DETERMINATION OF OPTIMAL CONTOURS OF OPEN PIT MINE DURING OIL SHALE EXPLOITATION, BY MINEX 5.2.3. PROGRAM

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ABSTRACT By examination and determination of optimal solution of technological processes of exploitation and oil shale processing from Aleksinac site and with adopted technical solution and exploitation of oil shale, derived a technical solution that optimize contour of the newly defined open pit mine.

In the world, this problem is solved by using a computer program that has become the established standard for quick and efficient solution for this problem. One of the computer’s program, which can be used for determination of the optimal contours of open pit mines is Minex 5.2.3. program, produced in Australia in the Surpac Minex Group Pty Ltd Company, which is applied at the Mining and Metallurgy Institute Bor (no. of licenses are SSI - 24765 and SSI - 24766). In this study, authors performed 11 optimization of deposit geo-models in Minex 5.2.3. based on the tests results, performed in a laboratory for soil mechanics of Mining and Metallurgy Institute, Bor, on samples from the site of Aleksinac deposits.

Keywords: Oil shale, sample testing, the Minex 5.2.3. program, the optimal open pit

Introduction

Determining the optimal contour of open pit mine is a necessary step in open pit mine exploitation. The main characteristic of this design phase is complexity and large number of possible solutions that meet technical – technological conditions, but with differences, according to economic effect. Therefore, it is necessary to undergo various solutions to techno-economic analysis of individual variants and adopt a solution that will be optimal for the given conditions [1, 6, 9]. This task can be solved by different methods, using classical technoeconomic analysis or using modern techniques of mathematical programming. Technoeconomic Analysis is performed using qualitative and quantitative predictions of all factors and conditions that can provide desired result. Qualitative assessment includes the following indicators: mining - geological and hydro - geological conditions [1], organizational and economic factors [3, 7, 8]. Quantitative assessments include: funds use for a certain period of time, dynamics of investments, costs tones of products, effects, use of legislative materials and so on.

Methods of linear and dynamic programming are applied for solving problems with a large number of variants and possible solutions. To solve this task, there are several computer programs for data processing and model setup. Application of mathematical models can be established if there is a certain analogies and similarities between the mathematical formula and the actual work processes to be modeled.

Description of MINEX 5.2.3 program

The development of computer technology, and due to information revolution in the mid eighties of the twentieth century, appeared the first software packages specialized in areas of geology and mining. Today, these
programs have evolved into extremely powerful and useful tool aimed at reducing time needed to produce geo-model of studied deposits and open pit mines, saving money and creating detailed 3D model of ore bodies and mines. One of these programs is Minex 5.2.3 which is a specialized program for 3D modeling, exclusively for layered deposits, especially coal deposits.

With this software it is possible to develop a geological model of layered deposits, to model faults, determine the optimal contour of open pit mines, construct a detailed appearance of open pit and tailing dumps, determine dynamics of excavation and disposal of tailings.

Starting point for work in this program is: situational map in digital format (topography for new mines or initial state of works on the open pits, usually in AutoCAD format) and data from exploratory drill holes about their spatial position, lithology and quality parameters in Excel format [1, 2, 3, 4, 6, 11]. Geo-model of the deposit is created based on data from the drill holes. Each layer in geo-model has its own grid (area represented by a network of certain dimension) of roof, floor and thickness of the deposit, as well as grid of quality for each observed component. Geo-model is produced by following tools:

- **Borehole DB** – Forming a base of boreholes for geological modeling
- **Statistical analysis** - Analysis of the regularities of components distribution in the deposit
- **Seam model** – Layers modeling and calculation of geological reserves

When the geo-model is created and initial state of terrain is put in, optimization is performing, i.e. determination of the optimal contour of open pit mine according to technical - economic parameters of exploitation. The resulting optimal contour is a guideline for detailed construction of open pit mine. This phase of design is done by Pit Optimizer tool.

In Minex 5.2.3 program, it is possible to construct a detailed layout of the final look of open pit mine and waste rock dumps with transport routes and top and bottom edges of each floor, as well as creating excavation dynamic by Pit design tool.

Also, with this program, it is possible to make full mining - geological graphic documentation.

