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ANALYSIS THE LONG-TERM DEVELOPMENT OF THE OPEN PIT NORTH MINING DISTRICT MAJDANPEK FOR THE CAPACITY OF 5×10^6 TONS OF ORE ANNUALLY***

Abstract

The work presents a consideration of a long-term development of the open pit North Mining District in terms of achieving maximum profit for the planned capacity of 5 million tons of copper ore annually, using the modern software Whittle for strategic planning of production. Software provides the ability to achieve a positive development of cash flow and maximum net present value by optimization the excavation limit and long-term mining dynamics. For planned technical and economic parameters, which are the input data for analysis, the boundary of the open pit is obtained for the service life of 26 years, and the value of the net present value is \$ 252,591,906.

Keywords: open pit North Mining District Majdanpek, optimization, development phase of open pit, cash flow, net present value, software Whittle

INTRODUCTION

Within the company, Copper Mine Majdanpek, which is part of the company Mining and Smelting Basin Bor (RTB Bor), there are two open pit mines as well as the North Mining District and South Mining District. Since the deposit stripping is done at the open pit South Mining District, the holder of copper ore production in recent years is the North Mining District with a capacity of 3.5 million tons per year. The construction of a new smelter in Bor It is necessary to provide the raw material for operation the New Smelter in Bor through increasing the capacity of excavation at open pit mines operating within RTB Bor. Due to this, an analysis of possibilities for long-term mining of copper ore at the open pit North

Mining District Majdanpek for a capacity of 5 million tons per year, which includes:

- 1) optimization the open pit and selection the optimum contour of open pit
- 2) defining the mining phase (push-backs)
- 3) optimization the mining dynamics
- 4) economic analysis in the Whittle software, which is based on an analysis of trends the discounted cash flow over the mining period, or the realized net present value, and that is an indicator of achieved economic results of mining the North Mining District for the given initial conditions.

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Techno-economic analysis was carried out for the part of the copper deposits "North Mining District - Majdanpek" and deposit of polymetallic mineral resources (Zn-Pb-Cu) "Tenka - North Mining District Majdanpek" in the software Whittle.

TECHNO-ECONOMIC PARAMETERS FOR ANALYSIS

A long term development of the open pit is defined on the basis of the following initial techno-economic parameters [1].

1 Mining recoveries and dilutions

- Dilution of copper ore 4.0%
- Dilution of lead-zinc ore 6.0%
- Exploitation losses of copper ore 4.0%
- Exploitation losses of PbZn ore 6.0%

2 Flotation recoveries:

Cu ore:

- Cu recovery 82.0%
- Ag recovery 50.0%
- Au recovery 50.0%

Pb-Zn ore:

- Zn recovery 60.0%
- Pb recovery 60.0%
- Ag recovery 51.5%
- Au recovery 35.0%

3 Metallurgical recoveries:

Cu concentrate:

- Cu recovery 95.0%
- Ag recovery 90.0%
- Au recovery 90.0%

Pb-Zn concentrate:

- Zn recovery 96.5%
- Pb recovery 95.0%
- Ag recovery 90.0%
- Au recovery 90.0%

4. Selling prices of metals:

- Copper (Cu) 6,000 US \$/t
- Silver (Ag) 800 US \$/kg
- Gold (Au) 30,000 US \$/kg

- Zinc (Zn) 1,800 US \$/t
- Lead (Pb) 1,800 US \$/t

5 Metal values in concentrate:

Cu concentrate:

- Copper (6.000 – 600) = 5,400 US \$/t,
- Gold (30.000 – 150) = 29,850 US \$/kg
- Silver (800 – 15) = 785 US \$/kg

Pb-Zn concentrate:

- ❖ Zinc (1,800×0.55) = 990 US \$/t
- ❖ Lead (1,800×0.55) = 990 US \$/t
- ❖ Gold (30,000×0.93) = 27,900 US \$/kg
- ❖ Silver (800×0.88) = 700 US \$/kg
- ❖ Profit 0.55%

6 Mining costs:

- ❖ Ore and waste mining 2.0 US \$/t excavation

7 Flotation costs:

- Cu flotation 4.0 US \$/t ore
- Pb-Zn flotation 6.0 US \$/t ore

8 Metallurgical treatment costs:

- Cu concentrate: 600 US \$/t concentrate
- Pb-Zn concentrate: 0.45 %

9 Adopted discount rate 10%

CAPACITY OF MINING AND DISPOSAL

The planned value of ore mining capacity per annum is as follows:

- in the 1st year of 3,000,000 t of ore
- from the 2nd year until the end of exploitation period 5,000,000 t of ore

Capacity of waste mining is limited to 16 million tons in the first year of operation. From the second to the fourteenth year, the

mining capacity of waste is 14 million tons per year, and then has steadily declined, except for the period from the eighteenth to the twentieth year when it is at the level of $12 \div 13$ million tons (Table 3).

Figure 1 shows the landfill Mali Ujevac and West landfill. The spatial capacity of these landfills allows accommodation of the total amount of waste that is mined during the exploitation period.

Figure 1 View the landfill location of the open pit North Mining District

OPTIMIZATION THE BOUNDARY OF THE OPEN PIT

An optimal boundary of open pit mining for the established techno - economic parameters was determined using the software Whittle for optimization and strategic planning of the open pits [2], [3]. The software generates several possible optimal contours of the open pits, using the revenue factor

(Revenue Factor). The obtained open pits (85 open pits were generated and shown in Table 1 and Figure 2) are further analyzed and selection of optimum open pits is done according to the criteria of discounted present value. The open pit No.31 was selected for further consideration [4].

