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COMPARATIVE OPTIMIZATION OF MINING THE KRAKU BUGARESKU CEMENTATION DEPOSIT USING WHITTLE AND NPV SCHEDULER SOFTWARE

Abstract

The paper is aimed to present a method of determining the final pit contour with maximum discounted profit, to determine the stages of excavation (Pushbacks) and mining schedule for the final pit using the software packages for strategic planning of open pit mining - Whittle and NPV Scheduler, in the case of optimization the Kraku Bugaresku Cementation deposit. In both cases the same techno - economic parameters were used and the same initial topography. The aim or intention of the authors was not to judge or advertise the aforementioned software packages, but to demonstrate the optimization procedure in a specific case, with reference to the basic differences. Comparison of the obtained results is also a verification of correctness of the optimization results.

Keywords: *optimization, optimal pit contour, pushbacks, mining schedule, software, NPV*

INTRODUCTION

The "Cerovo" deposit is located in the ore field Mali Krivelj - Cerovo, about fifteen kilometers northwest of the town of Bor.

Figure 1 *Cerovo Cementation 1*

* *Mining and Metallurgy Institute Bor, Serbia*

There are the following ore bodies on the site: "Cerovo - Cementation 1", "Cerovo - Cementation 2", "Cerovo - Cementation 3", "Cerovo - Cementation 4", “Drenova” and "Cerovo - Primary".

In 1990, the work began at the opening the open pit Cementation 1, and the pre-stripping period was dictated by the length of investment period for construction the facilities of Flotation Plant and hydro-transport system for ore pulp to the Flotation Plant in Bor, i.e. the infrastructure facilities of the mine. This period lasted more than 2 years. The Kraku Bugaresku Cementation deposit is a cementation zone of the secondary enrichment and the main oxide minerals are azurite, malachite, and even native copper as occurrence. The main holder of copper bearing mineralization of sulfide minerals is chalcopyrite accompanied by bornite, since pyrite is the most present mineral in the ore. Chalcocite, covellite and azurite are also presented to a lesser extent. [9]

The main problem with the Kraku Bugaresku Cementation deposit is a significant participation of oxide minerals in total ore what reduces the copper recovery in the flotation process of concentrate preparation, and by that the final effects of valorization the total production. In the process of flotation concentration, higher copper recovery can be achieved in the processing of sulfide ore than it is the case in processing of oxide ore. [7] In the world today, the hydrometallurgical processing technology, leaching and SX/EW (solvent extraction and electrochemical separation by electrowinning) are successfully used for the processing of oxide ores, which is particularly actual for low grade heaps like dumps or specially formed oxide ore heap piles. [4, 5] The leaching-SX/SW technology implies that copper from heap is recovered with a solution of sulfuric acid which, after the percolation through the pile, is collected, purified and, in the process of solvent extraction the copper ions are transferred from aqueous into organic phase. The aqueous phase is returned to the leaching process while the organic phase is sent to the process of re-extraction, where in copper is transferred into copper-sulfate solution from which it is further recovered in the process of electro-winning. The resultant copper cathode purity is 99.99 % Cu. [5]

In order to test the possibility and effects of two methods of processing ore at the deposit Kraku Bugaresku Cementation, it was necessary to revise the block model in the software *GEOVIA Gems* to clearly separate the zone of sulfide and oxide ore and enable optimization in the case of two processing methods, i.e. flotation of sulfide (Mill) ore and leaching of oxide ore (Leach). Therefore, the deposit Cerovo Cementation is a separate zone of sulfide ore with participation of oxide minerals by 10% and the oxide ore zone with participation of oxide minerals higher than 10%.

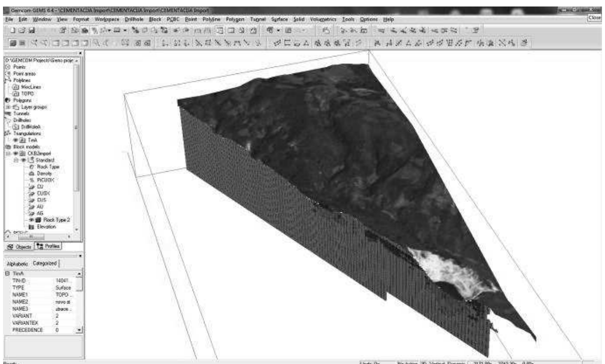
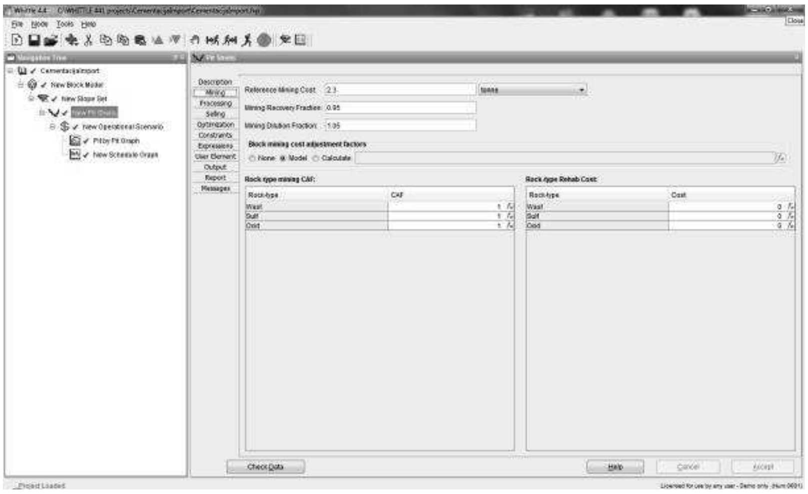


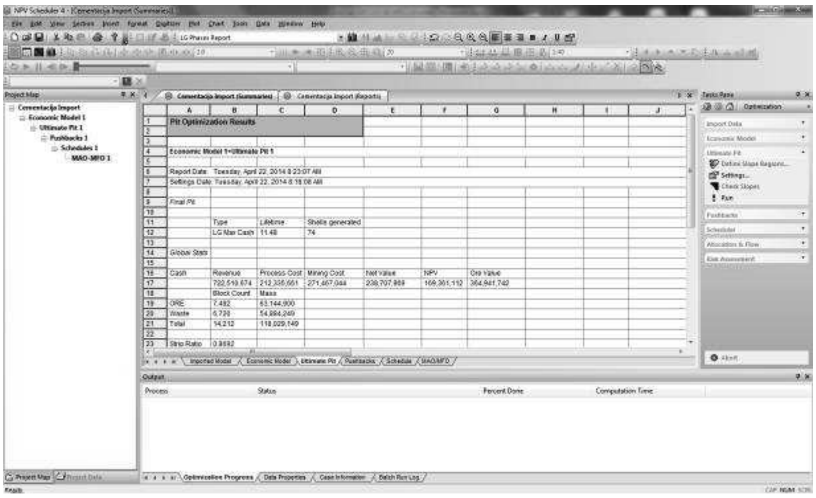
Figure 2 *View of a block model in GEMS with an oxide (red) and sulfide (green) ore zones*

Description the Software Packages Whittle and NPV Scheduler

Software packages *Whittle* from the company GEOVIA and *NPV Scheduler* (NPVS) from the company DATAMINE, are used for strategic planning in the open pit mining, in determining the optimal open pit contour, selection of appropriate open pit mine stages (Phases-Pushbacks) and defining the mining schedule in order to achieve the optimum techno-economic parameters and improved financial results (Figure 3).



a.



b.