**Geo – model of deposit**

Geo – model of oil shale deposit is made based on earlier data [1] and samples from the site, tested in the Mining and Metallurgy Institute Bor [6]. Following parameters have been systemized:

- Spatial position - X, Y and Z coordinates of a borehole’s mouth, the length of borehole pillar, azimuth and strike direction; deviation of borehole pillar;
- Lithology per borehole pillar;
- Content of important parameters (quality) per borehole pillar - oil content \((ulj)\) in the model); water content \((H_2O)\) in the model); content of coke \((pk)\) in the model); gas component with losses \((gg)\) in the model).

On location of Aleksinac oil shale deposits are defined two basic layers, S1 and S2 (roof and floor oil shale layers, between which are layers of coal and overburden), but the S1 layer is divided into two parts, S1a and S1b, because, inside layer S1 are overburden inter-layers of significant thickness. The amount of overburden above the layers, the amount of oil shale in layers and quality parameters are shown in Table 1. 3D model of oil shale layers in Minex 5.2.3 program is shown in Figure 1.
### Table 1. Quantities and quality of Aleksinac oil shale deposit

| Seam  | Volume | Tonnage | Tonnage | Tonnage | Strip ratio | Assay | H2O  |
|-------|--------|---------|---------|---------|-------------|-------|------|
|       | m³     | t       | m³/t    | t       | %           | %     | %    |
| S1a   | 458 714 392 | 688 071 588 | 91 726 433 | 190 607 527 | 2.41 | 12.31 | 5.17 | 76.65 | 6.03 |
| S1b   | 12 412 541  | 18 618 812  | 70 142 786  | 145 756 710  | 0.09 | 7.32  | 3.38 | 82.54 | 6.76 |
| S2    | 73 220 337  | 109 830 506  | 53 765 704  | 111 725 133  | 0.66 | 11.59 | 5.88 | 76.66 | 5.58 |
| TOTAL | 544 347 270 | 816 520 905 | 215 634 923 | 448 089 370 | 1.21 | 10.51 | 4.76 | 78.57 | 6.15 |

**Figure 1.** 3D model of oil shale layers in Minex 5.2.3 program
Selection of optimization input parameters

Optimization of open pit mine in Minex 5.2.3, i.e. in his tool Pit Design, is done with Pit Optimizer option, which is based on Lerches and Grossman algorithm. Lerches and Grossman algorithm is a procedure for determining optimal mining as one with the highest value for the corresponding set of costs and recovery factors.

Input parameters for the Pit Optimizer are:

1. Economic parameters:
   1.1. Selling price of oil
   1.2. Costs of tailings excavation
   1.3. Costs of oil shale excavation
   1.4. Costs increasing caused by increasing depth of open pit mine
   1.5. Costs of oil shale processing
   1.6. Initial and final discount factor and discount factor step

2. Technical parameters:
   2.1. Initial state of the terrain
   2.2. Geo – model of the deposit
   2.3. Bulk density of oil shale
   2.4. Final pit slope angle
   2.5. Minimum distance between floors in progress
   2.6. Utilization of the exploitation
   2.7. Utilization of processing oil shale

Selling price of oil has been adopted by current market conditions to 85 $ for barrel. Reduced to medium oil content in oil shale for the whole deposit, a value of 1% of oil is $ 2,57.

Costs of tailings and oil shale excavation for optimization [1, 6, 9, 12] were adopted based on experience from open pit mines with similar conditions and they are $ 5.00 / m3 of excavated overburden and 2,50 $ / t of excavated oil shale. Costs increasing, with increasing depth of the open pit, was adopted, based on experience with open pit mines with similar conditions, and it is 0,01 $ / m

Costs of oil shale processing [9, 12] include preparation of oil shale (shredding and separation from sterile and carbon components) and pyrolysis process. These costs, according to previous researches, are $ 12,00 / t.

Discount factor is varied in the range of 0.5 to 1.5 of the selling price of oil, with step of 0.1.

Oil shale bulk density is previously defined [1, 6]. The mean value of dry density of oil shale, according to this document, is 2,078 t/m³.

Final angle of the open pit slope [5, 10, 12], depending on its depth, is defined in [12] as the mean value of the final angle of the open pit, that will be used for optimization. Adopted value for an angle is 30°.

Minimum distance between floors, during progress of mining activities, is determined depending on the equipment used in the exploitation. Adopted distance is 20 m.

Utilization on the open pit mine [9, 10, 12] was adopted based on experience with open pit mines with similar conditions, and it is 90%.

Utilization of the fragmentation and separation [9, 10, 11, 12] of sterile and carbon components is estimated at 75%. Utilization of the pyrolysis is estimated at 85% on oil yield.