Figure 2 Graphical presentation the optimization results of open pit and selection the optimal contour

Table 1 Results of open pit optimization and selection the optimal contour

Kop	Faktor priroda	Cena metala (€)	Ruda	Jalovina	Isokepine	Novčani tok best	Novčani tok specified	Novčani tok worst
		(€)	(t)	(t)	(t)	(€ disc)	(€ disc)	(€ disc)
1	0.30	1.800	960.181	203.712	1.171.893	22.584.296	22.584.296	22.584.296
2	0.32	1.920	1.823.849	450.874	2.074.723	34.312.916	34.312.916	34.312.916
3	0.34	2.040	2.123.199	606.769	2.729.967	41.789.193	41.789.193	41.789.193
4	0.36	2.160	2.929.255	1.092.474	4.021.729	53.519.286	53.519.286	53.519.286
5	0.38	2.280	3.650.220	1.318.562	4.968.782	62.533.173	62.494.501	62.494.501
6	0.40	2.400	4.902.725	2.181.611	7.084.336	78.708.554	78.355.255	78.355.255
7	0.42	2.520	7.071.396	3.160.726	10.232.122	100.864.035	99.630.269	99.630.269
8	0.44	2.640	9.286.522	5.407.075	14.693.597	123.819.279	121.872.114	121.872.114
9	0.46	2.760	11.067.156	7.406.268	18.473.424	140.301.765	137.641.992	137.641.992
10	0.48	2.880	13.157.839	10.175.045	23.332.884	159.260.909	155.303.894	155.303.894
11	0.50	3.000	17.927.373	16.712.768	34.640.141	194.754.291	186.303.811	186.303.811
12	0.52	3.120	22.711.007	23.883.135	46.594.942	226.403.804	213.021.965	213.021.965
13	0.54	3.240	25.885.252	28.182.398	54.043.649	243.182.848	226.051.272	226.051.272
14	0.56	3.360	30.724.134	35.989.077	66.722.231	266.129.304	240.625.139	240.625.139
15	0.58	3.480	33.477.175	40.271.845	73.749.020	277.587.488	244.277.282	244.277.282
16	0.60	3.600	37.192.913	45.485.593	82.478.204	289.694.825	247.788.051	247.788.051
17	0.62	3.720	41.440.508	53.842.480	95.215.988	303.274.051	248.833.219	248.833.219
18	0.64	3.840	44.205.134	58.448.831	102.851.945	310.218.420	247.430.866	247.430.866
19	0.66	3.960	47.502.042	64.495.812	111.997.854	317.462.024	243.140.799	243.140.799
20	0.68	4.080	52.113.561	71.835.689	123.949.250	325.693.173	237.056.568	237.056.568
21	0.70	4.200	56.271.861	79.412.771	133.684.632	332.198.250	230.075.464	230.075.464
22	0.72	4.320	62.083.245	90.431.004	152.514.240	339.838.660	218.071.798	218.071.798
23	0.74	4.440	66.812.254	101.754.105	168.564.359	345.104.837	207.145.863	207.145.863
24	0.76	4.560	81.051.138	136.436.453	217.487.589	354.439.784	170.356.756	170.356.756
25	0.78	4.680	91.336.065	164.736.025	256.072.090	359.366.452	134.967.260	134.967.260
26	0.80	4.800	96.781.199	180.400.615	277.181.814	361.514.656	115.608.954	115.608.954
27	0.82	4.920	103.600.175	200.782.071	304.382.246	363.567.340	89.619.201	89.619.201
28	0.84	5.040	111.265.885	223.954.422	335.220.307	365.078.953	63.384.591	63.384.592
29	0.86	5.160	117.824.186	246.149.900	363.774.086	365.958.572	34.954.332	34.954.331
30	0.88	5.280	121.256.159	258.805.230	379.861.389	366.383.339	20.018.724	20.018.724
31	0.90	5.400	125.343.358	275.079.087	400.420.363	366.728.762	2.206.940	2.206.940
32	0.92	5.520	130.550.079	293.650.457	424.000.516	366.951.984	-16.975.286	-16.975.286
33	0.94	5.640	131.114.588	295.942.962	428.757.550	366.989.137	-18.888.088	-18.888.085
34	0.96	5.760	132.767.036	303.970.652	436.237.091	367.047.836	-26.505.753	-26.505.753
35	0.98	5.880	134.522.733	317.465.007	453.817.740	367.087.144	-38.261.700	-38.261.719
36	1.00	6.000	138.161.223	324.956.595	463.117.518	367.078.291	-45.597.457	-45.597.457
37	1.02	6.120	140.999.315	337.787.331	478.364.546	367.015.651	-57.484.923	-57.484.923
38	1.04	6.240	144.503.976	344.882.084	487.188.060	366.967.239	-62.747.899	-62.747.899
39	1.06	6.360	144.045.206	353.072.457	497.117.663	366.911.456	-71.303.357	-71.303.357
40	1.08	6.480	145.132.029	356.664.572	501.796.601	366.875.490	-73.811.425	-73.811.424
41	1.10	6.600	145.473.922	358.036.674	503.510.596	366.860.881	-74.384.990	-74.384.989
42	1.12	6.720	149.261.428	377.080.767	526.342.195	366.832.022	-88.296.985	-88.296.985
