COMPARATIVE ANALYSIS OF CONCENTRATE GRADING AND REVENUE IN POLISH COPPER MINES

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Abstract: The paper presents results of a comparative analysis of revenues of the Lubin, Polkowice-Sieroszowice and Rudna mines (KGHM Polska Miedź S.A). The criterion used for comparison is the Net Smelter Revenue formula (NSR) based on heuristic model of functional relationships between the concentration of metals in ore and copper concentrates, the operational efficiency, and the prices of concentrates and metals in the global markets. The calculations have been performed for the data coming from the mining practice. The NSR calculations show that the Lubin mine is nearly 2 times less profitable than the Rudna mine, yet if we compare Cu+Ag+Au grading to the best (Rudna) mine, that difference is only 1.6-fold. However, it must be noted here that the Rudna and Polkowice mines are much deeper than the Lubin mine, therefore the total profit from the mine are not as different as the NSR value.

Keywords: NSR, copper grading, revenue, optimisation

INTRODUCTION

The Net Smelter Revenue (NSR) method is commonly used to analyse the economic impact of the concentration grade of enriched minerals on mine revenue in the light of processing costs and metal market prices (Wills 2006, Strzelska-Smakowska, Paulo 1995). The method involves calculating profits achievable from the sale of the main product of the mine, i.e. the Cu concentrate, after deduction of the TC/RCs charges. This is an important piece of information for the mine, which may be a criterion for optimising extraction and beneficiation of ore according to the quality of the concentrates.

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This paper presents a comparative analysis of the revenue of three Polish mines operating in the area of Legnica-Głogów Copper Belt (LGOM) copper deposits (Fig. 1) which are characterised by diverse ore and concentrate grades of main and accessory metals: copper, silver and gold. At the same time mines and smelters are considered competitive entities, as it is commonly assumed in such studies. It is interesting to know what the optimum grading for concentrates is and how much the mines differ from one other in terms of expected revenues in the light of actual pricing of the metals in question. This is the subject which is discussed in this paper.
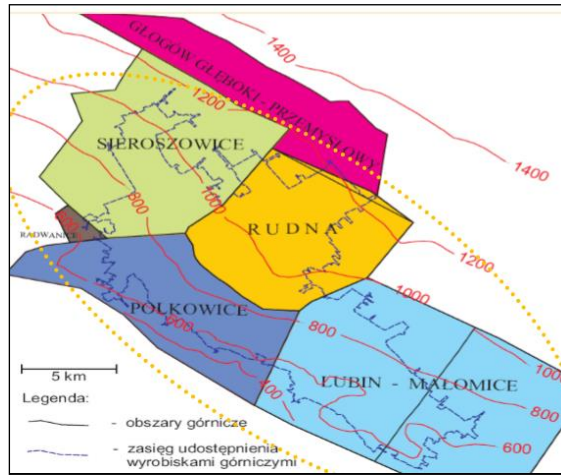

Fig. 1. Current and prospective copper ore deposits and mines in Poland (Bachowski, 2013)

NSR FORMULA

The NSR formula determines how much income can be obtained from the sale of the main product at a given stage of production taking into account its current quality/price and the processing costs at subsequent operations to the final level of quality acceptable in the open market. It is commonly known under the following expression:

$$NSR = \left[\sum_i (\beta_i \, \delta_i \, p_i) - (MC + DC) - P + B \right] \gamma_1, \qquad (1)$$

$$MC = \sum_i (\beta_i \, \delta_i \, RC_i) + TC \qquad (2)$$

where: *NSR* – net smelter revenue measured in $ per 1 Mg of ore,

β_i – share of *i*-component (metal) in the main product (concentrate),

δ_I – payable part of metal in the concentrate,

p_i – price of the *i*-component in the open market,

MC – metallurgical charge in $ per 1 Mg (Dry Meter Tone) of concentrate,

TC – concentrate treatment (smelting) charge,

RC_i – refining charge of *i*-metal contained in the concentrate,

DC – delivery ex-recipient charge,

P – penalties for the presence of harmful components (according to contractual terms),

B – bonuses for the presence of desirable components (according to contractual terms),

$\gamma_1 = 1 - \gamma_2$ – yield of the concentrate in the feed (ore),

where γ_2 – yield of tailings, and $\gamma_0 = 1$ – amount (unit) of feed (ore).