Figure 3 *"Windows" of Whittle (a) and NPVS (b) software*

Input Data for Determining the Final Pit Contour and Mining Schedule

The scenario considered in this work involves limited processing of sulfide ore in the flotation (Mill) with maximum of 2.5 mt/year in the first two years, with the expansion of the flotation processing capacity to 5.5 mt/year in the coming years. Processing of oxide ore by leaching (Leach) would not be limited annually, but would be adapted to the amounts of oxide ore that must be excavated within the total excavated rock as to allow for excavation of necessary amounts of sulfide ore for the planned capacity of flotation processing (2.5 mil.t or 5.5 mil.t). Table 1 shows the input economic-technological parameters used as the basis for the optimization process in both softwares. [1]

Table 1 *Input parameters for optimization in Whittle and NPVS*

Economic cut-off grade of copper	**0.15% Cu**
Metal prices	
copper	5 000 $/t
gold	30 000 $/kg
silver	400 $/t
Mining costs	2.3 $/t
Mineral processing costs	
flotation (Mill)	4 $/t
leaching (Leach)	1 $/t
Additional copper recovery costs	
flotation	450 $/t
leaching	100 $/t
Additional metal recovery costs	
gold	150 $/kg
silver	15 $/kg
Mining recovery	95%
Dilution from mining	5%
Metal recoveries	
copper (flotation and metallurgical treatment)	78.8%
copper (leaching and SX/EW)	75%
gold (in both processes)	50%
silver (in both processes)	40%
Discount rate	10%
Slope angle of open pit	37°

Mining layout as of 01. 04. 2014 was taken for the initial topography.

Selection the Optimal Open Pit Contour and Phase Determining

Both softwares are based on the Lerch-Grossman optimization algorithm. The essence of this algorithm is that, for a given techno-economic parameters, the most economical open pit contour is formed by movement from the lowest acceptable economic block to the highest block in the model, while respecting the defined pit slope angles. In order to determine the most economical direction of open pit development, and determination the appropriate stages when planning a mine schedule, software have an option of scaling the metal prices using a coefficient (*revenue factor*) resulting in a series of pits (*nested pits*) from the smallest (for the lowest price of metal) to the largest (depending on the increase of metal price). [2, 3, 4] Open pit with the coefficient of 1.0 (100 % revenue factor) is an open pit with unscaled selling price of metal. For selection the optimal open pit contour, in this case the pit contour with maximum discounted profit or NPV (net present value), it is necessary to determine the discount rate and define the annual production of ore.

In the Whittle software, NPV values are estimated based on the so-called *Best Case* and *Worst Case* Scenarios. The Best Case scenario is where the final pit is mined through all previously defined stages, one by one, in the form of pushbacks. The Worst Case is a scenario in which the final pit is mined without pushbacks, i.e.by benches within the final pit. These cases are uneconomical (Worst Case) and technologically unattainable in practice (Best Case), and therefore it is necessary to seek the adequate phases and, for them, the optimal final pit. In Whittle, this is referred to as the *Specified Case*. [8]

Figures 4 and 5 show the graphs for estimated NPV values in Whittle and NPVS.

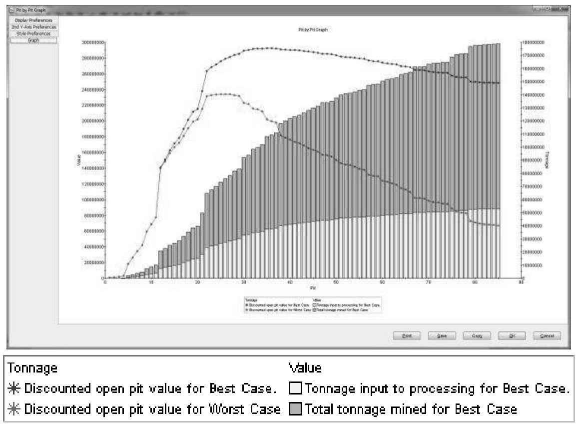


Figure 4 *NPV estimation "Pit by Pit graph" in Whittle*

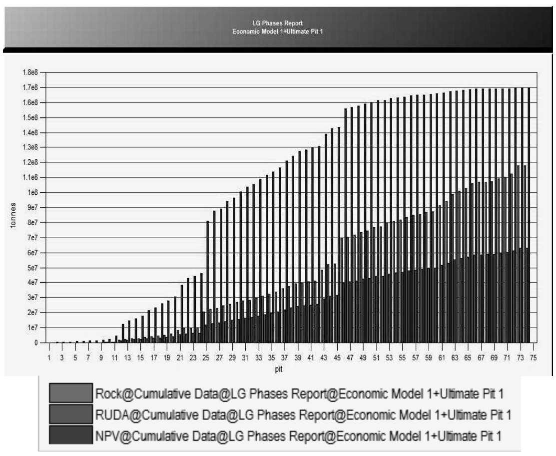


Figure 5 *NPV estimation for open pits in NPVS*

In order to facilitate the comparison of optimization results, it was necessary to select approximately the same pit contours for pushbacks and the final pit. Since the "Pit by Pit" for the Best Case of optimization gives the result of the best NPV value for an open pit with the revenue factor of 0.98 (98%), the open pit with the same revenue factor was also chosen as the final pit in NPVS. As pushbacks, the pits with revenue factors 62% (the first pushback) and 80% (the second pushback) were selected in both softwares. Table 2 and Figure 6 show the amounts of rock and ore in selected pushbacks and the final pit.

Table 2 *Amounts of rock and ore excavated in pushbacks and the final pit in Whittle and NPVS software*

Software	*Phase (Push-back)*	*Revenue factor*	*Total excavation*	*Oxide ore*	*Sulfide ore*	*Total ore*	*Stripping ratio*
Whittle	1	62%	33 426 102	10 782 047	9 123 921	19 905 968	0.68
NPVS			33 839 437	10 968 750	9 396 337	20 365 087	0.66
Whittle	2	80%	80 698 683	20 605 505	25 339 518	45 945 023	0.76
NPVS			80 999 662	20 823 750	25 602 075	46 425 825	0.74
Whittle	3	98%	117 459 790	26 686 638	35 720 999	62 407 636	0.88
NPVS			112 228 874	25 920 000	35 326 462	61 246 462	0.83