These data were put into the Pit Optimizer, which is shown in Figure 2.
Results of optimization

Eleven cases of optimal contour of open pit mine were analyzed by optimization, with varying of oil selling price discount factor ± 50% of market value, in steps of 10%. Optimization results are shown in Tables 2 to 12. Values of the open pit mines obtained by optimization are given in Table 13.

**Table 2. Quantities and quality for open pit mine 1 with discount factor of 0.5**

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | ulj | gg | pk | H2O |
|      | m³     | t       | m³     | t       |     | %  | %  | %   |
| S1a  | 14 675 | 22 013  | 295 566| 614 187 | 0.02| 12.12|5.28|75.88|6.69|
| S1b  | 0      | 0       | 0      | 0       | 0.00| 0.00| 0.00| 0.00| 0.00|
| S2   | 0      | 0       | 0      | 0       | 0.00| 0.00| 0.00| 0.00| 0.00|
| TOTAL| 14 675 | 22 013  | 295 566| 614 187 | 0.02| 12.12|5.28|75.88|6.69|

**Table 3. Quantities and quality for open pit mine 2 with discount factor of 0.6**

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | ulj | gg | pk | H2O |
|      | m³     | t       | m³     | t       |     | %  | %  | %   |
| S1a  | 7 601   | 11 402  | 9 666  | 20 086  | 0.38| 12.11|5.10|77.03|5.76|
| S1b  | 104 577 | 156 866 | 269 151| 559 296 | 0.19| 7.03|3.35|83.08|6.56|
| S2   | 0      | 0       | 0      | 0       | 0.00| 0.00| 0.00| 0.00| 0.00|
| TOTAL| 7 706   | 11 559  | 9 935  | 20 645  | 0.37| 11.97|5.06|77.19|5.78|
Table 4. Quantities and quality for open pit mine 3 with discount factor of 0.7

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | m³/t | ulj | gg | pk | H²O |
| S1a  | 14 030 | 21 046 | 14 181 | 29 468 | 0.48 | 11.87 | 5.03 | 77.39 | 5.72 |
| S1b  | 228 677 | 343 016 | 1 039 | 2 160 | 0.11 | 7.46 | 3.64 | 82.11 | 6.80 |
| S2   | 19 307 | 28 961 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOTAL| 14 278 | 21 418 | 15 221 | 31 629 | 0.45 | 11.57 | 4.93 | 77.71 | 5.79 |

Table 5. Quantities and quality for open pit mine 4 with discount factor of 0.8

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | m³/t | ulj | gg | pk | H²O |
| S1a  | 23 059 | 34 589 | 18 062 | 37 534 | 0.61 | 11.85 | 5.00 | 77.49 | 5.67 |
| S1b  | 543 918 | 815 877 | 4 908 | 10 200 | 0.05 | 7.35 | 3.51 | 82.51 | 6.64 |
| S2   | 1 228 803 | 1 843 205 | 73 795 | 153 346 | 8.01 | 16.42 | 8.13 | 69.72 | 5.72 |
| TOTAL| 24 832 | 37 248 | 23 045 | 47 888 | 0.52 | 10.91 | 4.70 | 78.53 | 5.88 |

Table 6. Quantities and quality for open pit mine 5 with discount factor of 0.9

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | m³/t | ulj | gg | pk | H²O |
| S1a  | 34 505 | 51 758 | 20 688 | 42 990 | 0.80 | 11.97 | 5.05 | 77.30 | 5.74 |
| S1b  | 726 930 | 1 090 395 | 7 226 | 15 015 | 0.05 | 7.31 | 3.49 | 82.58 | 6.63 |
| S2   | 7 234 006 | 10 851 009 | 1 840 925 | 3 825 443 | 1.89 | 12.99 | 7.02 | 74.99 | 5.00 |
| TOTAL| 42 466 | 63 700 | 29 755 | 61 831 | 0.69 | 10.90 | 4.79 | 78.44 | 5.91 |

