the steepest dip of the final slopes under technological and physical constraints, and minimal costs of mining desirable blocks, in other words the maximum net profit. Complexity of the geological conditions of a deposit and dynamism of the economical indicators define the choice of the most adequate method of design for the mining operation (Galić, 2002).

Methods mentioned above are made for the applications on the large open pits of metal deposits, which place serious question on their use on bedded deposits (nonmetallics and coal). That is, in bedded deposits of nonmetallics, especially in case of the inclined bedrock with crushed stone and dimension stone deposits including coal deposits, the number of unknowns for planning in mine design essentially diminishes in respect to the metal deposits. That can be easily explained because it is typical for metal deposits to have highly variable shapes, sizes, and often highly erratic distribution of valuable minerals within a deposit, which certainly presents complex work conditions for the mining operations. On the over hand we have coal deposits, where the footwall of high-grade layer usually presents one of the final slopes. Furthermore, oscillation, respective change of the ore grade in nonmetal deposits is much smaller in extent on the contrary to the metal deposits. These facts have encouraged authors to suggest and to test a new design method for open pit mines for primarily inclined bedded deposits of nonmetallics and coal, but it can be also applied on other types of deposits.

Key Assumptions of the Floating Slopes Method

Starting point of optimum open pit design using the Floating Slopes Method, as well as many others, is partitioning a deposit on blocks and adding economical values for the single block. Each block represents net value of the material in the block if it were independently mined and processed. The optimal pit outline will then be designed in respect of the rule that it should give maximum net profit.

Floating Slopes Method (FSM) bases on the following assumptions:

I. The geological model of a deposit has to be transformed into a block model by partitioning on blocks with equal dimensions.

II. Blocks are partitioned so that the relation of height and width or length presents tangent of the angle of the final slope.

III. Every block inside the block model has been subordinated to the belonging slope. Block can present the slope only if diagonally underneath or above do not exist other blocks (the first block from the surface of terrain). Slope can be presented with one or more blocks, where the block has the meaning only if it is in the function of mining the belonging slope.

IV. To all blocks in the block model the following characteristics have to be attached: specified quantities of ore and waste, average quality of ore, coal equivalent if mining coal, estimated mining costs and net value of a block.

V. The following input parameters have to be presented in the database (for every block): market price of the coal equivalent or valuable mineral (C_t), unit cost of block removal ($C_{i,j,k}$), quantity of ore in the block ($G_{i,j,k}$), average quality of ore in the block, coal equivalent if mining coal ($E_{i,j,k}$), quantity of waste in the block ($O_{i,j,k}$), and cost of mining the block (includes processing) ($T_{i,j,k}$).

VI. On the basis of input parameters following values are calculated: unit cost of mining the block in the pit slope (C_{unit}), net value of a single block (P_{unit}), average cost of mining (C_{av}), total quantity of ore (G_t), total coal equivalent in the pit if mining coal (E_t), total quantity of waste (O_t), and total cost of mining (T_t).

VII. Unit cost of mining the block in the pit slope (C_{unit}) always adds up with the sum of mining cost of the blocks, from considered to the lowest block in that particular pit slope.

VIII. Procedure of additions of favourable slopes begins from the shallowest part of the ore body.

IX. Procedure of additions of the favourable slopes can be applied on the following way: from left to right, from right to left and simultaneously from left and right.

X. There are three possible outlines of the pit: optimal outline of the pit (P_O) – this is evaluation for maximum net value of the pit, application outline of the pit (P_A) – this is evaluation of the pit value including the obliged economical factors (for example for coal ⇒ coal power plant ⇒ capacity of thermo block ⇒ the annual production ⇒ the number of years in operation etc.), and threshold outline of the pit (P_T) – this evaluation of the pit value is based on the long-term analyses and forecasts of trends in mineral prices on the market, beside the obliged time factor. In this outline there is neither profit nor loss.

XI. The procedure of adding up the favourable slopes stops when optimal outline is reached. This is achieved when the sum of block unit net values ($\sum P_{unit}$) is diverging from market price of the coal equivalent or valuable mineral (C_t), with no further possibility for convergence.

