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DEPENDENCE OF MINE REVENUE ON THE GRADE OF COPPER CONCENTRATE

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Abstract. The paper presents a method of calculating the Net Smelter Return or Revenue (NSR) formula for copper ore mines based on heuristic models of functional relationships between concentration of metals in ore and copper concentrates, the operational efficiency, and the metal prices in the global markets. A method has been proposed to identify these relationships as well as a way of estimating their parameters. The NSR optimization calculations have been performed for the data coming from the mining and smelting practise of KGHM Polska Miedź S.A., which demonstrate its practical usefulness in assessing the efficiency of production based on the current quality of ore, the efficiency of its beneficiation, and the market prices of metals.

keywords: NSR, copper grading, recovery, costs, revenue, modelling

1. Introduction

The Net Smelter Return or Revenue (NSR) method is commonly used to analyse the economic impact of the degree of concentration of enriched minerals in light of processing costs and metal market prices (Czeczott, 1937; Paulo and Strzelska-Smakowska, 2000; Wills, 2006). It involves calculating the profits achievable from the sale of the main product of the mine, i.e. the concentrate after deducting the processing costs. It is an important piece of information for the mine, which may be a criterion for optimizing extraction and beneficiation of ore according to the quality of the concentrates. This method also provides the basis for the structure of settlement contracts between the mine and the smelter, but it can also be used as a tool for studying the efficiency of investment projects (Płaneta et al., 2000) or optimization projects (Krzemińska, 2012).

In such a settings the mine, i.e. mining units and the processing plant taken together represent one side of the settlements, while the smelter is on the other side. Combining ore excavation and beneficiation into one technological body is due to the fact that shipment of ore over great distances to the processing plant and then to the smelter without beneficiation would be, for obvious reasons, completely uneconomical. Therefore, the processing plant is usually an integral part of the mine,

whereas smelters can be located anywhere in the world because they are not dependent on a specific mine and can operate safely through the concentrates markets or by entering into direct contracts with specific providers. The global mining practise is such that about half of that industry operates without processing while the other half operates in the form of mining and smelting groups (Fig. 1).

In the Polish copper industry metal production is organized in terms of technology and management as a mining and smelting group, which is functionally divided into extraction, ore beneficiation, and smelting divisions (Monografia KGHM, 2007). The divisions settle their mutual accounts according to the volume and quality of the main product, but not financially. Consequently, it is interesting to determine what maximum revenue can be achieved by the mine (extraction + ore beneficiation plant) from mining production (quality of the ore and concentrate) considering the processing costs and the price movements on the global market of non-ferrous metals. For this purpose we will use own structure of the NSR settlement formula built on relationships between the quality of ore, quality and yield of the concentrates, processing costs, and finally, metal prices in the open market.

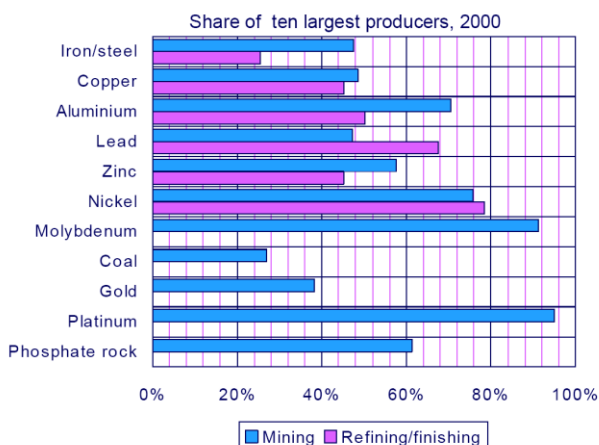


Fig. 1. The structure of production of the 10 largest producers of raw materials. Source: MMSD, CRUI report 2001

Figure 2 shows the revenue limits at each stage of production. In this article we will confine ourselves to the analysis of the cost and quality relationships between the mine and the Ore Beneficiation Plant (OBP) on one hand and the smelter on the other hand. However, it is also possible to put extraction on the one side and the OBP with the smelter on the other side, where the potential revenue of mining would be called Net Smelting & Processing Revenue (NSPR).