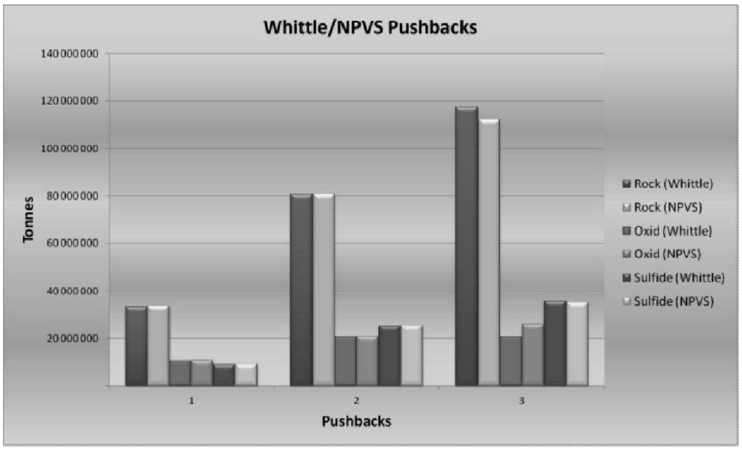
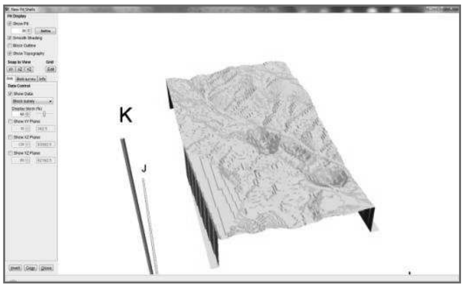


Figure 6 *Comparative review of rock and ore amounts in Whittle and NPV Scheduler pushbacks*

As it can be seen from Table 2 and Figure 6, the only noticeable difference is in total amounts of rock and oxide ore in the third phase, i.e. the final open pit. This can be explained by different approximation procedure of pit slope angle. In Whittle, pit slope angle is approximated across a number of benches, while in the NPVS this is achieved through so-called filters in the X and Y directions. In Whittle, the default value of 8 benches was adopted as a filter to approximate the pit slope angle. In NPVS, thanks to the *Check Slope* option, the accuracy of pit slope angle approximation was checked and the filter value was adopted at 17. From the above mentioned reasons, the final pit in NPVS, although with smaller amounts of total ore, also has sma-ller amounts of overburden and therefore more favorable stripping ratio. Figure 7 presents the open pit contours for the *revenue factor* of 0.98 (98%) in Whittle and NPVS.



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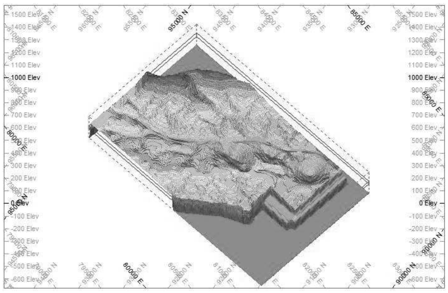


b.

Figure 7 *The final open pit contour (revenue factor 98%): a –contour in Whittle; b –contour in NPVS*

Defining the Mining Schedule

Noticeable difference in the application of these two programs is in the procedure of determining the mining schedule.

Determining the mining schedule in Whittle implies the mining and ore processing limit. In this case, the program defines the schedule by achieving the first limit (either mining or processing). With the *Milawa Balanced* option, it is possible to balance the amount of overburden to be mined per years and, thus determine the appropriate mining schedule that will follow the ore processing limit as close as possible while maintaining the constant mining limit. The mining schedule, obtained in Whittle, is shown in Table 3 and Figure 8.

Determining mining schedule in NPVS allows for the "primary" limit (target) for ore processing and "secondary" limit (tracking), i.e. maintaining the total amount of rock mined per years, to define the mining schedule that follows the primary limit exactly, but also just closely maintains the total rock. The program tries to find the ideal scenario and when unable to find it, it begins to gradually relax the secondary limit until the primary objective is achieved, i.e. the "target" limit. The resulting mining schedule obtained in NPVS-in is shown in Table 4 and Figure 9.

The mining schedules shown in Tables 3 and 4 were obtained in the case of mining the final pit in three stages, i.e. two pushbacks and the final pit, and with limited mining and sulfide ore processing capacities. In both cases, a possible scenario for a mining schedule is achieved, which, if necessary, could be modified changing the selected or introducing the additional pushbacks or changing the limits.

Table 3 *Mining schedule in Whittle*

Year / Period	Rock	Oxide ore	Input to Leach	Sulfide ore	Input to Mill	Total ore	Waste	Stripping ratio	NPV
	t	t	Cu%	t	Cu%	t	t		$
1	17 000 000	3719981	0.24	1111045	0.37	4 831 026	12 168 974	2.52	4 836 966
2	17 000 000	4792264	0.31	2496350	0.45	7 288 615	9 711 385	1.33	40 597 954
3	17 000 000	4068033	0.23	5499785	0.36	9 567 818	7 432 182	0.78	41 462 231
4	17 000 000	6350167	0.21	5283643	0.29	11 633 810	5 366 190	0.46	35 248 060
5	17 000 000	1666371	0.20	5422840	0.28	7 089 211	9 910 789	1.4	8 107 899
6	17 000 000	4368596	0.20	5499436	0.23	9 868 032	7 131 968	0.72	15 347 140
7	10 053 699	1551532	0.18	5500000	0.23	7 051 532	3 002 167	0.43	8 416 079
8	5 406 091	169693	0.19	4907900	0.24	5 077 594	328 498	0.06	9 271 679
Total	**117 459 790**	**26 686 637**		**35 720 999**		**62 407 638**	**55 052 153**	**0.88**	163 288 008

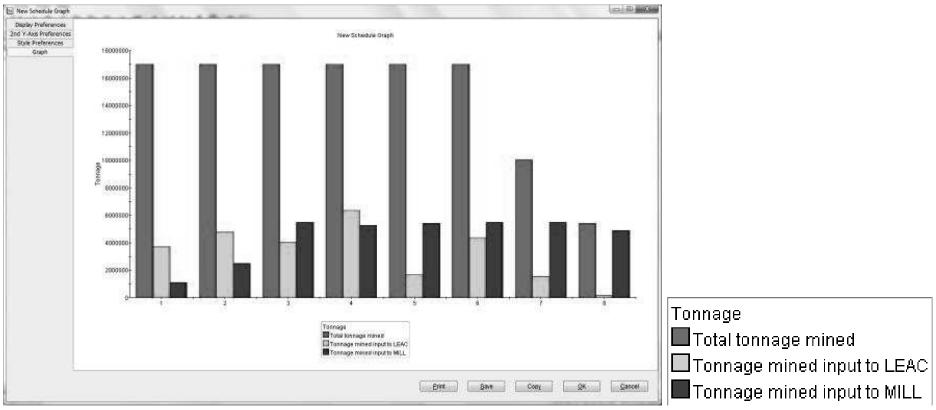


Figure 8 *Graph of mining schedule in Whittle*

Table 4 *Mining schedule in NPVS*

Year / Period	*Rock*	*Oxide ore*	*Input to Leach*	*Sulfide ore*	*Input to Mill*	*Total ore*	*Waste*	*Stripping ratio*	*NPV*
	t	*t*	*Cu%*	*t*	*Cu%*	*t*	*t*		*$*
1	17 003 250	3 020 625	0.25	1 266 300	0.43	4 286 925	12 716 325	2.97	1 375 127
2	16 967 812	4 488 750	0.30	2 503 575	0.47	6 992 325	9 975 487	1.43	37 055 864
3	16 707 262	4 995 000	0.27	5 499 900	0.37	10 494 900	6 212 362	0.59	52 671 121
4	16 500 712	6 572 813	0.22	5 498 550	0.31	12 071 362	4 429 350	0.37	40 169 189
5	13 000 500	1 282 500	0.22	5 501 250	0.29	6 783 750	6 216 750	0.92	13 289 510
6	13 688 662	2 244 375	0.21	5 499 900	0.25	7 744 275	5 944 387	0.77	11 529 474
7	13 568 175	3 155 625	0.19	5 498 550	0.24	8 654 175	4 914 000	0.57	10 330 821
8	4 792 500	160 313	0.17	4 058 438	0.23	4 218 750	573 750	0.14	5 465 836
Total	**112 228 874**	**25 920 000**		**35 326 462**		**61 246 462**	**50 982 412**	**0.83**	171 886 941