Table 7. Quantities and quality for open pit mine 6 with discount factor of 1.0

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | m³/t | ulj | gg | pk | H²O |
| S1a  | 46 550 | 69 826 | 23 031 | 47 859 | 0.97 | 12.00 | 5.05 | 77.29 | 5.71 |
| S1b  | 935 102 | 1 402 653 | 8 375 012 | 17 403 275 | 0.05 | 7.32 | 3.48 | 82.59 | 6.62 |
| S2   | 9 104 509 | 13 656 764 | 2 970 218 | 6 172 114 | 1.48 | 12.78 | 6.88 | 75.23 | 5.10 |
| TOTAL| 56 590 | 84 885 | 34 376 | 71 435 | 0.79 | 10.93 | 4.82 | 78.40 | 5.88 |

Table 8. Quantities and quality for open pit mine 7 with discount factor of 1.1

| Seam | Waste | Oil shale | Strip ratio | Assay |
|------|-------|-----------|-------------|-------|
|      | Volume | Tonnage | Volume | Tonnage | m³/t | ulj | gg | pk | H²O |
| S1a  | 52 142 | 78 213 | 23 936 602 | 49 740 258 | 1.05 | 12.02 | 5.05 | 77.27 | 5.71 |
| S1b  | 1 045 077 | 1 567 616 | 8 915 357 | 18 526 111 | 0.06 | 7.36 | 3.48 | 82.55 | 6.60 |
| S2   | 10 083 711 | 15 125 567 | 3 871 409 | 8 044 787 | 1.25 | 12.72 | 6.82 | 75.28 | 5.15 |
| TOTAL| 63 271 | 94 006 | 36 723 367 | 76 311 156 | 0.83 | 10.97 | 4.86 | 78.34 | 5.87 |
**Table 9. Quantities and quality for open pit mine 8 with discount factor of 1.2**

| Seam  | Waste | Oil shale | Strip ratio | Assay |
|-------|-------|-----------|-------------|-------|
|       | Volume | Tonnage | Volume | Tonnage | ulj | gg | pk | H2O |
|       | m³     | t        | m³     | t        |     |     |     |     |
| S1a   | 54 947 053 | 82 420 580 | 24 325 325 | 50 548 025 | 1,09 | 12,02 | 5,05 | 77,28 | 5,70 |
| S1b   | 1 084 609 | 1 626 914 | 9 225 289 | 19 170 150 | 0,06 | 7,39 | 3,49 | 82,51 | 6,60 |
| S2    | 10 554 901 | 15 832 352 | 4 200 550 | 8 728 743 | 1,21 | 12,74 | 6,83 | 75,27 | 5,14 |
| TOTAL | 66 586 563 | 99 879 845 | 37 751 164 | 78 446 918 | 0,85 | 10,97 | 4,87 | 78,34 | 5,86 |

**Table 10. Quantities and quality for open pit mine 9 with discount factor of 1.3**

| Seam  | Waste | Oil shale | Strip ratio | Assay |
|-------|-------|-----------|-------------|-------|
|       | Volume | Tonnage | Volume | Tonnage | ulj | gg | pk | H2O |
|       | m³     | t        | m³     | t        |     |     |     |     |
| S1a   | 58 173 776 | 87 260 664 | 24 655 576 | 51 234 287 | 1,14 | 12,03 | 5,06 | 77,27 | 5,70 |
| S1b   | 1 125 081 | 1 687 622 | 9 547 078 | 19 838 829 | 0,06 | 7,44 | 3,51 | 82,46 | 6,59 |
| S2    | 10 962 963 | 16 444 445 | 4 547 052 | 9 448 774 | 1,16 | 12,73 | 6,81 | 75,29 | 5,14 |
| TOTAL | 70 261 820 | 105 392 730 | 38 749 706 | 80 521 890 | 0,87 | 10,98 | 4,88 | 78,31 | 5,85 |

**Table 11. Quantities and quality for open pit mine 10 with discount factor of 1.4**

| Seam  | Waste | Oil shale | Strip ratio | Assay |
|-------|-------|-----------|-------------|-------|
|       | Volume | Tonnage | Volume | Tonnage | ulj | gg | pk | H2O |
|       | m³     | t        | m³     | t        |     |     |     |     |
| S1a   | 69 488 143 | 104 232 215 | 25 681 690 | 53 366 552 | 1,30 | 12,06 | 5,06 | 77,24 | 5,69 |
| S1b   | 1 143 174 | 1 714 761 | 10 075 819 | 20 937 551 | 0,05 | 7,41 | 3,49 | 82,51 | 6,58 |
| S2    | 11 507 914 | 17 261 871 | 5 000 209 | 10 390 435 | 1,11 | 12,72 | 6,82 | 75,33 | 5,10 |
| TOTAL | 82 139 231 | 123 208 847 | 40 757 718 | 84 694 538 | 0,97 | 10,99 | 4,89 | 78,31 | 5,84 |