Equations for the Calculation of Optimal Open Pit Outline

Basic formula from which net value of open pit can be calculated is

$$P = E_t \cdot (C_t - C_{av}) \tag{1}$$

where P is net profit expressed in monetary units (in the further text mon. units), E_t is total quantity of ore expressed in coal equivalent if mining coal or cubic meters in e.g. quarrying, which will be excavated inside the pit outline (for coal (J), stone (m^3)), C_t is the price of valuable mineral on the world market, (mon. units) and C_{av} is average cost of mining (mon. units per Joules, cubic meters or tonnes).

Total quantity of ore expressed in coal equivalent if mining coal or cubic meters or tonnes in other mining operations will be

$$E_t = \sum E_{i,j,k} \tag{2}$$

where $E_{i,j,k}$ is coal equivalent if mining coal or cubic meters or tonnes for block $b_{i,j,k}$ and *i, j, k* are number of rows (i=1...n), columns (j=1...m) and colons (k=1...r). Average cost of mining can be calculated from the equation

$$C_{\alpha} = \frac{T_t}{E_t} \quad (3)$$

where T_t is total cost of mining, (mon. units).
Total cost of mining will be

$$T_t = \sum T_{i,j,k} \quad (4)$$

where $T_{i,j,k}$ is cost of mining the block $b_{i,j,k}$, (mon. units). The cost of mining the block is composed from two components

$$T_{i,j,k} = T^E_{i,j,k} + T^O_{i,j,k} \quad (5)$$

where $T^E_{i,j,k}$ is the cost of removing the block $b_{i,j,k}$, (mon. units) and $T^O_{i,j,k}$ is the cost of processing minerals in the block $b_{i,j,k}$, (mon. units).

Determination of the optimum open pit outline, by means of FSM, can be carried out from left to right and inversely or combined, which means simultaneously from left and right. That will certainly depend on the shape of mineral deposit and starting point of the block model. Depending upon the incline of mineral deposit (milder or steeper incline from the dip of the final slope of open pit) the best approach will be applied.

Total value of open pit can be calculated from the formula

$$P_t = P^{L-R}_{i,j,k} + P^{R-L}_{i,j,k} - P^{L-R}_{i,j,k} \cap P^{R-L}_{i,j,k} \quad (6)$$

where P_t is total value of open pit, to the block $b_{i,j,k}$, which includes optimization from left to right and vice versa, and eliminates values which occurs two times in progress of calculation, $P^{L-R}_{i,j,k}$ is the value of open pit obtained by the optimization from left to right, to the block ($b_{i,j,k}$), $P^{R-L}_{i,j,k}$ is the value of open pit obtained by the optimization from right to left, to the block ($b_{i,j,k}$), $P^{L-R}_{i,j,k} \cap P^{R-L}_{i,j,k}$ is the intersection value of blocks which appears in both procedures.

Optimization of open pit outline from left to right can be preformed using the expression

$$P^{L-R}_{i,j,k} = S^{L-R}_{i,j,k} + \max \begin{Bmatrix} k_{i+1,j,k} \\ k_{i+1,j+1,k} \\ k_{i,j+1,k} \\ k_{i-1,j+2,k} \\ k_{i-2,j+3,k} \\ \vdots \\ k_{0,j+r,k} \end{Bmatrix} \quad (7)$$

where $P^{L-R}_{i,j,k}$ is the value of open pit, obtained by optimization from left to right, to the block ($b_{i,j,k}$) which beside cone ($S_{i,j,k}$) has included and most favourable slope from the right (most favourable slope from the right of the cone is one which makes possible the maximum value of open pit, beside the condition that it is within the exploitation field), $S^{L-R}_{i,j,k}$ is the value of open pit (from left to right) to the slope in which block ($b_{i,j,k}$) would present the lowest level, $k_{i+1,j,k}$ is the value of slope which begins on the block ($b_{i+1,j,k}$) (excavation for the one height of the block, in the equal width of the block), $k_{i+1,j+1,k}$ is the value of slope which begins on the block ($b_{i+1,j+1,k}$) (excavation for the one height of the block and in width of two widths of blocks), $k_{i,j+1,k}$ is the value of slope which begins on the block ($b_{i,j+1,k}$) (expansion of the pit for the one width of the block without further excavation in depth), $k_{i-1,j+2,k}$ is the value of slope which begins on the block ($b_{i-1,j+2,k}$) (reduction of deepening of the pit for the one height of the block and expansion for two widths of blocks), $k_{i-2,j+3,k}$ is the value of slope which begins on the block ($b_{i-2,j+3,k}$) (reduction of deepening of the pit for the two heights of the block and expansion for three widths of blocks), $k_{0,j+r,k}$ is the value of slope which begins on the block ($b_{0,j+r,k}$) (the block of air).