The final beneficiary of the mining and smelting production is the investor, whose expected benefit from the investment is the revenue after deducting total production costs, i.e. Net Smelting & Processing & Mining Revenue (NSPMR). The volume

calculated this way is useful for analyzing the efficiency of investment projects, e.g. at the stage of the feasibility study.

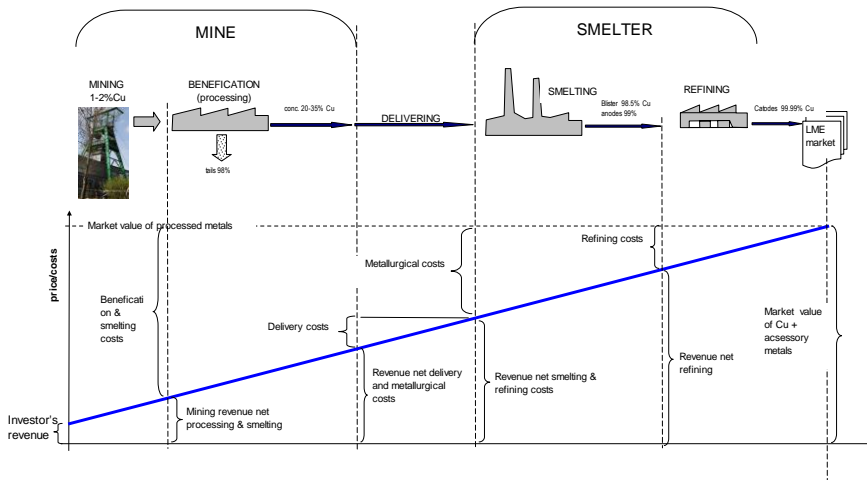


Fig. 1. The diagram of the expected revenue from final production

2. The structure of the NSR formula

The NSR formula determines how much income can be obtained from the sales 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 (Strzelska-Smakowska and Paulo, 1995; Wills, 2006) as the following expression:

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

where

NSR – net smelter return measured in \$ per 1 Mg of ore,

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

δ_i - payable part of metal in concentrate

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

$MC=TC+RC$ - metallurgical charge

TC - treatment (smelting) charge dependent on quality of concentrate.

RC - refining charge, \$/unit of metal

DC- cost of delivery ex-recipient

P - penalties for the presence of harmful components (according to contract terms)

B - bonuses for the presence of desirable components (according to contract terms)

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

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

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

3. Concept of calculation

In the optimization 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 one component (metal, mineral), but not each one is the subject of beneficiation even though it will be recovered in subsequent smelting operations. This is precisely the case that will be considered in this work on the example of copper production technology at KGHM Polska Miedź S.A.

Under 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 that is well-known in the processing, which is derived from the mass balance of the processing operation (Drzymala, 2007):

$$\varepsilon = \frac{\beta}{\alpha} \cdot \gamma_1, \quad (2)$$

where α is a metal (Cu) content in the feed (ore) or concentrate, β is a metal (Cu) content in the concentrate.

The second relationship useful for further calculations will be the empirical hypothesis (Malewski, 2008) of a relationship between Cu recovery and the desired concentration of that metal in the concentrate which we will write down as follows:

$$\varepsilon = 1 - \left[\frac{\beta - \alpha}{\beta_{\max} - \alpha} \right]^A, \quad (3)$$

where:

$A=f(\pi, z, t)$ is a function of current values of the operation parameters $\{\pi\}$, 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 (2); γ_1 as in (1).

So, from (3) we can determine recovery for a given quality of concentrate and then from (2) calculate actual concentrate yield, or after appropriate transformations we obtain a formula for yield of the main component in the concentrates as follows

$$\gamma_1 = \frac{\alpha}{\beta} \cdot \left[1 - \left(\frac{\beta - \alpha}{\beta_{\max} - \alpha} \right)^A \right], \quad \alpha \leq \beta \leq \beta_{\max}. \quad (4)$$

Parameter A in formula (3) can be determined experimentally by using a series of observations $\{\varepsilon\}$ and $\{\beta\}$ or by using the hypothesis that it will progress as in Fig. 3a. Then, by knowing the current value ε and β parameter A can be adjusted iteratively for compliance of the calculated result with the measured one.