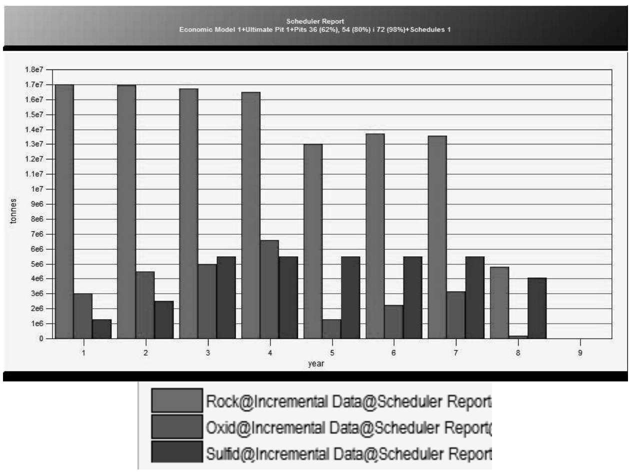
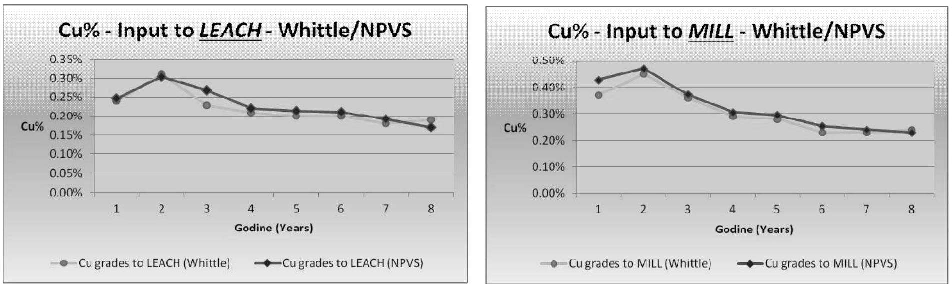


Figure 9 *Graph of mining schedule in NPVS*

The difference in approximation the pit slope angle in this software has led to some differences between the amounts of ore and waste rock which caused the software to "choose" somewhat different pit contours as the most economical ones for selected revenue factors. In addition to the differences in ore amounts for the final pit, this has led to occurrence of difference in the average grades of copper in the mining schedules, as shown in Tables 3 and 4 and Figure 10.



a. *b.*

Figure 10 *Anual ratio of the average copper grade in the input ore to LEACH (a) and MILL (b) processes for mining schedules in Whittle and NPVS*

Table 5 shows the amounts of recovered metals as the final products from Whittle and NPVS final pits. Due to larger amounts of ore and the same technological parameters of ore processing and metal extraction, slightly higher amounts of final products were obtained in the case of the final pit contours obtained in Whittle software.

Table 5 *Amounts of recovered metals from Whittle and NPVS final pit contours*

	Oxide (process LEACH)			Sulfide (process MILL)			Total		
	Cu	Au	Ag	Cu	Au	Ag	Cu	Au	Ag
	t	kg	kg	t	kg	kg	t	kg	kg
Whittle	46 337	907	11 335	81 260	1 442	15 838	**127 597**	**2 349**	**27 173**
NPVS	44 869	875	10 828	80 185	1 419	15 557	**125 054**	**2 294**	**26 385**

CONCLUSION

Due to a different procedure of setting the parameters necessary for optimization, in this case the choice of an appropriate filter or number of benches to approximate the pit slope angle, there was a difference in the ore and rock amounts that led to differences in NPV between these two cases. It might be expected that the pit, although with somewhat smaller amounts of ore, but also with a more favorable stripping ratio, resulted in higher NPV profit. Also, at least in this case, it was shown that an excess of ore in the Whittle final pit has led to reduction in the average grade of copper in the mining schedule in relation to the NPVS final pit, which has further influenced the difference in NPV. Due to relatively small differences, both softwares lead to satisfactory results in terms of the mining schedule. Therefore, one software can be used to verify the results obtained from the other software and, possibly, to improve the mining schedule.

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UPOREDNA OPTIMIZACIJA OTKOPAVANJA LEŽIŠTA KRAKU BUGARESKU CEMENTACIJA POMOĆU SOFTVERA WHITTLE I NPV SCHEDULER

Izvod

Rad ima za cilj da prikaže postupak određivanja konačne konture kopa sa maksimalnim diskontovanim profitom, određivanje faza u otkopavanju kopa (Pushbacks) i dinamike otkopavanja za konačni kop, pomoću softverskih paketa za strateško planiranje površinske eksploatacije - Whittle i NPV Scheduler, na primeru optimizacije ležišta Cerovo Cementacija. U oba slučaja korišćeni su isti tehno - ekonomski parametri i isto početno stanje terena. Cilj ili namera autora nije da ocenjuje ili reklamira pomenute softverske pakete već da prikaže proceduru optimizacije na konkretnom primeru, uz osvrt na osnovne razlike. Upoređenje dobijenih rezultata takođe predstavlja i proveru ispravnosti rezultata optimizacije.

Ključne reči: *optimizacija, optimalna kontura kopa, faze, dinamika otkopavanja, softver, NPV*

UVOD

Ležište „Cerovo“ nalazi se u rudnom polju Mali Krivelj – Cerovo, petnaestak kilometara severozapadno od Bora.

Sl. 1. *Cerovo – Cementacija 1*

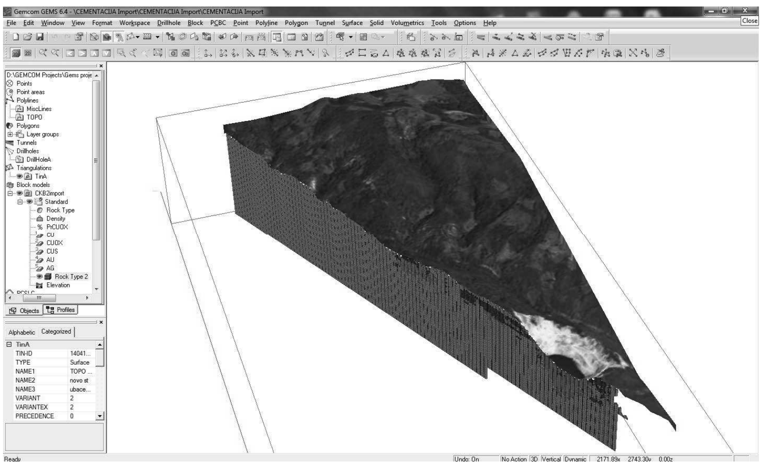
* *Institut za rudarstvo i metalurgiju Bor*

Na lokalitetu se nalaze rudna tela „Cerovo – Cementacija 1“, „Cerovo – Cementacija 2“, „Cerovo – Cementacija 3“, „Cerovo – Cementacija 4“, ležište „Drenova“ i „Cerovo – primarno“.