Net value of a block is determined on the basis of calculation and it is understood as the lowest, the most favourable block, and on that block are also attached costs of mining and coal equivalent if mining coal or quantities expressed in other units if mining for other minerals. Every treated block subordinates to the slope in which it belongs, because only in favourable circumstances of removing of all blocks above mentioned can lead to adding up the lowest block. As distinction from that, we are able to say that removing the blocks above the block ($b_{i,j,k}$) separately would not come in the consideration if there is no economic justification.

For example, let the block ($b_{i,j,k}$) present the ore and blocks above present the waste in the belonging slope. Mining of block ($b_{i,j,k}$) would be impossible (by open pit mining) without removing of waste blocks, and removing of waste blocks would be considered as unmeaningful without the mining of block ($b_{i,j,k}$). Of course, by that it is understood that stability of the final slopes of the pit should be respected.

Towards the general equation (1), the next equation determines the value of open pit, where the block ($b_{i,j,k}$) is the lowest in the last slope that would be excavated.

$$S_{i,j,k}^{L-R} = \sum E_{i,j,k}^{L-R} \cdot (C_t - C_{av}) \tag{8}$$

Because towards the equation (3), average cost of mining (C_{av}) can be calculated dividing the total cost of mining and total quantity of ore excavated, therefore the equation (8) can be transformed in the following shape

$$S_{i,j,k}^{L-R} = \sum E_{i,j,k}^{L-R} \cdot \left(C_t - \frac{\sum T_{i,j,k}^{L-R}}{\sum E_{i,j,k}^{L-R}} \right)$$

which after simplification turns into it's final shape, intended for the computer use

$$S_{i,j,k}^{L-R} = C_t \cdot \sum E_{i,j,k}^{L-R} - \sum T_{i,j,k}^{L-R} \tag{9}$$

where $\sum E^{L-R}_{i,j,k}$ is the sum of block ore quantities or coal equivalents if mining coal inside the pit outline, where the block ($b_{i,j,k}$) presents the lowest level of the last slope and $\sum T^{L-R}_{i,j,k}$ is the sum of mining costs for blocks inside the pit outline, where the block ($b_{i,j,k}$) presents the lowest level of the last slope.

Addition of ore quantities, mining costs and net values of blocks are carried out along slopes, towards the universal formula for all three factors

$$E_{i,j,k}^{k} \vee T_{i,j,k}^{k} \vee P_{i,j,k}^{k} = b_{i,j,k} + b_{i-1,j+1,k} + b_{i-2,j+2,k} + \ldots + b_{i-r+1,j+r-1,k} + b_{i-r,j+r,k} \quad \ldots..(10)$$

where $E^k_{i,j,k}$ is the sum of ore quantities in the slope, where the block ($b_{i,j,k}$) presents the lowest level of the slope, $T^k_{i,j,k}$ is the sum of mining costs in the slope, where the block ($b_{i,j,k}$) presents the lowest level of the slope, $P^k_{i,j,k}$ is the sum of net values of blocks in the slope, where the block ($b_{i,j,k}$) presents the lowest level of the slope, $b_{i,j,k}$ is the belonging value (depending what is adding: cost, quantities or profit) in the lowest block of the slope (k_n), $b_{i-1,j+1,k}$ is the second block of the slope (k_n), which is positioned diagonally above the block ($b_{i,j,k}$), $b_{i-2,j+2,k}$ is the third block of the slope (k_n),which is positioned diagonally above the block ($b_{i-1,j+1,k}$), $b_{i-r+1,j+r-1,k}$ is the next to the last block of the slope (k_n) (the second block from the surface of the terrain), $b_{i-r,j+r,k}$ is the last-highest block of the slope (k_n) (the first block from the surface of the terrain) and r is the total number of blocks in the slope (k_n) above the block ($b_{i,j,k}$).

Sum of the net values of blocks in one slope presents profit for that slope and this value is used for the prompt acceptance or the rejection of that specific slope.