The hypothesis (3) also has a physical meaning because it determines the limits of metal beneficiation depending on its stoichiometric concentration in the mineral. Confirmation of the shape of that function in practical ranges β can be found in many studies and publications (Strzelska-Smakowska and Paulo, 1995; Łuszczkiewicz and Chmielewski, 2006; Wills, 2006; Drzymała, 2007).

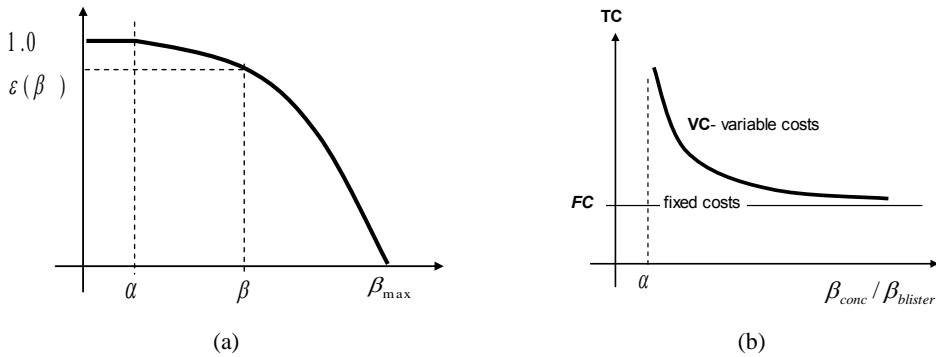


Fig. 3. Models/hypotheses: (a) efficiency of industrial beneficiation of copper minerals, (b) cost of smelting of concentrates depending on the metal content in the concentrate

4. Costs of production

Calculation of formula (1) requires costs of processing of the concentrates to the form of pure metals as the metallurgical costs impact on revenue charge. At the metallurgical stage there are two operations: one is smelting of copper matte and fire refining to the anode copper (99% Cu), second - is electrolytic refining to commercial purity (99.99% Cu). The smelting TC and refinery RC charge will depend strictly on the amount of Cu in concentrate.

Determining the functional dependence of the metallurgical processing costs on the results of the preceding technological operations is a relatively difficult issue without performing appropriate experiments on real objects. In such case certain heuristic models of those relationships may be useful, as presented in Fig. 3b. This is energy dependence relationship extracting amount β [%] metallic Cu by smelting 1 Mg of concentrate. The model in general form may be of the type:

$$\frac{TC}{TC^*} = C \cdot \left(\frac{\beta}{\beta^*}\right)^{-k} + D, \tag{5}$$

where

β, β^* - actual and observed grade of concentrate, respectively,

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

$D=FC/TC^*$ – constant, representing relative fixed treatment cost,

TC^* – observed treatment costs

k – curve form factor determined experimentally by iteration in a way similar to how it was described in the case of formula (3).

If $\beta=\beta^*$ and $TC=TC^*$ then from formula (5) we have $C+D=1$.

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

Content and recovery of precious metals from refining tailings is usually beyond the control of concentrates production but could theoretically be the subject of considering more sophisticated technology for this aim on the stages of deposit exploitation or ore beneficiation.

The content of accessory metals will be taken into account in our *NSR* equation in a simplified manner from the relationship:

$$\frac{\beta_i}{\beta_i^*} \approx b_{Cu} = \frac{\beta_{Cu}}{\beta_{Cu}^*}. \quad (6)$$

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 concentrate.

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

5. Sample calculations

Now, we will perform calculations to optimize the quality of the concentrate for the content of copper and/or accessory metals using the previously derived relationships. We will use industrial data of metals content in the operations streams throughout the copper production cycle. Input data for calculations are presented in Table 1.