Formula (1) may additionally introduce costs of chemical analyses of quality testing and other contractual limitations.

YIELD OF CONCENTRATE

In optimisation analyses the basic problem is to identify the relationship between the efficiency of beneficiation operations (recovery, ε) and the concentration of the enriched minerals. In the case of complex ores the producer may be interested in any of the components (metal, mineral), but not every one is the subject of beneficiation even though it would be recovered in subsequent smelting operations. This is precisely the case that is discussed in this work using the example of copper production technology at the Polish mines owned by KGHM Polska Miedź S.A.

On the basis of the qualitative and quantitative calculations of the yield of the main component (*Cu*) depending on the efficiency of the beneficiation operations, we use a relationship which is well-known in processing and which is derived from the mass balance of the processing operation (Drzymala 2007, Wills 2006):

$$\varepsilon = \frac{\beta}{\alpha} \cdot \gamma_1, \tag{3}$$

where α is the metal (Cu) content in the feed (ore) or concentrate and β is the metal (Cu) content in the concentrate.
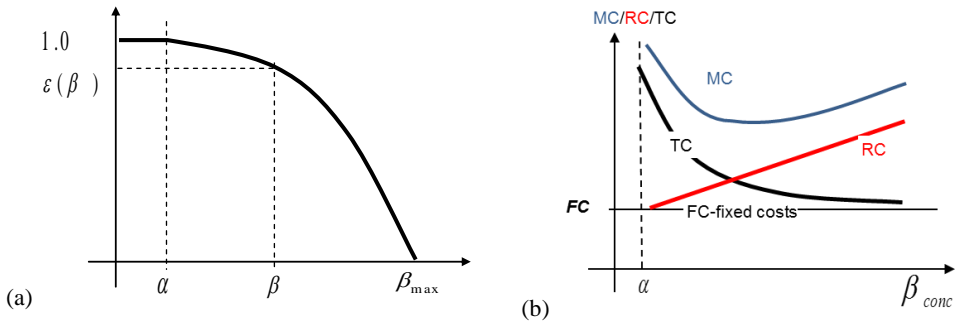
Fig. 2. Models/hypotheses: (a) efficiency of industrial beneficiation of copper minerals,
(b) cost of metallurgical treatment depending on Cu content in the concentrate

Equation (2) relationship used for further calculations will be the empirical hypothesis of a relationship between Cu recovery and the desired concentration of that metal in the concentrate, which we will express as follows:

$$\varepsilon = 1 - \left[\frac{\beta - \alpha}{\beta_{max} - \alpha} \right]^{A}, \tag{4}$$

where: $A = f(\pi, z, t)$ is a function of current values of the operation parameters π, environmental variables z and duration of the beneficiation operation t,

β_{max} – limit of the metal (Cu) content in processed minerals,

α, β – as in (3); γ_1 – relative concentrate yield.

Thus, from (4) we can determine recovery for a given quality of the concentrate, and then from (3) calculate the actual concentrate yield, or after appropriate transformations we arrive at the following formula for calculating yield of the main component in concentrates:

$$\gamma_1 = \frac{\alpha}{\beta} \cdot \left[1 - \left(\frac{\beta - \alpha}{\beta_{max} - \alpha} \right)^{A} \right], \quad \alpha \leq \beta \leq \beta_{max}. \tag{5}$$

Parameter A in formula (4)–(5) may be determined experimentally by using a series of observations ε and β or by using the hypothesis that it will progress as in Fig. 2a. Then, by knowing the current value of ε and β, parameter A can be adjusted iteratively for compliance of the calculated result with the measured one.