Net value of any slope inside the pit outline is calculated from the formula

$$k_{i,j,k} = C_t \cdot \sum E_{i,j,k}^{k} - \sum T_{i,j,k}^{k} \tag{11}$$

where $k_{i,j,k}$ is the value of slope which begins on the block ($b_{i,j,k}$).

The expression for optimization of the open pit outline in opposite direction is similar to (7), with reversed indexes.

Order of the working phases

Procedure of optimum open pit design using FSM comprises from more interdependence entirety whose order strictly has been determined, for example, it is not possible to determine the value of blocks while the geological model hasn't been made and same model isn't partitioned on blocks.

Procedure of FSM consists of the following phases:

A. Building a geological database

Inside this database, among others, are results of on-site investigations like core drilling, which are the most important. These results provide data about:

- heights (depths) of layers that proved to be positive (ore) and accompanying layers,
- hanging wall and footwall of high-grade layer(s),
- ore quality, etc.

B. Construction of the deposit model

The deposit model is, in fact, 3D interpretation of geometrical and geological data. This model has to be transformed into block model, so the main influential factors for the ore reserve estimation can be attached to individual blocks. The summation of blocks provides a reserve estimate quantity with analyses of certan cost and earnings data.

C. Developing mining database

This database includes:

1. Data about characteristics of mining equipment:

- excavation equipment (the purchase price, hour capacity, standards of consumption lubrications and fuel, period of time for amortization),

- transport equipment (the purchase price, hour capacity, standards of consumption lubrications and fuel, period of time for amortization),

- auxiliary equipment (the purchase price, hour capacity, standards of consumption lubrications and fuel, period of time for amortization),

- water pumps (the purchase price, hour capacity, standards of consumption materials and energy, period of time for amortization).

2. Data about the work force:

- number of workers,

- structure of qualifications and professional degrees.

3. Data about the excavation technology:

- heights of benches (towards the equipment for excavation and physical characteristics of materials),

- angle of the working bench,

- angle of the final slopes,

- transportation distances for the ore and waste,

- other influential factor of ore and waste.

D. Processing of economical factors for the optimization and attaching them to the mining database. In this phase, on the basis of physical and technological influential factors, calculations of certain parameters are preformed. These parameters are attached to every block $b_{i,j,k}$, and after that used for the optimization of open pit outline.

E. Optimization of the open pit outline
In the final part of procedure it is necessary to determine which outlines of the pit are economically interesting. There are three possible outlines: optimal, application and threshold.

Determination of the optimal outline of the pit (P_O) consists of:

- setting up of condition for the optimal outline of the pit (P_O) that is $C^O{}_{av} < C_t$,
- calculation of the average cost (C_{av}) and profit for the optimal open pit (P_O),
- illustration of the optimal open pit outline in graphical form.

Determination of the application outline of the pit (P_A) consists of:

- setting up of condition for the application outline of the pit (P_A) that is $C^O{}_{av} \neq C^A{}_{av} < C_t$, in the function of determined purpose, (this case is valid for the optimum open pit which is to small in order to enclose the allotted object),
- open pit purpose factor subjoins and according to this obtain open pit outline (for example for the coal deposit influential factor on the power of the thermoelectric power plant is quantity of coal and number of years of possible production of electricity in the thermoelectric power plant),
- calculation of the average cost (C_{av}) and profit for the application open pit (P_A),
- illustration of the application open pit outline in graphical form.

Determination of the threshold outline of the pit (P_T) consists of:

- setting up of condition for the threshold outline of the pit (P_T) that is $C^T{}_{av} \approx C_t$,
- calculation of the average cost (C_{av}) and threshold value for the open pit (P_T).
- illustration of the threshold open pit outline in graphical form.

Case studies

Hereafter have been analysed and are presented two examples of optimum open pit design where have been set above mentioned conditions: for the optimal outline condition is $C^O{}_{av} < C_t$; for the threshold outline condition is $C^T{}_{av} \approx C_t$. In this examples application outline of the pit has been neglected.

First Example

The first example of optimization has been carried out from left to right, for the mild inclined strata of coal. The profile of deposit is shown in figure 1, with the net of blocks to which have been subjoined total costs, coal equivalents and unit costs for every block. Table 1 has been fed with mentioned data and by the relation of the same data optimal and threshold outline of the pit have been determined, with the average cost of mining and profit or loss for every slope.