43	1.14	6.840	149.466.138	378.583.793	528.049.931	366.814.915	-89.278.295	-89.278.295
44	1.16	6.960	150.016.034	379.953.771	529.974.805	366.585.864	-91.100.702	-91.100.702
45	1.18	7.080	150.850.043	385.656.957	536.507.000	366.504.709	-94.941.362	-94.941.362
46	1.20	7.200	151.819.471	391.796.162	543.615.633	366.423.017	-99.707.899	-99.707.899
47	1.22	7.320	152.797.499	395.913.378	548.710.877	366.360.418	-101.886.755	-101.886.755
48	1.24	7.440	154.095.441	404.049.312	558.144.753	366.242.969	-108.521.828	-108.521.828
49	1.26	7.560	154.993.811	405.961.093	560.554.904	366.208.247	-109.366.215	-109.366.214
50	1.28	7.680	154.781.049	407.179.922	561.960.971	366.183.588	-110.048.394	-110.048.394
51	1.30	7.800	154.884.895	407.845.052	562.777.947	366.176.500	-110.353.097	-110.353.097
52	1.32	7.920	156.991.452	418.211.707	576.203.159	365.977.282	-116.030.127	-116.030.127
53	1.34	8.040	158.440.134	429.768.959	583.239.093	365.812.883	-123.772.365	-123.772.363
54	1.36	8.160	158.496.574	429.947.801	583.444.375	365.809.317	-123.864.336	-123.864.336
55	1.38	8.280	159.556.554	434.348.748	593.905.502	365.723.281	-126.450.957	-126.450.957
56	1.40	8.400	159.595.857	434.537.270	594.133.127	365.719.686	-126.479.454	-126.479.454
57	1.42	8.520	160.056.057	437.834.259	597.890.316	365.684.811	-128.701.097	-128.701.098
58	1.44	8.640	160.324.985	439.293.394	599.618.379	365.638.059	-129.382.131	-129.382.131
59	1.46	8.760	160.579.643	441.490.045	602.069.688	365.603.014	-130.873.799	-130.873.799
60	1.48	8.880	160.755.538	442.824.454	603.579.992	365.580.228	-131.903.169	-131.903.169
61	1.50	9.000	161.049.360	445.038.086	606.087.366	365.542.337	-133.029.393	-133.029.393
62	1.52	9.120	161.058.884	445.077.723	606.136.587	365.541.347	-133.056.935	-133.056.935
63	1.54	9.240	162.275.935	453.695.298	618.271.233	365.357.635	-138.432.927	-138.432.928
64	1.56	9.360	163.095.727	453.654.209	621.749.831	365.382.145	-140.311.918	-140.311.918
65	1.58	9.480	164.216.964	467.619.247	631.556.151	365.154.350	-145.366.524	-145.366.524
66	1.60	9.600	164.397.954	468.929.719	633.327.673	365.133.146	-145.789.757	-145.789.757
67	1.62	9.720	164.519.065	469.717.034	634.254.699	365.110.259	-146.159.169	-146.159.169
68	1.64	9.840	164.640.566	470.502.220	635.142.786	365.102.546	-146.775.402	-146.775.401
69	1.66	9.960	164.855.493	472.074.991	636.930.484	365.070.343	-147.283.405	-147.283.405
70	1.68	10.080	165.335.219	476.021.343	641.556.542	365.014.381	-149.745.086	-149.745.086
71	1.70	10.200	165.542.970	478.091.662	643.634.532	364.983.174	-150.521.976	-150.521.976
72	1.72	10.320	165.547.266	478.132.427	643.679.693	364.982.500	-150.534.725	-150.534.725
73	1.74	10.440	165.624.374	478.459.438	644.083.812	364.975.915	-150.792.040	-150.792.039
74	1.76	10.560	165.805.749	480.927.794	644.733.543	364.940.505	-152.582.138	-152.582.138
75	1.78	10.680	166.131.945	482.706.428	648.838.373	364.908.502	-153.443.285	-153.443.285
76	1.80	10.800	167.027.893	489.333.476	656.361.249	364.795.419	-156.132.521	-156.132.521
77	1.82	10.920	167.433.655	493.448.141	660.881.796	364.734.158	-159.135.313	-159.135.313
78	1.84	11.040	167.442.355	493.550.673	660.972.826	364.723.931	-159.166.791	-159.166.791
79	1.86	11.160	167.746.140	495.729.794	663.476.534	364.687.424	-159.499.253	-159.499.253
80	1.90	11.400	168.322.556	498.800.283	667.122.844	364.640.469	-160.863.959	-160.863.959
81	1.92	11.520	168.349.812	498.917.026	667.126.878	364.637.993	-160.888.915	-160.888.915
82	1.94	11.640	169.216.976	507.066.195	676.283.171	364.514.195	-163.687.724	-163.687.724
83	1.96	11.760	169.277.495	507.620.162	676.905.657	364.504.058	-163.824.049	-163.824.049
84	1.98	11.880	170.327.443	516.924.107	687.251.550	364.365.935	-169.860.135	-169.860.134
85	2.00	12.000	170.560.005	518.387.985	689.947.990	364.342.172	-170.132.690	-170.132.690