PAYMENT AND DEDUCTIONS

The payable part of a metal in formula (1) is always less than 100% of its amount in the concentrate[**]. Typical deduction formulas are as follows (Soderstrom 2008):

$$\delta_{Cu} = \frac{\beta_{Cu} - 1\%}{\beta_{Cu}}, \ \beta_{Cu} - \% \text{ in DMT (dry metric tonne of concentrate)}, \quad (6)$$

$$\delta_{Ag} = \frac{\beta_{Ag} - 30}{\beta_{Ag}}, \ \beta_{Ag} - \text{g/DMT (grams/dry metric tonne of concentrate)}, \quad (7)$$

$$\delta_{Au} = \frac{\beta_{Au} - 1}{\beta_{Au}}, \ \beta_{Au} - \text{g/DMT (grams/dry metric tonne of concentrate)}. \quad (8)$$

Metal prices on global market can vary substantially depending on the condition of global economy. Presently, we observe a bear market in the London Metal Exchange, as seen in the chart in Fig. 3. This is a hard time for miners, also because of smelters raise the TC/RCs charges.
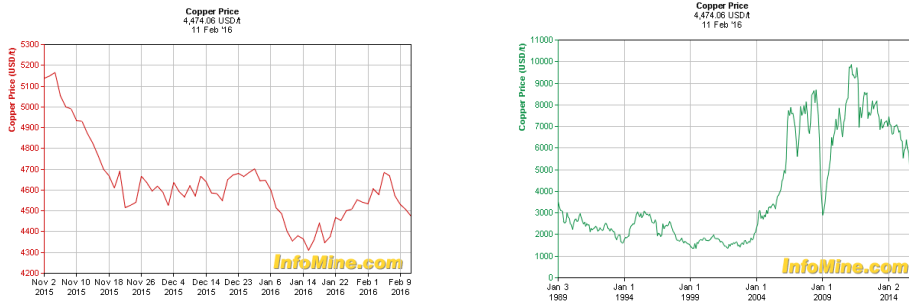

Fig 3. Copper price (InfoMine 2016)

Treatment Charge (TC) in long term prognoses for 2016 amounts to 97 \$/DMT and Refining Charge (RCs) amounts to 215 \$/DMT of payable metal (Plats McGraw Hill Finance, 2016). These data are valid for standard grading of 24% concentrate, therefore we need to recalculate the TC/RCs according to their actual values. For these

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[**] www.InfoMine.com (2016) - Copper: some smelters will pay for as much as 40% of contained copper, while some other smelters it is considered deleterious. Gold: deduct 0.03 to 0.07 troy ounce (troz) per dry tonne and pay for 95% of the remaining gold at market value. Silver: deduct 0.5 to 2.0 troy ounce per dry tonne and pay for 95% of the remaining silver at market value

reasons we will use a hypothetical model as presented in Fig. 2b, which can be expressed by the following general formula:

$$\frac{RC}{RC^*}; \frac{TC}{TC^*} := C\left(\frac{\beta}{\beta^*}\right)^{-k} + D ,$$
(9)

where: β, β^*– actual and observed grade of concentrate, respectively,

$C = VC^*/TC^*$ – constant, representing relative variable treatment (or refining) costs,

$D = FC/TC^*$ – constant, representing relative fixed treatment (or refining) costs,

TC^*, RC^* – observed treatment or refining costs

k – curve form factor determined experimentally by iteration in a way similar to how it was described in the case of formulas (4-5).

Note: If $\beta = \beta^*$ then $TC = TC^*$ (or $RC = RC^*$) because from formula (5) we get $C + D = 1$. In both cases $C = 2/3$ and $D = 1/3$ were assumed for calculation, but $k = 2$ for TC_{Cu} and $k = 1$ for RCs.

The metallurgical costs, however, depend on the presence of components harmful to the refining technology or the environment. Therefore, formula (1) introduces optionally the penalty component (P) for the presence of undesirable components in the concentrate. For the purpose of the present calculations, these components have been ignored.

For precious metals RCs is 0.6 \$/troz or 0.01926 \$/DMT of payable silver, and 8 \$/troz or 0.25680 \$/DMT of payable gold.

COMPARATIVE REVENUE PERFORMANCE

We will now perform calculations to optimise the quality (copper content) of the concentrate and/or accessory metals using the previously derived relationships. We will use the industrial data of metals content in the operations streams throughout the copper production cycle. The input data for calculations are presented in Table 1.

The RCs values are following β_i actual grade of i-metal by formula (6)–(8). However, we also need to know how the grade of silver and gold in Cu concentrate change following grade of Cu in ore and concentrate. There are two ways to know it: use CF values as constant or use the Cu/Cu* relationship in the ore and concentrate. Here, we are going to use the second approach.