Godine 1990. započeti su radovi na otvaranju kopa Cementacija 1, i prestriping period je bio diktiran dužinom trajanja investicionih radova na objektima flotacije i hidrotransporta pulpe do flotacije u Boru, tj. infrastrukturnim objektima rudnika. Taj period je trajao nešto više od 2 godine. Ležište Kraku Bugaresku Cementacija, je cementaciona zona sekundarnog obogaćenja i glavni oksidni minerali su azurit, malahit, čak i samorodni bakar kao pojava. Od sulfidnih minerala glavni nosilac bakronosnog orudnjenja je halkopirit praćen bornitom, dok je pirit najzastupljeniji mineral u orudnjenju. U manjoj meri zastupljeni su halkozin, kovelin i azurit. [9]

Osnovni problem kod ležišta Kraku Bugaresku Cementacja je u znatnom učešću oskidnih minerala u ukupnoj rudi što smanjuje iskorišćenje bakra u flotacijskom procesu pripreme koncentrata, time i konačne efekte valorizacije ukupne proizvodnje. U procesu flotacijske koncentracije veće iskorišćenje bakra se postiže u preradi sulfidne rude nego što je to slučaj sa preradom oksidne rude. [7] Danas se u svetu za dobijanje bakra iz oksidne rude uspešno primenjuju procesi hidrometalurške prerade tehnologijom luženja i SX/EW (Solvent extraction and electrowinning, tj. solventna ekstrakcija i elektrohemijsko izdvajanje), što je pogotovu aktuelno kod formiranih gomila sa manjim sadržajem bakra poput jalovišta ili posebno formiranih "haldi" oksidne rude. [4, 5] Tehnologija luženje - SX/EW podrazumeva iskorišćenje bakra sa gomile pomoću rastvora sumporne kiseline koja se nakon perkolacije kroz gomilu prikuplja, prečišćava i u procesu solventne ekstrakcije bakarni joni prevode iz vodene u organsku fazu. Vodena faza se vraća u proces luženja dok organska faza odlazi u proces reekstrakcije, gde bakar prelazi u bakarsulfatni rastvor, iz koga se dalje dobija procesom elektrolize. Ovako dobijeni katodni bakar je čistoće 99,99% Cu. [5]

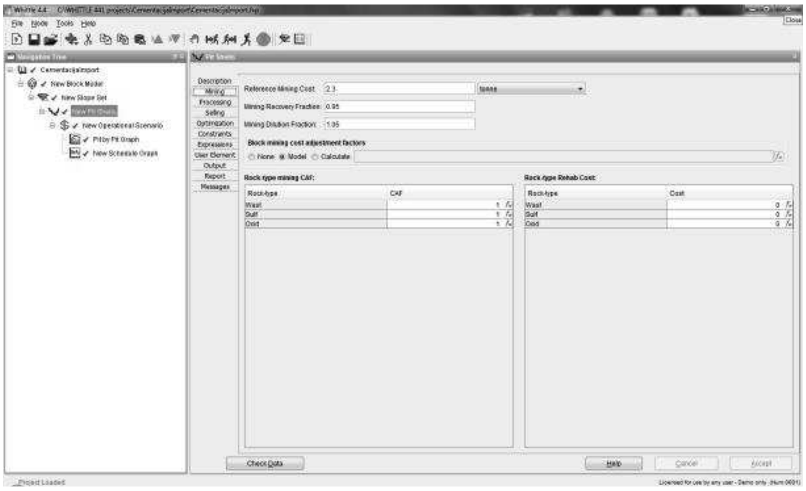
Da bi se ispitala mogućnost i efekti primene dve metode prerade rude i na ležištu Kraku Bugaresku Cementacija, bilo je potrebno prethodno preraditi blok model u softveru *GEOVIA Gems* da bi se jasno razdvojile zone sulfidne i oksidne rude i omogućila optimizacija za slučaj dve metode prerade, tj. flotiranje sulfidne (*Mill*) i luženje oksidne rude (*Leach*). Samim tim, u ležištu Cerovo Cementacija je izdvojena zona sulfidne rude sa učešćem oksidnih minerala do 10% i zona oksidne rude sa učešćem oksidnih minerala većim od 10%.



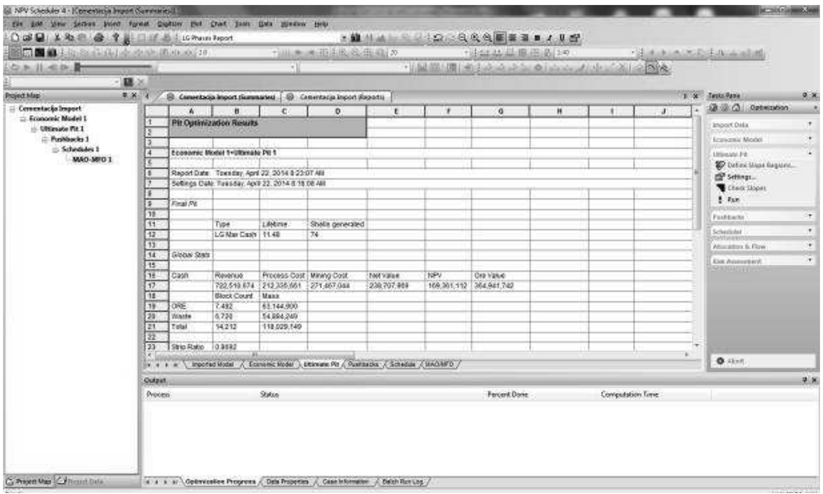
Sl. 2. *Prikaz blok modela u GEMSu sa oksidnom (crvena) i sulfidnom (zelena) rudom*

Opis softverskih paketa Whittle i NPV Scheduler

Softverski paketi *Whittle* kompanije GEOVIA i *NPV Scheduler* (NPVS) kompanije DATAMINE se koriste za strateško planiranje u površinskoj eksploataciji, kod određivanja optimalne konture površinskog kopa, izbora adekvatnih zahvata (Faze-Pushbacks) i definisanja dinamike otkopavanja u cilju ostvarivanja optimalnih tehno-ekonomskih parametara i boljih finansijskih rezulatata (slika 3).



a.



b.