DEFINING THE MINING PHASES (PUSHBACKS)

After determining the final border of mining, the next step in design process of

open pits is to define the mining phases [5].

The results obtained in the software Whittle are shown in Table 2.

Table 2 Results of defining the mining phases

Basic exploitation parameters	Mining phases (pushbacks)		
	Phase 1 (pushback 1)	Phase 2 (pushback 2)	Phase 3 (pushback 3)
Total amount of excavations, t	46 631 341	170 986 143	183 003 754
Total amount of overburden, t	23 883 136	112 553 318	138 642 554
Amount of ore, t	22 748 205	58 432 825	44 361 200
Cut-off grade of copper in the ore, % C_u	0.100	0.100	0.100
Average copper content in the ore, % C_u	0.385	0.291	0.302
Cut-off grade of zinc in the ore, % Z_n	1.000	1.000	1.000
Average zinc content in the ore, % Z_n	1.924	1.658	1.508
Overburden coefficient, t/t	1.050	1.930	3.130

View the final contours of development phases of the open pit, resulting in

the software Whittle, is shown in Figure 3.

Figure 3 View the final contours of development phases of the open pit (3D view)
a) Phase 1, b) Phase 2, c) Phase 3

Figures 4 and 5 show the mining phases in the software Gemcom Gems where, in addition to the phase boundary, it is

also noticed the block model of metal content in the ore in the deposit North Mining District.

Figure 4 Cross section of the open pit with a view of development phases of the open pit and block model of copper content (coordinates of the points $X = 4973341$ and $Y = 7520652$; $X = 4974575$ and $Y = 7520652$; azimuth $\nu = 90^\circ$)

Figure 5 View the development phase of open pit and block model of copper content in the plan (level of floor $E + 425$)

OPTIMIZATION THE MINING DYNAMICS

Mining dynamics by years of exploitation was obtained in the software Whittle, in the module New Schedule Graf. To optimi-

ze the mining dynamics, the software uses the Milava algorithm, which can operate in NPV mode when maximum net present

value (NPV) is required or in the balancing regime in which maximum utilization of production capacities in mining and flotation processing is required in the first years of

exploitation. A balancing regime (Milawa Balanced) was used in this work.

Results of optimization the mining dynamics are shown in Table 3.

Table 3 Mining dynamics by years of exploitation with a view of cash flow

Year	Ore	Waste	Excavation	Overburden coefficient	Cash flow	Cash flow disc
	(t)	(t)	(t)	(t/t)	\$	\$
1	2 979 345	16 020 655	19 000 000	5.38	11 246 634	10 224 213
2	4 734 069	14 265 931	19 000 000	3.01	34 996 063	28 922 366
3	4 845 618	14 154 382	19 000 000	2.92	33 451 016	25 132 244
4	4 876 619	14 123 381	19 000 000	2.90	31 150 733	21 276 370
5	4 971 615	14 028 385	19 000 000	2.82	34 912 504	21 677 918
6	4 996 616	14 003 384	19 000 000	2.80	40 871 924	23 071 135
7	4 982 021	14 017 979	19 000 000	2.81	21 689 710	11 130 251
8	4 994 294	14 005 706	19 000 000	2.80	26 008 360	12 133 092
9	4 985 137	14 014 863	19 000 000	2.81	13 143 992	5 574 336
10	4 969 517	14 030 484	19 000 001	2.82	18 102 666	6 979 361
11	4 964 874	14 035 126	19 000 000	2.83	17 222 757	6 036 471
12	4 975 731	14 024 269	19 000 000	2.82	18 713 860	5 962 812
13	5 000 000	12 848 645	17 848 645	2.57	25 731 559	7 453 516
14	5 000 000	10 082 085	15 082 085	2.02	36 509 799	9 614 171
15	4 999 998	9 922 013	14 922 011	1.98	37 432 610	8 961 069
16	5 000 000	9 538 805	14 538 805	1.91	31 437 699	6 841 759
17	5 000 000	9 939 543	14 939 543	1.99	24 695 897	4 885 952
18	4 999 998	11 698 016	16 698 014	2.34	22 904 849	4 119 638
19	5 000 000	13 430 083	18 430 083	2.69	18 038 165	2 949 384
20	5 000 000	12 269 592	17 269 592	2.45	23 636 188	3 513 369
21	5 000 000	7 704 188	12 704 188	1.54	33 055 309	4 466 783
22	5 000 000	4 216 883	9 216 883	0.84	31 765 187	3 902 225
23	5 000 000	1 814 944	6 814 944	0.36	35 382 772	3 951 483
24	5 000 000	715 856	5 715 856	0.14	43 949 792	4 462 029
25	5 000 000	162 320	5 162 320	0.03	57 185 004	5 277 947
26	3 065 906	11 490	3 077 396	0.00	46 774 308	4 072 012
Total	125 341 358	275 079 008	400 420 366	2.19	770 009 357	252 591 906

Figure 6 presents the amount of ore and waste by years of exploitation with associated stripping ratio.

Figure 7 shows the changes in the amount of ore and waste by years of exploitation and development phases of open pit.

Figure 6 Amount of ore and waste by years of exploitation with associated stripping ratio

Figure 7 Amounts of ore and waste by years of exploitation and development phases of open pit

Change of medium content of copper, silver and gold in copper ore and stripping ratio by years of exploitation can be read from the graph in Figure 8.

Figure 9 shows the movement of discounted cash flow and amount of ore and waste by years of exploitation.

Figure 8 Change of medium content of copper, silver and gold in copper ore and stripping ratio by years

Figure 9 Change of discounted cash flow and amount of ore and waste by years of exploitation

CONCLUSION

Based on the carried out analysis, the following is concluded:

- 1) The specified capacity in copper ore mining at the open pit North Mining District Majdanpek of 5 million tons

per year is achieved in the second year of operation. In the first year, the capacity is at the level of 3 million tons.

- 2) Service life of the open pit is 26 years.

- 3) The stripping ratio in the first year of exploitation is 5.38 t/t. From the second to the fourteenth year, this ratio has a value of around 2.8 t/y, and then steadily declines, except for a period from the eighteenth to the twentieth year when it is at approximately level of 2.5 t/t.
- 4) Movement in cash flow is positive during the whole period of exploitation.
- 5) The net present value is achieved in the amount of **\$ 252,591,906** (calculation in the software Whittle).