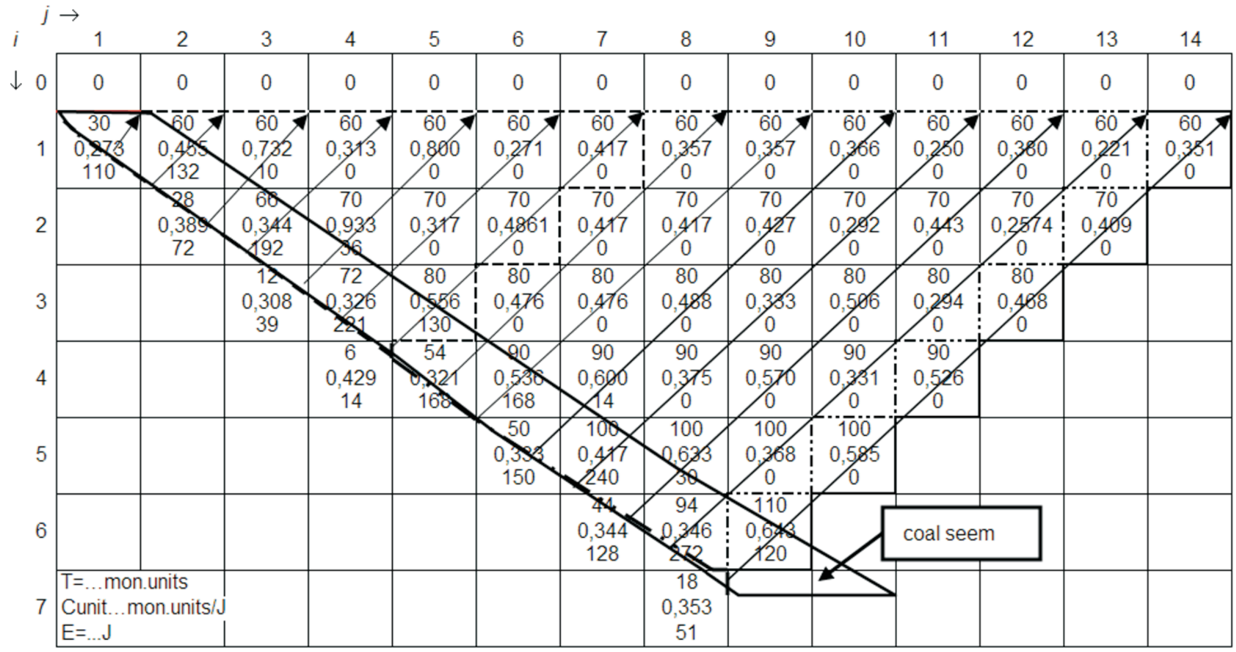

Figure 1 Determination of optimum open pit outline by the Floating Slopes Method, from left to right
***Slika 1.** Određivanje optimalne konture površinskog kopa metodom pomičnih kosina s lijeva nadesno*

Table 1 Input data and output results for optimization of open pit outline, obtained by floating slopes from left to right
***Tablica 1.** Ulazni podaci i rezultati optimalizacije konture površinskog kopa metodom pomičnih kosina s lijeva nadesno*

No. outline	Cone S_{ij}	Market price, C_t mon.un./J	Expences T, mon.un.		Equivalent value E, J		Average costs C_{av}, mon.un./J		Profit $P=E*(C_t-C_{av})$, mon.un.	
			In slope	Cumulativ.	In slope	Cumulativ.	In slope	Total	In slope	Cumulativ.
		(1)	(2)	(3)	(4)	(5)	(6)=(2)/(4)	(7)=(3)/(5)	(8)=(4)*((1)-(6))	(9)
1	11	1,500	30	30	110	110	0,273	0,273	135	135
2	12	1,500	60	90	132	242	0,455	0,372	138	273
3	22	1,500	88	178	82	324	1,073	0,549	35	308
4	23	1,500	126	304	192	516	0,656	0,589	162	470
5	33	1,500	142	446	75	591	1,893	0,755	-29,5	441
6	34	1,500	202	648	221	812	0,914	0,798	129,5	570
7	44	1,500	216	864	144	956	1,500	0,904	0	570
OPTIMAL OUTLINE										
8	45	1,500	264	1.128	168	1.124	1,571	1,004	-12	558
9	46	1,500	300	1.428	168	1.292	1,786	1,105	-48	510
10	56	1,500	350	1.778	164	1.456	2,134	1,221	-104	406
11	57	1,500	400	2.178	240	1.696	1,667	1,284	-40	366
12	67	1,500	444	2.622	158	1.854	2,810	1,414	-207	159
13	68	1,500	494	3.116	272	2.126	1,816	1,466	-86	73
TRESHOLD OUTLINE										
14	78	1,500	528	3.644	179	2.305	2,950	1,581	-259,5	-187
END OF MODEL										