The content of main and accessory metals will be estimated in a simplified manner from the relationship:

$$\frac{\beta_i}{\beta_i^*} \approx b_{Cu} = \frac{\beta_{Cu}}{\beta_{Cu}^*} .$$ (10)

Thus, $\beta_i \approx b_{Cu} \cdot \beta_i^*$ is a current grade β_i of *i*-component proportionally to the relative change of copper grade of the concentrate.

The same approach is applied to calculate the *i*-component of ore for the purposes of calculation of the current ore value, i.g. $\alpha_i \approx a_{Cu} \cdot \alpha_i^*$.

Treating the data in Table 1 as empirical (α_i^*, β_i^*), we will calculate the relative yield of the concentrate γ_1. Taking the empirical α_{Cu}^*, β_{Cu}^*, ε_{Cu}^* and assuming the metal content in the mineral to be $\beta_{max}^* = 65\%$, and also applying the iterative method, we will assess the parameters of the function (3) that crosses the empirical point as shown in Fig. 4. Knowing the relationship as described above and comparing it to (4) we will calculate the yields $\gamma_{Cu} = f(a_{Cu} \cdot \beta_{Cu})$ for the current values of copper grading in the concentrate and in the ore.

Table 1. Data adopted for calculations. Component grades
of the main product of operations. LME prices as of 9 Feb 2016

ConcFactor	Metal	Mine	Concentrator	Market 9 Feb 2016	
CF		Cu grade of product		(lb = 0.4536kg; troz = 31.1035g)	
		LUBIN			
18.9	Cu*	0.90%	17.00%	2.07	$/lb
13.4	Ag*	0.00692%	0.093%	15.4	$/troz
8.2	Au*	0.000001%	0.000010%	1192.9	$/troz
		POLKOWICE-SIEROSZOWICE			
15.0	Cu*	1.67%	25.76%	2.07	$/lb
12.8	Ag*	0.00350%	0.047%	15.4	$/troz
13.4	Au*	0.000004%	0.000050%	1192.9	$/troz
		RUDNA			
15.2	Cu*	1.78%	25.00%	2.07	$/lb
13.1	Ag*	0.004925%	0.065%	15.4	$/troz
10.5	Au*	0.000001%	0.000010%	1192.9	$/troz

Once we have the γ_1/TC/RC – β dependence models (Fig. 2) and the estimated parameters, we can simulate revenue limits from production of concentrates for the mine. Figures 5 – 6 show the results of such calculations for a practical scope of metal grading in ore and concentrate. The NSR values are presented with reference to the values of metals in the concentrate in two variants: (a) without accessory metals, and

(b) taking those metals into account in the revenue calculation. Penalties (*P*) for undesirable components and bonuses (*B*) for desirable ones are ignored in these examples.
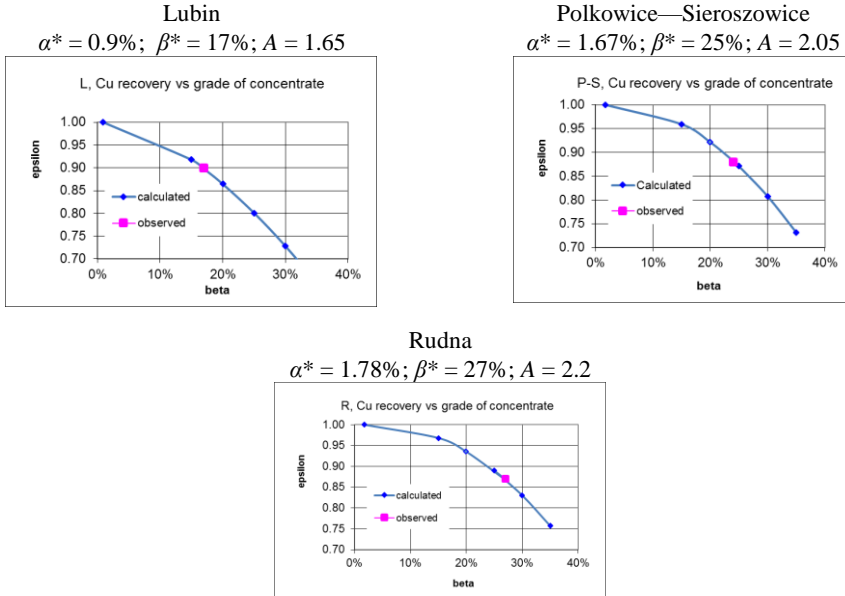