REFERENCES

- [1] Elaborate on reserves of the Copper Deposit "South Mining District – Majdanpek" and Deposit of Polymetallic Mineral Resources (Zn-Pb-Cu) "Tenka – North Mining District Majdanpek", Mining and Metallurgy Institute Bor, 30/06/2011;
- [2] D. Kržanović, R. Rajković, M. Mikić: The Effect of Open Pit Slope Design on Net Present Value for Long Term Planning, The 46th International October Conference on Mining and Metallurgy, Bor Lake, Serbia, 2014;
- [3] G. Whittle, W. Stange and N. Hanson, Optimizing Project Value and Robustness, Project Evaluation Conference, Melbourne, Vic, 19 - 20 June 2007, pp. 1-10;
- [4] D. Kržanović, R. Rajković, M. Mikić: Application of Software Packages Gemcom and Whittle for Design in Mining Aimed to Rational and Cost-Effective Utilization the Copper Deposit Veliki Krivelj near Bor, Serbia, Mining Engineering, Mining and Metallurgy Institute Bor, 2012, pp. 91-98;
- [5] D. Kržanović, R. Rajković, M. Mikić, M. Ljubojev: Effect of Stage Development of Mining Operations on Maximization the Net Present Value in Long-Term Planning of Open Pits, Mining and Metallurgy Engineering Bor, 4/2014, pp. 33-40.

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ANALIZA DUGOROČNOG RAZVOJA POVRŠINSKOG KOPA SEVERNI REVIR MAJDANPEK ZA KAPACITET 5×10^6 TONA RUDE GODIŠNJE***

Izvod

U radu je izvršeno sagledavanje dugoročnog razvoja površinskog kopa Severni revir sa aspekta ostvarivanja maksimalne dobiti za planirani kapacitet od 5 miliona tona rude bakra godišnje, primenom savremenog softvera za strateško planiranje proizvodnje Whittle.

Softver pruža mogućnost da se optimizacijom granice otkopavanja i dugoročne dinamike otkopavanja ostvari pozitivno kretanje novčanog toka i maksimalna neto sadašnja vrednost.

Za planirane tehnokonomske parametre, koji su ulazni podaci za analizu, dobijena je granica površinskog kopa za vek eksploatacije od 26 godina, a vrednost neto sadašnje vrednosti iznosi 252.591.906 \$.

***Ključne reči:** površinski kop Severni revir Majdanpek, optimizacija, fazni razvoj kopa, novčani tok, neto sadašnja vrednost, softver Whittle*

UVOD

U okviru preduzeća Rudnik bakra Majdanpek, koji je deo kompanije Rudarsko topioničarski basen Bor (RTB Bor), posluju dva površinska kopa i to Severni revir i Južni revir. S obzirom da se na površinskom kopu Južni revir vrši raskrivanje ležišta, nosilac proizvodnje rude bakra poslednjih godina je kop Severni revir, sa kapacitetom oko 3,5 miliona tona godišnje. Izgradnjom nove topionice u Boru neophodno je obezbediti sirovinu za njen rad kroz povećanje kapaciteta otkopavanja na površinskim kopovima koji posluju u okviru RTB Bor. U tom cilju izvršena je analiza mogućnosti dugoročnog otkopavanja rude bakra na površinskom kopu Severni revir Majdanpek

za kapacitet od 5 miliona tona godišnje, koja obuhvata:

- 1) optimizaciju površinskog kopa i izbor optimalne konture kopa
- 2) definisanje faza otkopavanja (push-backs)
- 3) optimizaciju dinamike otkopavanja
- 4) ekonomsku analizu u softveru Whittle, koja se zasniva na analizi kretanja diskontovanog novčanog toka tokom eksploatacionog perioda, odnosno ostvarene neto sadašnje vrednosti, i koja je pokazatelj postignutih ekonomskih rezultata eksploatacije ležišta Severni revir za zadate početne uslove.

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Tehničko-ekonomska analiza izvršena je za deo ležišta bakra „Severni revir – Majdanpek“ i ležišta polimetaličnih mineralnih sirovina (Zn-Pb-Cu) „Tenka – Severni revir Majdanpek“ u soferu Whittle.

TEHNOEKONOMSKI PARAMETRI ZA ANALIZU

Dugoročni razvoj površinskog kopa definisan je na osnovu sledećih polaznih tehnoekonomske parametara [1].

1. Rudarska iskorišćenja i osiromašjenja

- Osiromašjenje rude bakra 4,0%,
- Osiromašjenje olovo-cinkane rude 6,0%,
- Eksploatacioni gubici bakarne rude 4,0%,
- Eksploatacioni gubici PbZn rude 6,0%.

2. Flotacijska iskorišćenja:

Ruda Cu:

- Iskorišćenje Cu 82,0%,
- Iskorišćenje Ag 50,0%,
- Iskorišćenje Au 50,0%.

Ruda Pb-Zn:

- Iskorišćenje Zn 60,0%,
- Iskorišćenje Pb 60,0%,
- Iskorišćenje Ag 51,5%,
- Iskorišćenje Au 35,0%,

3. Metalurška iskorišćenja:

Koncentrat Cu:

- Iskorišćenje Cu 95,0%,
- Iskorišćenje Ag 90,0%,
- Iskorišćenje Au 90,0%,

Koncentrat Pb-Zn:

- Iskorišćenje Zn 96,5%,
- Iskorišćenje Pb 95,0%,
- Iskorišćenje Ag 90,0%,
- Iskorišćenje Au 90,0%.

4. Prodajne cene metala:

- Bakar (Cu) 6.000 US \$/t,
- Srebro (Ag) 800 US \$/kg,

- Zlato (Au) 30.000 US \$/kg,
- Cink (Zn) 1.800 US \$/t,
- Olovo (Pb) 1.800 US \$/t,

5. Vrednost metala u koncentratu:

Koncentrat Cu:

- Bakar (6.000 – 600) = 5.400 US \$/t,
- Zlato (30.000 – 150) = 29.850 US \$/kg,
- Srebro (800 – 15) = 785 US \$/kg.