Figure 2 shows graph of the profit function for the data and results given in table 1.

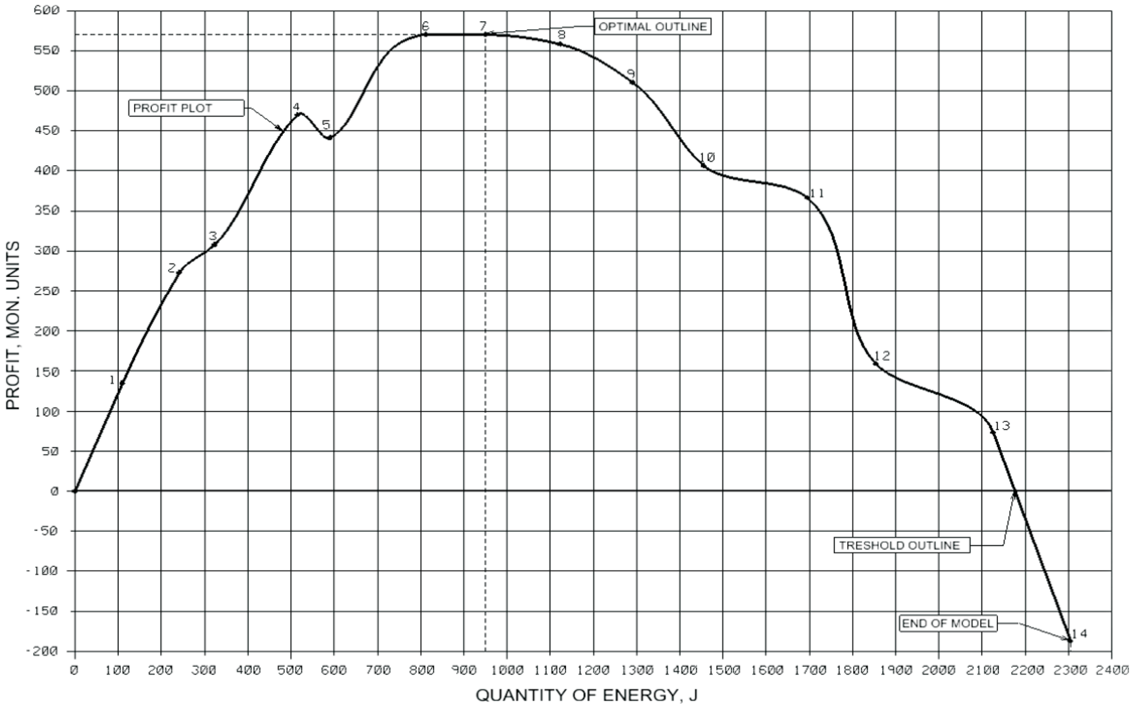

Figure 2 Ratio of cumulative coal equivalent and profit, obtained by floating slopes from left to right
Slika 2. *Odnos kumulativne ogrjevne moći ugljena i dobiti, dobivenog pomicanjem kosina s lijeva nadesno*

Although the quantity of energy grow, after the point of maximum (the optimal outline) the profit falls to the zero value (the threshold outline) and after that gets negative sign, in other words presents the loss (end of the model).

Second Example

The second example of open pit optimization has been carried out by the synchronous additions of the favourable slopes from left and right of the deposit beginning with its shallowest part, which is presented on figure 3 and has been dealt with in the table 2.