Sl. 3. *"Prozori" programa Whittle (a) i NPV Scheduler (b)*

Ulazni podaci za određivanje konačne konture kopa i dinamike otkopavanja

Scenario koji je razmatran u ovom radu podrazumeva limitiranu preradu sulfidne rude u flotaciji (*Mill*) od maksimalno 2.5 mt/god u prve dve godine, sa proširenjem flotacijskog kapaciteta prerade na 5.5 mt/god u narednim godinama. Prerada oksidne rude luženjem (*Leach*) ne bi bila limitirana po godinama, već bi se prilagođavala količinama oksidne rude koje se moraju otkopati u sklopu ukupnih iskopina, kako bi se omogućilo otkopavanje količina sulfidne rude za planirani kapacitet flotacijske prerade (2.5 mil.t, odnosno 5.5 mil.t). U tabeli 1. prikazani su ulazni ekonomsko-tehnološki parametri koji su poslužili kao osnova u procesu optimizacije u oba softvera. [1]

Tabela 1. *Ulazni parametri za optimizaciju u softverima Whittle i NPVS*

Ekonomski granični sadržaj bakra u rudi	**0.15% Cu**
Cene metala	
bakar	5 000 $/t
zlato	30 000 $/kg
srebro	400 $/t
Troškovi otkopavanja	2.3 $/t
Troškovi pripreme mineralne sirovine	
flotiranje (Mill)	4 $/t
luženje (Leach)	1 $/t
Dodatni troškovi dobijanja bakra	
kod flotiranja	450 $/t
kod luženja	100 $/t
Ostali troškovi dobijanja metala	
za zlato	150 $/kg
za srebro	15 $/kg
Iskorišćenje na otkopavanju	95%
Osiromašenje na otkopavanju	5%
Iskorišćenje u procesu dobijanja metala	
bakar (flotiranje i metalurška prerada)	78.8%
bakar (luženje i SX/EW)	75%
zlato (u oba procesa)	50%
srebro (u oba procesa)	40%
Diskontna stopa	10%
Ugao boka kopa	37°

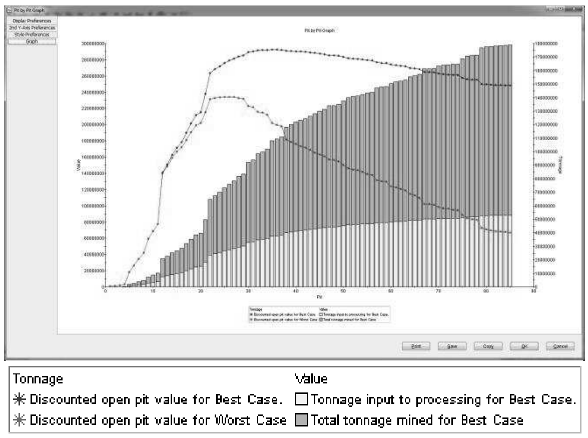
Za početno stanje uzeta je situacija terena na dan 01. 04. 2014. godine.

Izbor optimalne konture površinskog kopa i određivanje faza

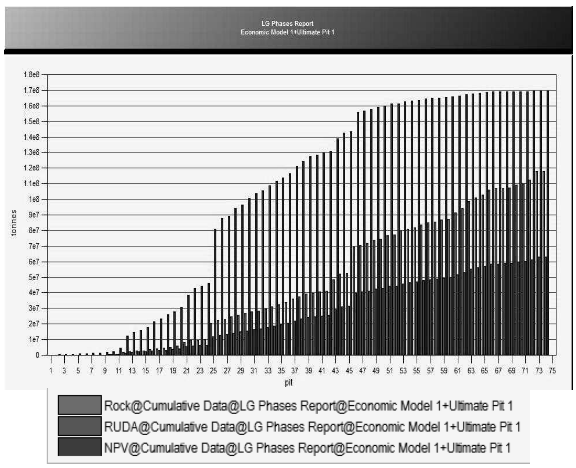
Oba softvera su bazirana na Lerch Grossman algoritmu optimizacije. Suština ovog algoritma je da, za zadate tehno-ekonomske parametre, formira najekonomičniju konturu kopa krećući se od najnižeg ekonomski prihvatljivog bloka do najvišeg bloka u modelu, pri tome poštujući definesane uglove kosina kopa. Zbog određivanja najekonomičnijeg pravca razvoja kopa, i određivanje adekvatnih faza u planiranju otkopavanja, softveri imaju mogućnost skaliranja prodajne cene metala pomoću koeficijenta (*revenue factor*) čime se dobija serija kopova (*nested pits*) od najmanjeg (za najnižu prodajnu cenu) do najvećeg (zavisno od uvećanja prodajne cene). [2, 3, 4] Kop sa koeficijentom 1.0 (100% revenue factor) predstavlja kop sa neskaliranom prodajnom metala. Za izbor optimalne konture kopa, u ovom slučaju konture kopa sa maksimalnim diskontovanim profitom ili NPV (*net present value*) potrebno je odrediti diskontnu stopu i definisati godišnju proizvodnju rude.

U softveru Whittle, NPV vrednosti se procenjuju na bazi tzv. *Best Case* i *Worst Case* scenaria. *Best Case* je scenario u kome se do konačne konture kopa stiže preko otkopavanja etaža svih određenih kontura do konačne u vidu faza (*Push-backs*). Worst Case predstavlja scenario u kome se do konačne konture kopa stiže otkopavanjem svih etaža u konačnoj konturi, tj. bez faza. Oba slučaja su, kako neekonomična (Worst Case) tako i tehnološki neostvariva u praksi (Best Case), pa je potrebno tražiti adekvatne faze i, za njih, optimalnu konačnu konturu kopa. U Whittlu se ovo označava kao *Specified Case*. [8]

Na slikama 4 i 5 prikazani su dijagrami procenjenih vrednosti za NPV u programima Whittle i NPVS



Sl. 4. *Procena NPV vrednosti "Pit by Pit graph" u softveru Whittle*

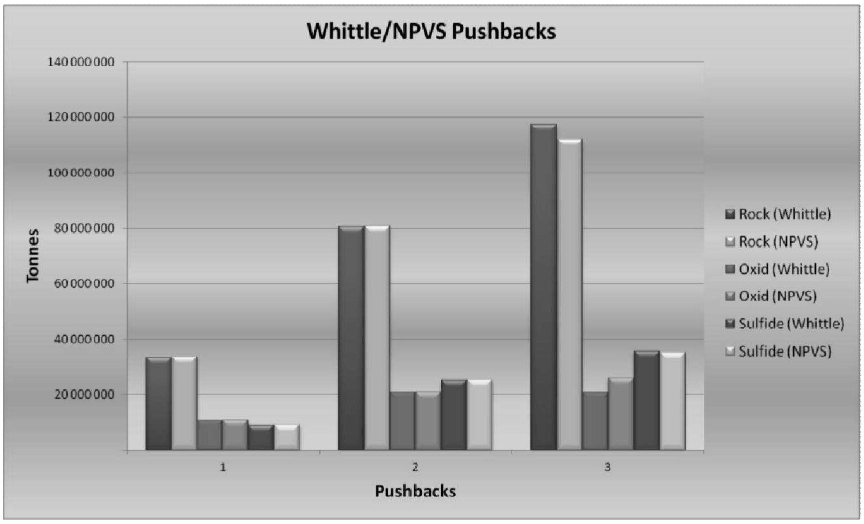


Sl. 5. *Procena NPV vrednosti za kopove u softveru NPVS*

Kako bi se omogućilo upoređivanje rezultata optimizacije bilo je potrebno odabrati približno iste konture kopova za faze i za konačnu konturu. Budući da je "Pit by Pit" optimizacija za Best Case kao razultat dala najbolju vrednost NPVa za kop sa revenue faktorom 0.98 (98%), kop sa istim revenue faktorom je izabran kao konačni kop i u NPVSu. Kao faze, u oba softvera, izabrane su konture kopova za revenue faktore 62% (prva faza) i 80% (druga faza). U tabeli 2 i na slici 6 prikazane su količine iskopina i rude u izabranim fazama.