Koncentrat Pb-Zn:

- ❖ Cink (1.800×0,55) = 990 US \$/t,
- ❖ Olovo (1.800×0,55) = 990 US \$/t,
- ❖ Zlato (30.000×0,93) = 27.900 US \$/kg,
- ❖ Srebro (800×0,88) = 700 US \$/kg,
- ❖ Dobit 0,55%.

6. Troškovi otkopavanja:

- ❖ Otkopavanje rude i jalovine 2,0 US \$/t iskopa.

7. Flotacijski troškovi:

- Flotiranje Cu 4,0 US \$/t rude,
- Flotiranje Pb-Zn 6,0 US \$/t rude.

8. Troškovi metalurške prerade:

- Koncentrat Cu: 600 US \$/t koncentrata,
- Koncentrat Pb-Zn: 0,45 %.

9. Usvojena diskontna stopa 10%.

KAPACITETI OTKOPAVANJA I ODLAGANJA

Planirana vrednost kapaciteta otkopavanja rude na godišnjem nivou je sledeća

- u 1. godini 3.000.000 t rude
- od 2. godine do kraja eksploatacionog perioda 5.000.000 t rude.

Kapacitet otkopavanja jalovine ograničen je na 16 miliona tona u prvoj godini eksploatacije. Od druge do četrnaeste godine

kapacitet otkopavanja na jalovini iznosi 14 miliona tona godišnje, a zatim konstantno opada, sem u periodu od osamnaeste do dvadesete godine kada je na nivou od 12÷13 miliona tona (tabela 3).

Na slici 1 prikazana su odlagališta Mali Ujevac i Zapadno odlagalište. Prostorni kapacitet navedenih odlagališta omogućava smeštaj celokupne količine jalovine koja se otkopava u toku eksploatacionog perioda.

Sl. 1. Prikaz lokacija odlagališta površinskog kopa Severni revir

OPTIMIZACIJA GRANICE POVRŠINSKOG KOPA

Optimalna granica otkopavanja površinskog kopa, za utvrđene tehno – ekonomski parametre određena je korišćenjem softvera za optimizaciju i strateško planiranje površinskih kopova Whittle [2], [3]. Softver generiše više mogućih optimalnih kontura kopova, primenom faktora prihoda

(Revenue Factor). Dobijeni kopovi (generisano je 85 kopova koji su prikazani u tabeli 1 i na slici 2) dalje se analiziraju i vrši se izbor optimalnog kopa po kriterijumu diskontovane sadašnje vrednosti. Za dalje sagledavanje izabran je kop broj 31 [4].

Sl. 2. Grafički prikaz rezultata optimizacije površinskog kopa i izbora optimalne konture

Tabela 1. Rezultati optimizacije površinskog kopa i izbor optimalne konture

Kop	Faktor priroda	Cena metala (Cn)	Ruda	Jalovina	Iskopine	Novi tisk tok best	Novi tisk tok specified	Novi tisk tok worst
		(t)	(t)	(t)	(t)	(t)	(t)	(t)
1	0.30	1.800	960.181	203.712	1.171.893	22.584.296	22.584.296	22.584.296
2	0.32	1.920	1.023.849	450.874	2.074.723	34.312.916	34.312.916	34.312.916
3	0.34	2.040	2.123.198	806.769	2.729.987	41.789.193	41.789.193	41.789.193
4	0.36	2.160	2.929.255	1.092.474	4.021.729	53.519.286	53.519.286	53.519.286
5	0.38	2.280	3.650.220	1.318.562	4.968.782	62.533.173	62.494.501	62.494.501
6	0.40	2.400	4.902.725	2.181.611	7.084.336	78.355.255	78.355.255	78.355.255
7	0.42	2.520	7.071.396	3.180.736	10.235.122	100.864.035	99.450.269	99.450.269
8	0.44	2.640	9.246.522	5.407.075	14.685.597	123.819.739	121.872.134	121.872.134
9	0.46	2.760	11.047.156	7.404.248	18.474.424	140.301.765	137.641.892	137.641.892
10	0.48	2.880	13.157.839	10.175.045	23.332.884	159.240.909	155.303.894	155.303.894
11	0.50	3.000	17.927.373	16.712.748	34.440.141	194.754.291	186.303.811	186.303.811
12	0.52	3.120	22.711.807	23.883.135	46.594.942	226.403.804	213.021.965	213.021.965
13	0.54	3.240	25.863.252	28.182.596	54.045.648	243.162.048	226.051.272	226.051.272
14	0.56	3.360	30.724.154	35.998.077	66.722.231	266.129.304	240.625.139	240.625.139
15	0.58	3.480	33.477.175	40.271.845	73.749.020	277.057.488	244.277.282	244.277.282
16	0.60	3.600	37.192.913	45.485.293	82.878.208	289.834.825	247.798.051	247.798.051
17	0.62	3.720	41.443.508	53.842.480	95.285.988	303.274.051	248.883.219	248.883.219
18	0.64	3.840	44.205.134	58.448.831	102.653.965	310.218.420	247.430.866	247.430.866
19	0.66	3.960	47.502.442	64.495.812	111.997.854	317.482.426	243.140.799	243.140.799
20	0.68	4.080	52.113.561	71.835.689	123.949.250	325.693.173	237.056.568	237.056.568
21	0.70	4.200	56.271.861	79.412.771	135.684.632	332.189.250	230.075.464	230.075.464
22	0.72	4.320	62.083.245	90.431.004	152.514.249	339.836.560	218.071.798	218.071.798
23	0.74	4.440	68.012.254	101.754.105	168.568.359	345.104.837	207.145.863	207.145.863
24	0.76	4.560	81.051.138	138.436.433	217.487.589	354.419.784	170.358.758	170.358.758
25	0.78	4.680	91.338.065	164.736.025	256.072.090	359.368.452	134.967.260	134.967.260
26	0.80	4.800	96.781.199	180.400.015	277.181.814	361.514.456	115.608.954	115.608.954
27	0.82	4.920	103.660.176	200.782.071	304.383.244	363.567.140	89.619.201	89.619.201
28	0.84	5.040	111.245.885	223.854.422	335.220.207	365.078.953	49.384.591	49.384.591
29	0.86	5.160	117.424.188	246.149.900	363.774.066	365.958.573	34.954.332	34.954.332
30	0.88	5.280	123.245.156	265.055.330	379.861.389	366.983.359	20.018.724	20.018.724
31	0.90	5.400	125.341.356	273.079.007	400.420.343	366.729.762	2.208.940	2.208.940
32	0.92	5.520	130.550.079	293.650.437	424.000.516	366.951.984	-16.975.286	-16.975.286
33	0.94	5.640	131.114.588	295.642.942	426.757.550	366.939.137	-18.886.086	-18.886.086
34	0.96	5.760	132.767.039	303.470.052	436.237.091	367.047.835	-26.505.753	-26.505.753
35	0.98	5.880	136.322.733	317.495.007	453.817.740	367.087.144	-38.381.780	-38.381.780
36	1.00	6.000	138.161.223	324.956.295	463.117.518	367.078.291	-45.537.457	-45.537.457
37	1.02	6.120	140.999.315	337.397.231	478.398.546	367.015.651	-57.484.923	-57.484.923
38	1.04	6.240	142.503.976	344.882.084	487.186.060	366.967.239	-62.747.899	-62.747.899
39	1.06	6.360	144.043.206	353.072.457	497.117.663	366.911.456	-71.308.357	-71.308.357
40	1.08	6.480	145.132.029	356.664.372	501.796.601	366.875.490	-73.811.424	-73.811.424
41	1.10	6.600	145.473.922	358.036.674	503.510.594	366.860.881	-74.384.989	-74.384.989
42	1.12	6.720	149.261.428	377.080.787	528.342.195	366.832.022	-88.286.985	-88.286.985