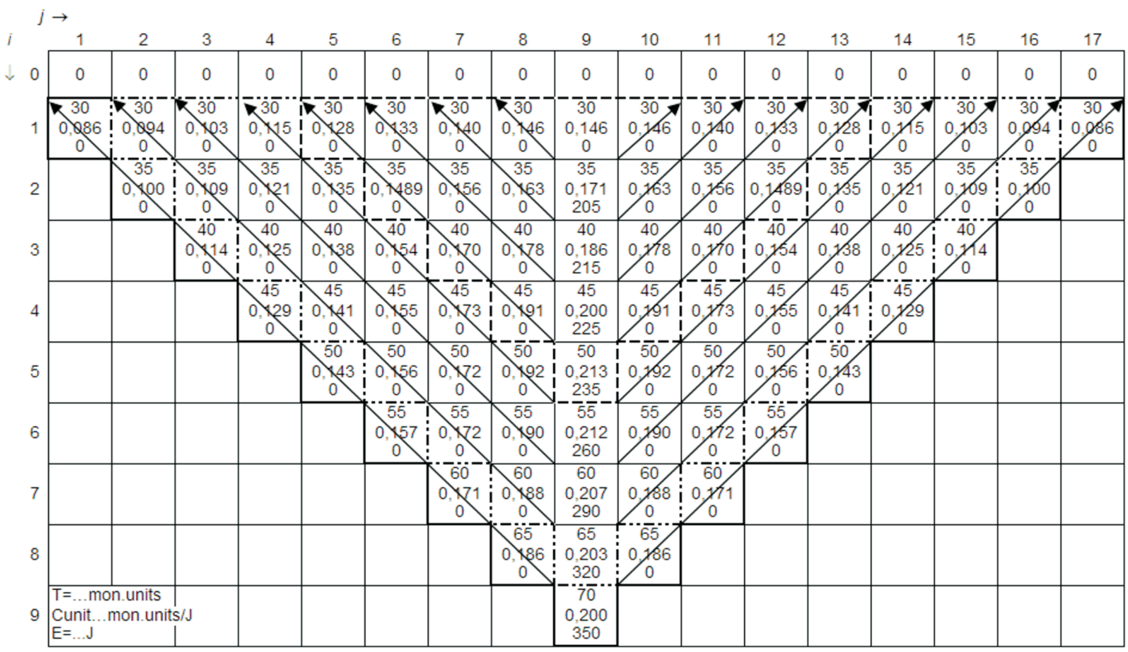

Figure 3 Determination of optimum open pit outline by the Floating Slopes Method, with synchronous floating slopes leftwards and rightwards
Slika 3. *Određivanje optimalne konture površinskog kopa metodom pomičnih kosina istodobnim pomicanjem kosina nalijevo i nadesno*

Table 2 Input data and output results for optimization of open pit outline, obtained by floating slopes floating leftwards and rightwards simultaneously

Tablica 2. *Ulazni podaci i rezultati optimalizacije konture površinskog kopa metodom pomičnih kosina istodobnim pomicanjem kosina nalijevo i nadesno*

No. outline	Cone S_{ij}	Market price, C_t mon.un./J	Expences T, mon.un.		Equivalent value E, J		Average costs C_{av}, mon.un./J		Profit $P=E*(C_t-C_{av})$, mon.un.	
			In slope	Cumulativ.	In slope	Cumulativ.	In slope	Total	In slope	Cumulativ.
		(1)	(2)	(3)	(4)	(5)	(6)=(2)/(4)	(7)=(3)/(5)	(8)=(4)*((1)-(6))	(9)
1	29	1,500	125	125	205,00	205	0,610	0,610	182,5	182,5
2	39	1,500	170	295	215,00	420	0,791	0,702	152,5	335,0
3	49	1,500	255	550	225,00	645	1,133	0,853	82,5	417,5
4	59	1,500	350	900	235,00	880	1,489	1,023	2,5	420,0
OPTIMAL OUTLINE										
5	69	1,500	455	1.355	260,00	1.140	1,750	1,189	-65	355,0
6	79	1,500	570	1.925	290,00	1.430	1,966	1,346	-135	220,0
7	89	1,500	695	2.620	320,00	1.750	2,172	1,497	-215	5,0
TRESHOLD OUTLINE										
8	99	1,500	830	3.450	350,00	2.100	2,371	1,643	-305	-300,0
END OF MODEL										

In the second example, optimal and threshold pit outline have been clearly shown. The fourth slope (left and right) presents the outline of optimal open pit, the seventh slope is final in the threshold outline of the pit and the eighth outline is the last in the shown model.