**Table 12. Quantities and quality for open pit mine 11 with discount factor of 1.5**

| Seam  | Waste | Oil shale | Strip ratio | Assay |
|-------|-------|-----------|-------------|-------|
|       | Volume | Tonnage | Volume | Tonnage | ulj | gg | pk | H2O |
|       | m³     | t        | m³     | t        |     |     |     |     |
| S1a   | 74 890 758 | 112 336 137 | 26 423 161 | 54 907 329 | 1,36 | 12,06 | 5,06 | 77,26 | 5,68 |
| S1b   | 1 212 326 | 1 818 489 | 10 216 726 | 21 230 357 | 0,06 | 7,43 | 3,50 | 82,49 | 3,58 |
| S2    | 11 948 171 | 17 922 257 | 5 247 721 | 10 904 765 | 1,10 | 12,69 | 6,80 | 75,37 | 5,10 |
| TOTAL | 88 051 255 | 132 076 883 | 41 887 609 | 87 042 451 | 1,01 | 11,01 | 4,90 | 78,30 | 5,83 |

**Table 13. Review of the open pit mines values got by optimization**

| Pit | Waste, m³ | Oil shale, t | ulj, % | Costs, $ | Revenue, $ | Profit, $ |
|-----|-----------|-------------|--------|----------|------------|-----------|
| 1   | 14 675    | 614 187     | 12,12  | 8 979 087 | 12 534 593 | 3 555 007   |
| 2   | 7 706 361 | 20 645 318  | 11,97  | 337 888 916 | 416 123 976 | 78 235 060  |
| 3   | 14 278 668 | 31 629 406  | 11,57  | 530 019 727 | 616 213 781 | 86 194 054  |
| 4   | 24 832 123 | 47 888 215  | 10,91  | 818 539 733 | 879 752 302 | 61 212 570  |
| 5   | 42 466 823 | 61 831 959  | 10,90  | 1 108 897 521 | 1 134 871 047 | 25 973 526  |
| 6   | 56 590 376 | 71 435 287  | 10,93  | 1 318 763 542 | 1 314 740 278 | - 4 023 264 |
| 7   | 63 271 172 | 76 311 156  | 10,97  | 1 422 867 622 | 1 409 618 764 | - 13 248 858 |
| 8   | 66 586 563 | 78 446 918  | 10,97  | 1 470 413 126 | 1 449 070 534 | - 21 342 924 |
| 9   | 70 261 820 | 80 521 890  | 10,98  | 1 518 876 505 | 1 488 755 271 | - 30 121 234 |
| 10  | 82 139 231 | 84 694 538  | 10,99  | 1 638 766 956 | 1 567 328 778 | - 71 438 178 |
| 11  | 88 051 255 | 87 042 451  | 11,01  | 1 702 371 815 | 1 613 709 823 | - 88 661 991 |
Conclusion

Based on existing and new technical parameters, authors of mentioned technical solutions were determined optimal contour of newly-projected open pit mine that achieves the maximum possible profit and the estimated economic parameters.

Based on a result analysis of election the optimum contour of open pit mine for exploitation of oil shale from Aleksinac deposit, conclusion is that the optimum border for excavation is open pit mine No. 3, which gives maximum profit in relation to other projected contours. Quantities of waste and oil shale with its quality are shown in Table 4.

Optimal contour of the open pit mine for oil shale exploitation from Aleksinac deposits contains 31,629,406 tons of oil shale with 14,278,668 m$^3$ of waste.

Overburden coefficient for the optimal outline is $Kr = 0.45$ m$^3$ / t. Bottom of the mine is on elevation of +25 m. Maximum depth of the open pit mine is 200 m.

An important factor in using Minex 5.2.3 is ability of changing and comparing several versions of input parameters of optimization. It is also important that less time is needed to determine the optimal contours, comparing with conventional projecting.

Projecting is much more improved by using this program, in terms of time and quality, due to the possibility of rapid analysis in order to select the best solution. The application of this and similar programs has become a necessity and standard in projecting of open pit mines.

This and other specialized computer programs for the mining industry provides great opportunities in design of open pit mines because, with them, it is possible to solve a series of complex problems in this area quickly and with high-quality.

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