DEFINISANJE FAZA OTKOPAVANJA (PUSHBACKS)

Nakon određivanja konačne granice otkopavanja, sledeći korak u procesu dizaj-

niranja površinskih kopava jeste definisanje faza otkopavanja [5].

Dobijeni rezultati u softveru Whittle prikazani su u tabeli 2.

Tabela 2. Rezultati definisanja faza otkopavanja

Osnovni eksploatacioni parametri	Faze otkopavanja (pushbacks)		
	Faza 1 (pushback 1)	Faza 2 (pushback 2)	Faza 3 (pushback 3)
Ukupna količina iskopina, t	46 631 341	170 986 143	183 003 754
Ukupna količina otkrivke, t	23 883 136	112 553 318	138 642 554
Količina rude, t	22 748 205	58 432 825	44 361 200
Granični sadržaj bakra u rudi, % C_u	0,100	0,100	0,100
Prosečan sadržaj bakra u rudi, % C_u	0,385	0,291	0,302
Granični sadržaj cinka u rudi, % Z_n	1,000	1,000	1,000
Prosečan sadržaj cinka u rudi, % Z_n	1,924	1,658	1,508
Koeficijent otkrivke, t/t	1,050	1,930	3,130

Prikaz završnih kontura Faza razvoja kopa, dobijena u softveru Whittle, dat je na sl. 3.

Sl. 3. Izgled završnih kontura Faza razvoja kopa (3D prikaz)
a) faza 1, b) faza 2, c) faza 3

Na slikama 4 i 5 prikazane su Faze otkopavanja u softveru Gemcom Gems, na kojima se pored granica Faza uočava i blok model sadržaja metala u rudi u ležištu Severni revir.

Sl. 4. Poprečni presek kopa sa prikazom Faza razvoja kopa i blok modela sadržaja bakra (koordinate tačkaka $X=4973341$ i $Y=7520652$; $X=4974575$ i $Y=7520652$; azimut $\alpha=90^\circ$)

Sl. 5. Prikaz Faza razvoja kopa i blok modela sadržaja bakra u planu (nivo etaže E+425)

OPTIMIZACIJA DINAMIKE OTKOPAVANJA

Dinamika otkopavanja po godinama eksploatacije dobijena je u softveru Whittle, u modulu New Schedule Graf. Za optimi-

zaciju dinamike otkopavanja softver koristi Milava algoritam, koji može da radi u režimu NPV kada se traži maksimalna neto

sadašnja vrednost (NSV) ili u režimu balansiranja u kome se traži da se maksimalno iskoriste proizvodni kapaciteti na otkopavanju i flotacijskoj pripremi u prvim godinama

eksploatacije. U ovom radu primenjen je režim balansiranja (Milawa Balanced).

Rezultati optimizacije dinamike otkopavanja prikazani su u tabeli 3.