Treating the data in Table 1 as empirical (α_i^* , β_i^*), we will calculate the relative yield of the concentrate γ_j . Taking $\alpha_{Cu}^*=1.67\%$, $\beta_{Cu}^*=25.76$, $\varepsilon_{Cu}^*=88\%$ and assuming metal content in the mineral $\beta_{max}^*=70\%$ applying iterative method we will assess the parameters of the function (3) that it 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 $\gamma_{Cu}=f(a_{Cu}, \beta_{Cu})$ for the current values of copper grading in the concentrate and in the ore.

The next task is the estimation of smelting costs. Using approximation method as above for the parameters as in Table 2 we will obtain the result presented in Fig. 4.

When we have the dependence models and assessment of their parameters, we can simulate revenue limits from production of concentrates for the mine and processing plant complex. Figures 6-7 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 neglected in these examples.

Table 1. The data adopted for calculations. Component grades of the main product of operations. Prices on the LME of 23 Dec. 2011

Concentrate Factor CF(i)	Components Metal	Mine	Concentrator	Smelter	Market
		Grade, %			Price \$/Mg
15.43	Cu	1.67000	25.76000	98.50	7 590
13.00	Ag	0.00462	0.06010	0.23	942 581
15.00	Au	0.00002	0.00034	0.00	51 838 710
11.11	Pb	0.19777	2.19713	8.57	0
11.16	As	0.14492	1.61666	4.85	0
1.60	C	4.49703	7.19495	0.00	0
1.75	H2O	4.87000	8.51000	0.00	0
	ε_{Cu}	100.00	88.00	98.50	
	γ_1	100.00	5.70	1.42	

Table 2. Parameters and calculations of $\beta=f(\alpha_{Cu}^*, \beta_{Cu}^*)$ function

α	β	$\varepsilon(\beta)$	γ_1
1.67%	25.76%	0.880	0.057
$\beta_{max}=0.7$	1.67%	1.000	1.000
	15%	0.962	0.107
A=2	20%	0.928	0.072
	25%	0.883	0.059
	30%	0.828	0.046
	35%	0.762	0.036

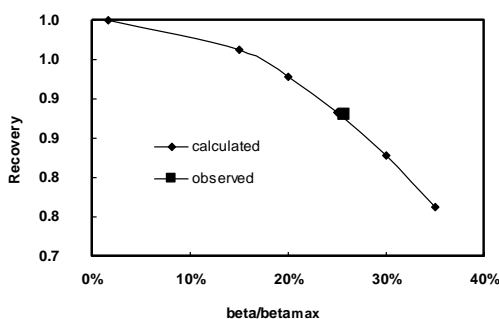


Fig. 4 Approximation of the recovery function $\varepsilon_{Cu}=f(\beta_{Cu})$ for the parameters $A=2$ and $\beta_{max}=70\%$. The square marks the empirical value

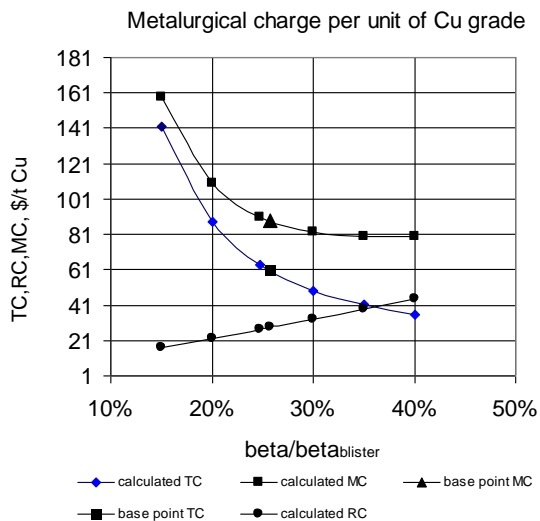


Fig. 5. Base (base point) and calculated costs of treatment (TC), refining (RC) and total metallurgical costs (MC) according to the data and parameters in Table 2