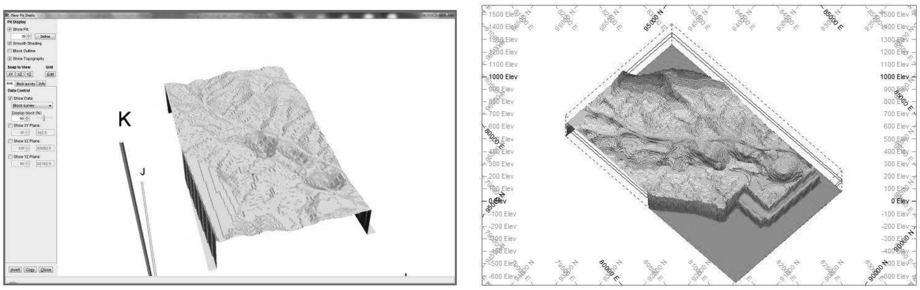
Tabela 2. *Količine rude i iskopina u fazama i konačnoj konturi u softverima Whittle i NPVS*

Softver	Faza (Push-back)	Revenue faktor	Iskopine	Oksidna ruda	Sulfidna ruda	RUDA ukupno	Koef. rask-rivke
Whittle	1	62%	33 426 102	10 782 047	9 123 921	19 905 968	0.68
NPVS			33 839 437	10 968 750	9 396 337	20 365 087	0.66
Whittle	2	80%	80 698 683	20 605 505	25 339 518	45 945 023	0.76
NPVS			80 999 662	20 823 750	25 602 075	46 425 825	0.74
Whittle	3	98%	117 459 790	26 686 638	35 720 999	62 407 636	0.88
NPVS			112 228 874	25 920 000	35 326 462	61 246 462	0.83



Sl. 6. *Uporedni prikaz količina rude i iskopina u fazama u softverima Whittle i NPV Scheduler*

Kako se to može videti iz tabele 2, i sa slike 6, jedina primetna razlika je u ukupnim količinama iskopina i oksidne rude za treću fazu, odnosno konačni kop. Ovo se može objasniti različitom procedurom aproksimacije ugla kosine boka kopa. U Whittlu se ugao aproksimira preko broja etaža, dok se u NPVSu to radi preko tzv. filtera po X i Y pravcima. U Whittlu je usvojena difoltna vrednost od 8 etaža za aproksimaciju ugla kosine kopa. U NPVSu je, zahvaljujući opciji *Slope Chek*, izvršena provera tačnosti aproksimacije ugla kosine kopa i usvojena vrednost filtera 17. Iz pomenutog razloga konačna kontura u NPVSu, iako sa manjim količinama rude, ima i manje količine jalovine a samim tim i povoljniji koeficijent raskrivke. Na slici 7 prikazane su konture za *revenue factor* 0.98 (98%) u softverima Whittle i NPVS.



a. *b.*

Sl. 7. *Konačna kontura kopa (Revenue factor 98%): a – kontura iz Whittla; b – kontura iz NPVSa*

Definisanje dinamike eksploatacije

Primetna razlika u primeni ova dva programa je kod procedure određivanja dinamike otkopavanja.

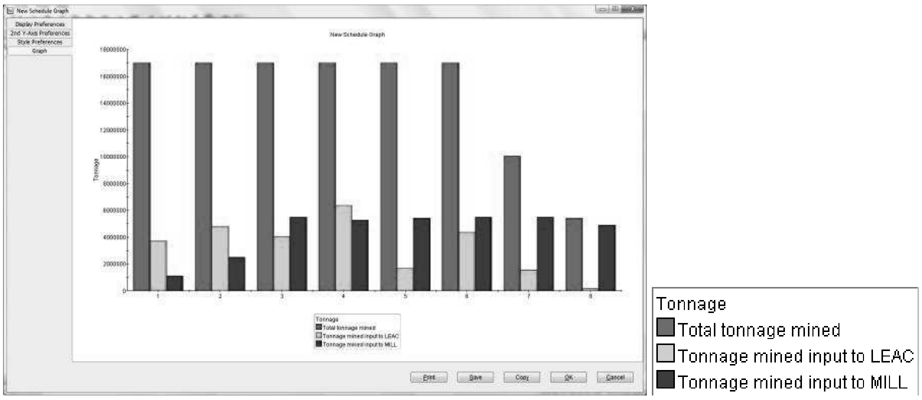
Određivanje dinamike otkopavanja u Whittle-u podrazumeva uvođenje limita na otkopavanju i u preradi rude. U ovom slučaju program dolazi do dinamike pri dostizanju prvog limita (bilo na otkopavanju ili preradi). Uz opciju *Milawa balanced* moguće je uravnotežiti količine jalovine koje se otkopavaju po godinama i time odrediti adekvatnu dinamiku otkopavanja koja najpribližnije moguće prati limit na preradi rude uz konstantan limit na otkopavanju. Dinamika dobijena u Whittlu je prikazana u tabeli 3 i na slici 8.

Određivanje dinamike otkopavanja u NPVS-u omogućuje da se uz "primarni" limit (target) na preradi rude i "sekundarni" limit (tracking), odnosno praćenje (balansiranje) ukupnih količina iskopina po godinama, odredi dinamika koja tačno prati glavni limit, ali zato samo približno prati iskopine. Program pokušava da nađe idealan scenario i u nemogućnosti da ga pronađe počinje postupno da opušta sekundarni limit (relaxing) dok ne ostvari primarni cilj, tj. "target" limit. Dobijena dinamika otkopavanja u NPVS-u je prikazana u tabeli 4 i na slici 9.

Dinamike prikazane u tabelama 3 i 4 je dobijene su za slučaj otkopavanja kopa u tri zahvata, tj. dve faze i konačni kop, i sa limitiranim kapacitetima na otkopavanju iskopina i na preradi sulfidne rude. U oba slučaja se dolazi do jedne od mogućih varijanti za dinamiku otkopavanja koja se, po potrebi, može izmeniti promenom izabranih ili uvođenjem dodatnih faza (Pushbacks) ili sa izmenom limita.