Tabela 3. *Dinamika otkopavanja po godinama eksploatacije sa prikazom novčanog toka*

God.	Ruda	Jalovina	Iskopine	Koef. rask.	Novčani tok	Novčani tok disc
	(t)	(t)	(t)	(t/t)	\$	\$
1	2 979 345	16 020 655	19 000 000	5.38	11 246 634	10 224 213
2	4 734 069	14 265 931	19 000 000	3.01	34 996 063	28 922 366
3	4 845 618	14 154 382	19 000 000	2.92	33 451 016	25 132 244
4	4 876 619	14 123 381	19 000 000	2.90	31 150 733	21 276 370
5	4 971 615	14 028 385	19 000 000	2.82	34 912 504	21 677 918
6	4 996 616	14 003 384	19 000 000	2.80	40 871 924	23 071 135
7	4 982 021	14 017 979	19 000 000	2.81	21 689 710	11 130 251
8	4 994 294	14 005 706	19 000 000	2.80	26 008 360	12 133 092
9	4 985 137	14 014 863	19 000 000	2.81	13 143 992	5 574 336
10	4 969 517	14 030 484	19 000 001	2.82	18 102 666	6 979 361
11	4 964 874	14 035 126	19 000 000	2.83	17 222 757	6 036 471
12	4 975 731	14 024 269	19 000 000	2.82	18 713 860	5 962 812
13	5 000 000	12 848 645	17 848 645	2.57	25 731 559	7 453 516
14	5 000 000	10 082 085	15 082 085	2.02	36 509 799	9 614 171
15	4 999 998	9 922 013	14 922 011	1.98	37 432 610	8 961 069
16	5 000 000	9 538 805	14 538 805	1.91	31 437 699	6 841 759
17	5 000 000	9 939 543	14 939 543	1.99	24 695 897	4 885 952
18	4 999 998	11 698 016	16 698 014	2.34	22 904 849	4 119 638
19	5 000 000	13 430 083	18 430 083	2.69	18 038 165	2 949 384
20	5 000 000	12 269 592	17 269 592	2.45	23 636 188	3 513 369
21	5 000 000	7 704 188	12 704 188	1.54	33 055 309	4 466 783
22	5 000 000	4 216 883	9 216 883	0.84	31 765 187	3 902 225
23	5 000 000	1 814 944	6 814 944	0.36	35 382 772	3 951 483
24	5 000 000	715 856	5 715 856	0.14	43 949 792	4 462 029
25	5 000 000	162 320	5 162 320	0.03	57 185 004	5 277 947
26	3 065 906	11 490	3 077 396	0.00	46 774 308	4 072 012
Total	125 341 358	275 079 008	400 420 366	2.19	770 009 357	252 591 906

Na slici 6 dat je prikaz količina rude i jalovine po godinama eksploatacije sa pripadajućim koeficijentom otkrivke.

Slika 7 prikazuje promenu količina rude i jalovine po godinama eksploatacije i Fazama razvoja kopa

SI. 6. Količine rude i jalovine po godinama eksploatacije sa pripadajućim koeficijentom otkrivke

SI. 7. Količine rude i jalovine po godinama eksploatacije i Fazama razvoja kopa

Promena srednjeg sadržaja bakra, srebra i zlata u rudi bakra i koeficijenta raskrivke po godinama eksploatacije može se očitati sa grafika na slici 8.

Slika 9 prikazuje kretanje diskontovanog novčanog toka i količina rude i jalovine po godinama eksploatacije.

Sl. 8. Promena srednjeg sadržaja bakra, srebra i zlata u rudi bakra i koeficijenta raskrivke po godinama

Sl. 9. Promena diskontovanog novčanog toka, količina rude i jalovine po godinama eksploatacije

ZAKLJUČAK

Na osnovu sprovedene analize zaključuje se sledeće:

- 1) Zadati kapacitet na otkopavanju rude bakra na površinskom kopu Severni revir Majdanpek od 5 miliona tona

godišnje postiže se u drugoj godini eksploatacije. U prvoj godini kapacitet je na nivou od 3 miliona tona.

- 2) Vek eksploatacije kopa iznosi 26 godina.

- 3) Koeficijent raskrivke u prvoj godini eksploatacije iznosi 5,38 t/t. Od druge do četrnaeste godine ovaj koeficijent ima vrednost oko 2,8 t/t, a zatim konstantno opada, sem u periodu od osamnaeste do dvadesete godine kada je na približno na nivou od 2,5 t/t.
- 4) Kretanje novčanog toka je pozitivno tokom celog perioda eksploatacije.
- 5) Ostvaruje se neto sadašnja vrednost u iznosu od **252.591.906 \$** (obračun u softveru Whittle).

LITERATURA

- [1] Elaborat o rezervama ležišta bakra „Severni revir – Majdanpek“ i ležišta polimetalčnih mineralnih sirovina (Zn-Pb-Cu) „Tenka – Severni revir Majdanpek“, Institut za rudarstvo i metalurgiju Bor, 30.06.2011.
- [2] D. Kržanović, R. Rajković, M. Mikić: The Effect of Open Pit Slope Design on Net Present Value for Long Term Planning, The 46th International October Conference on Mining and Metallurgy, Borsko jezero, Serbia, 2014.
- [3] G. Whittle, W. Stange and N. Hanson, Optimising Project Value and Robustness, Project Evaluation Conference, Melbourne, Vic, 19 - 20 June 2007, str. 1-10.
- [4] D. Kržanović, R. Rajković, M. Mikić: Primena softverskih paketa za projektovanje u rudarstvu Gemcom i Whittle u cilju racionalnog i ekonomičnog iskorišćenja ležišta bakra Veliki Krivelj kod Bora, Srbija, Rudarski radovi, Institut za rudarstvo i metalurgiju Bor, 3/2012, str. 85-90.
- [5] D. Kržanović, R. Rajković, M. Mikić, M. Ljubojev: Efekat faznog razvoja rudarskih radova na maksimizaciju neto sadašnje vrednosti kod dugoročnog planiranja površinskih kopova, Mining and Metallurgy Engineering Bor, 4/2014, str. 41-48.