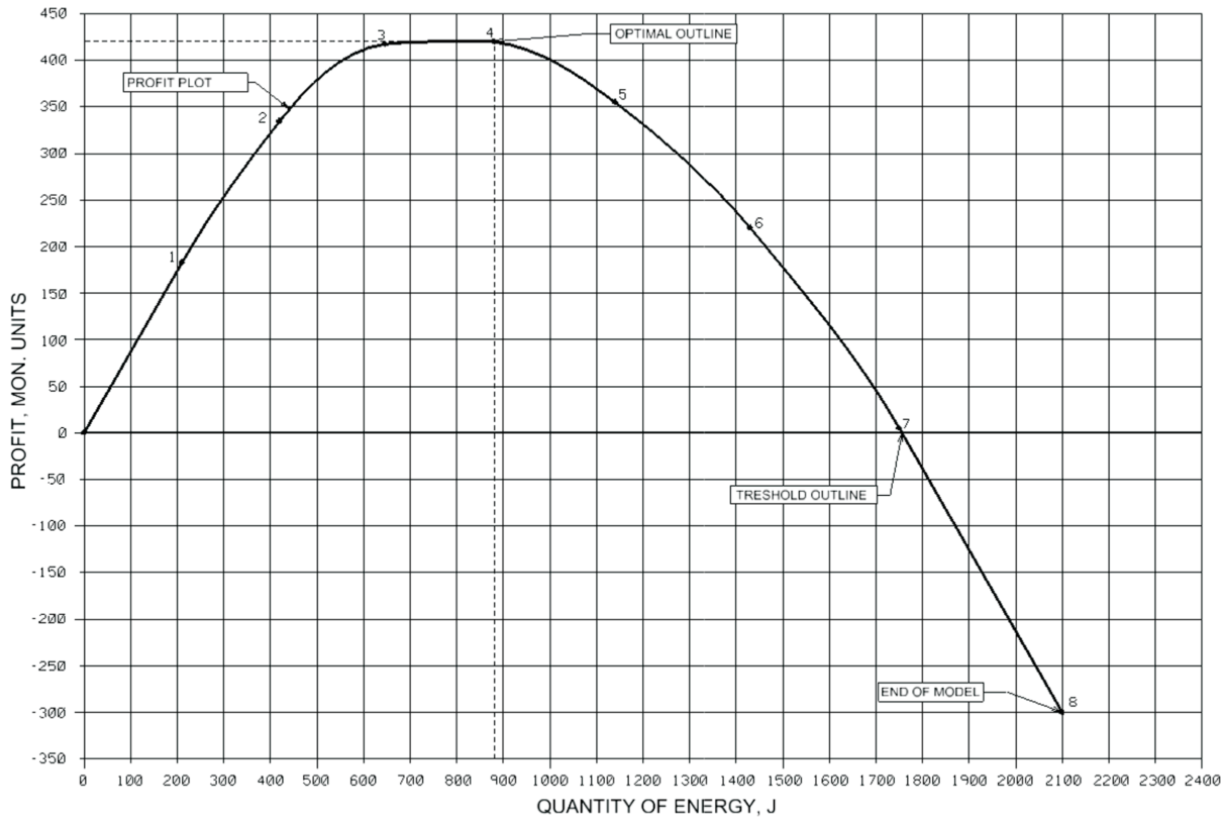

Figure 4 Ratio of cumulative coal equivalent and profit, obtained by synchronous floating slopes floating leftwards and rightwards ultaneously

Slika 4. *Odnos kumulativne ogrjevne moći ugljena i dobiti, dobivenog istodobnim pomicanjem kosina nalijevo i nadesno*

Conclusion

In this work, the principles of optimum open pit design which is usable primarily for bedded ore bodies of nonmetallics and coal have been presented. The principle assumptions and equations are given inside the same entirety (components of algorithm of method) and, in the end, the tests of the method have been preformed. Obtained results gave the first confirmations of principles that have been set, expressions and introduced notions just as are optimal, application and threshold outlines of the pit.

In the first example of optimization of open pit outline the deposit model with the uneven schedule of coal seem has been presented, which results in irregularly curves on diagrams (figure 2). By the even schedule of valuable mineral, such as shown case on the second model of deposit (figure 4), the uniform curves of growth or fall of profit function are obtained, in other words certain regularity is noticeable.

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