Tabela 3. *Dinamika otkopavanja u softveru Whittle*

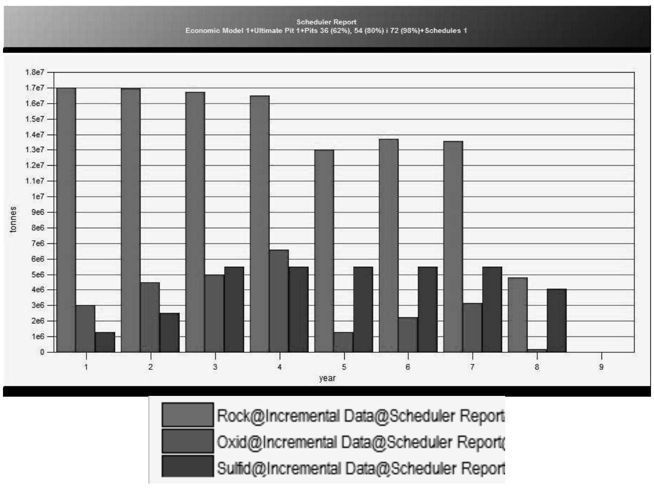
God. / Period	*Iskopine*	*Oksidna ruda*	*Input to Leach*	*Sulfidna ruda*	*Input to Mill*	*RUDA (ukupno)*	*JALOVINA*	*Koef. raskri-vke*	*NPV*
	t	*t*	*Cu%*	*t*	*Cu%*	*t*	*t*		*$*
1	17 000 000	3 719 981	0.24	1 111 045	0.37	4 831 026	12 168 974	2.52	4 836 966
2	17 000 000	4 792 264	0.31	2 496 350	0.45	7 288 615	9 711 385	1.33	40 597 954
3	17 000 000	4 068 033	0.23	5 499 785	0.36	9 567 818	7 432 182	0.78	41 462 231
4	17 000 000	6 350 167	0.21	5 283 643	0.29	11 633 810	5 366 190	0.46	35 248 060
5	17 000 000	1 666 371	0.20	5 422 840	0.28	7 089 211	9 910 789	1.4	8 107 899
6	17 000 000	4 368 596	0.20	5 499 436	0.23	9 868 032	7 131 968	0.72	15 347 140
7	10 053 699	1 551 532	0.18	5 500 000	0.23	7 051 532	3 002 167	0.43	8 416 079
8	5 406 091	169 693	0.19	4 907 900	0.24	5 077 594	328 498	0.06	9 271 679
Total	**117 459 790**	**26 686 637**		**35 720 999**		**62 407 638**	**55 052 153**	**0.88**	**163 288 008**



Sl. 8. *Grafički prikaz dinamike otkopavanja u softveru Whittle*

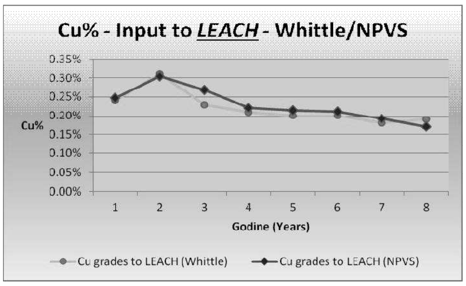
Tabela 4. *Dinamika otkopavanja u softveru NPVS*

God. / Period	*Iskopine*	*Oksidna ruda*	*Input to Leach*	*Sulfidna ruda*	*Input to Mill*	*RUDA (ukupno)*	*JALOVINA*	*Koef. raskrivke*	*NPV*
	t	*t*	*Cu%*	*t*	*Cu%*	*t*	*t*		*$*
1	17 003 250	3 020 625	0.25	1 266 300	0.43	4 286 925	12 716 325	2.97	1 375 127
2	16 967 812	4 488 750	0.30	2 503 575	0.47	6 992 325	9 975 487	1.43	37 055 864
3	16 707 262	4 995 000	0.27	5 499 900	0.37	10 494 900	6 212 362	0.59	52 671 121
4	16 500 712	6 572 813	0.22	5 498 550	0.31	12 071 362	4 429 350	0.37	40 169 189
5	13 000 500	1 282 500	0.22	5 501 250	0.29	6 783 750	6 216 750	0.92	13 289 510
6	13 688 662	2 244 375	0.21	5 499 900	0.25	7 744 275	5 944 387	0.77	11 529 474
7	13 568 175	3 155 625	0.19	5 498 550	0.24	8 654 175	4 914 000	0.57	10 330 821
8	4 792 500	160 313	0.17	4 058 438	0.23	4 218 750	573 750	0.14	5 465 836
Total	**112 228 874**	**25 920 000**		**35 326 462**		**61 246 462**	**50 982 412**	**0.83**	171 886 941



Sl. 9. *Grafički prikaz dinamike otkopavanja u softveru NPVS*

Razlika u aproksimaciji ugla u primenjenim softverima dovela je do određene razlike između količina rude i jalovine što je izazvalo da softveri "biraju" nešto drugačije najekonomičnije konture za odabrane *revenue* faktore. Ovo je dovelo do toga se pored razlike u količinama rude u konačnim konturama, javi i razlika u srednjem sadržaju bakra u dinamici otkopavanja, što je prikazano u tabelama 3 i 4 i na slici 10.



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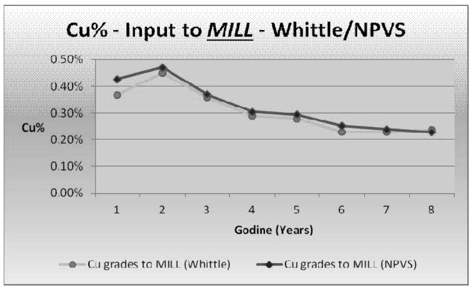

b.

Sl. 10. *Odnos srednjeg sadržaja bakra u ulaznoj rudi u procese LEACH (a) i MILL (b) po godinama dinamike u softverima Whittle i NPVS*

U tabeli 5 prikazane su količine dobijenog (recovered) metala kao finalnog proizvoda u konačnim konturama Whittla i NPVSa. Obzirom na veće količine rude i na iste tehnološke parametre prerade rude i dobijanja metala, dobijene su nešto veće količine finalnog proizvoda u slučaju konture dobijene u softveru Whittle.

Tabela 5. *Količine dobijenog metala u konturama Whittle i NPVS*

	Oxid (proces LEACH)			Sulfide (proces MILL)			Total		
	Cu	Au	Ag	Cu	Au	Ag	Cu	Au	Ag
	t	kg	kg	t	kg	kg	t	kg	kg
Whittle	46.337	907	11.335	81.260	1.442	15.838	**127.597**	**2.349**	**27.173**
NPVS	44.869	875	10.828	80.185	1.419	15.557	**125.054**	**2.294**	**26.385**

ZAKLJUČAK

Zbog različite procedure podešavanja parametara neophodnih za optimizaciju, u ovom slučaju izbor odgovarajućeg filtera ili broja etaža za aproksimaciju ugla kosine boka kopa, javila se određena razlika u količinama rude i iskopina koja je dovela do razlike u NPVu između ova dva slučaja. Ono što se moglo očekivati je da je kop sa, iako nešto manjim količinama rude, ali i povoljnijim koeficijentom raskrivke (Stripping Ratio) rezultovao sa većim NPV profitom. Takođe, barem u ovom slučaju, se pokazalo da je višak rude u konturi iz Whittla doveo do smanjenja srednjeg sadržaja bakra u dinamici otkopavanja u odnosu na konturu iz softvera NPVS, što je dodatno uticalo na razliku u NPVu. Obzirom na relativno male razlike, primenom oba softvera dolazi se do zadovoljavajućih rezultata u pogledu dinamike otkopavanja. Samim tim jedan softver može da posluži za proveru dobijenih rezultata iz drugog softvera i, eventualno, za poboboljšanje dinamike otkopavanja.

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