Table 3. Parameters of TC function and calculations of metallurgical costs

β	TC	RC	MC
	\$/Mg concentrate		
15%	142	17	158
20%	88	22	110
25%	63	27	91
25.76%	60	28	88
30%	49	33	82
35%	41	39	79
40%	35	44	79
k	C	D	
	0.7	0.3	
β^*	TC*	RC*	
25.76%	60	110	

6. Conclusions

Calculations of the *NSR* revenue show that there is a certain optimum region of mining operations (α) and beneficiation (β) at which we achieve the greatest benefits from the concentrates. This method of analysis will be useful to establish or modify contractual terms in settlements between the mine and the smelter but the results of the calculations do not mean at all that the component concentrations that are optimal in the formula will be optimal at the investor level (the *NSPM* formula), that is after taking into account the costs of mining and beneficiation, which obviously depend on

the quality of mineral and the desired quality of ore and concentrates. This is a topic worthy of further investigation in that interesting field of study.

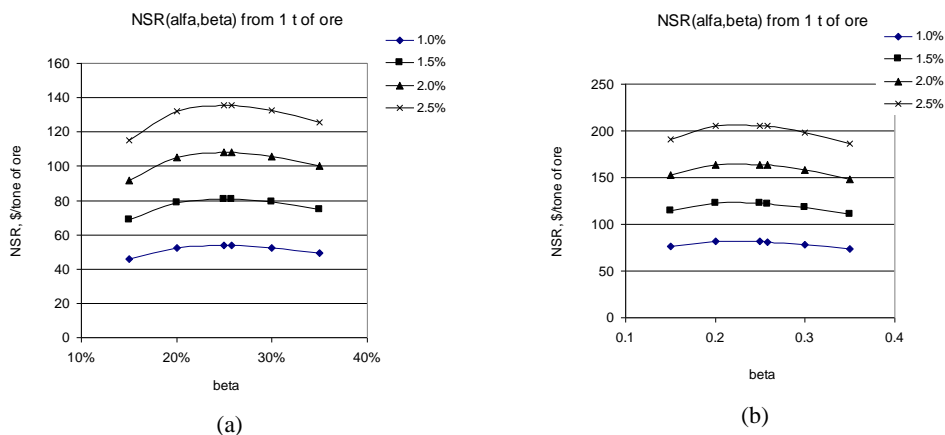


Fig. 6. The NSR revenue of the mine for different quality of ores and concentrates: (a) paid ($\delta=0.95$) copper only, (b) paid ($\delta=0.95$) Cu and accessory metals: Ag and Au

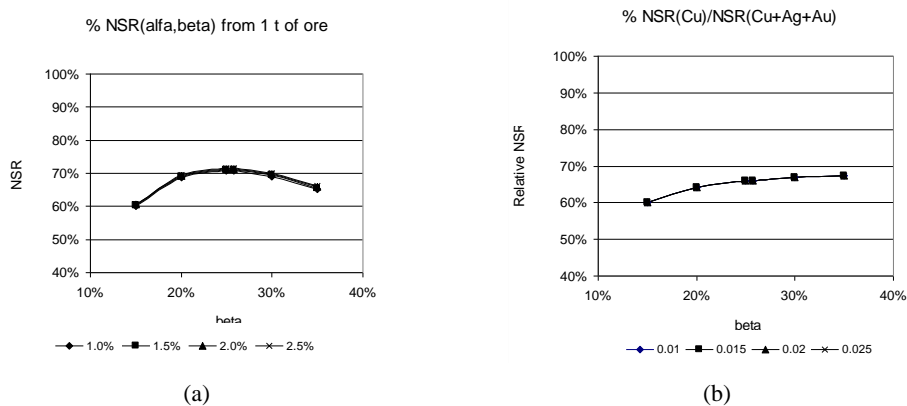


Fig. 7. (a) Relative NSR (only Cu in concentrate)/(value of Cu in ore), (b) Relative NSR (concentrate Cu)/NSR (concentrate Cu+Ag+Au)

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