Fig. 4 Approximation of the recovery function $\varepsilon Cu = f(\beta Cu)$ for the parameters.
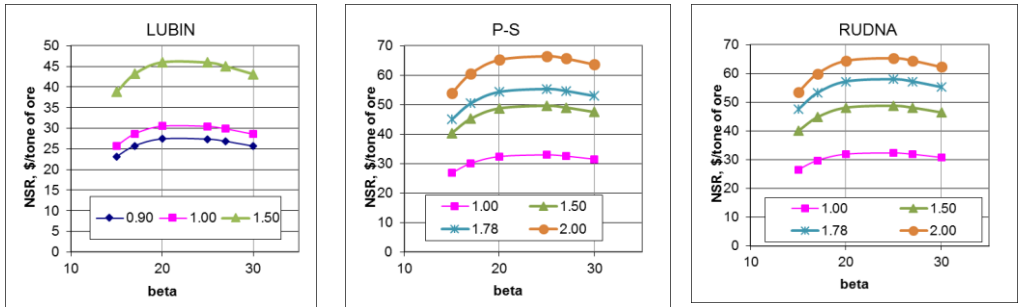The square marks the empirical (*) values

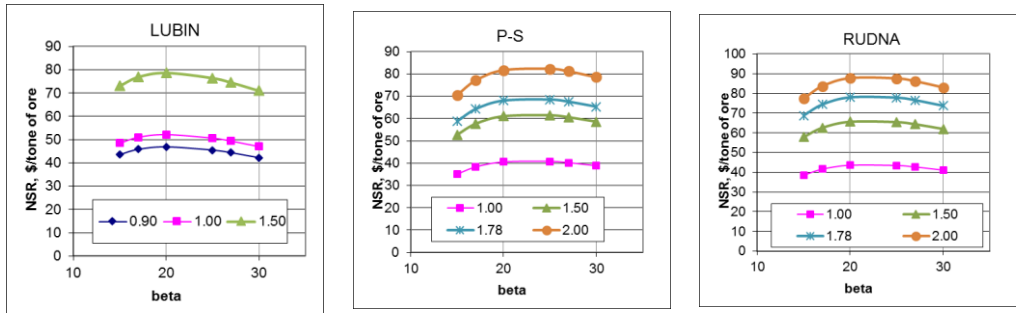Fig. 5. Revenue of mines Ag+Au excluding

Fig. 6. Revenue of mines Ag+Au including

CONCLUSIONS

The results of calculations of NSR show that there is a certain optimum range of mining operations (α) and beneficiation (β) parameters at which we can achieve the greatest benefits from the concentrates. Comparisons between mines are significant because of different ore grading. Also, silver and gold content play a significant role in production profitability. The results of the study are presented in Table 2.

Table 2. Net Smelter Revenue of the mines at actual and optimal mode, $/Mg of ore

	α(Cu)	β(Cu)	NSR(Cu)	NSR(CuAuAg)
NSR at actual grade ore and concentrates				
L	0.90	17	25.8	44.1
P-S	1.67	25	55.3	66.2
R	1.78	27	57.3	75.2
NSR actual grade ore and optimum grade concentrate				
L	0.90	20	27.4	45.2
P-S	1.67	25	55.3	66.2
R	1.78	25	58.0	75.3

Table 2 presents two cases: 1) actual mode and revenue, 2) revenue at actual grade ore but optimal grade concentrate. Based on the obtained data one can infer that relative NSRs of the analysed mines L:P-S:R are 1.00:1.46:1.67. However, we should also note that Polkowice-Sieroszowice and Rudna mines operate much deeper than the

Lubin mine, therefore the running costs of the mines under comparison are not so much different, i.e. 1:1.36:1.58 (Malewski, 2016).

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