Modeling of energy consumption costs for Polish copper ore processing plants

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ABSTRACT

The aim of the article is an economic analysis of energy consumption costs and then an economic assessment of work efficiency for copper ore enrichment processes in Poland, resulting from that analysis. On the basis of above analysis it was built a model with the following target function: a measure of work efficiency of enrichment plant, understood as cost of energy consumed for production of the concentrate with content of copper β from ore with content of copper α. In that model there was described consumption of energy per unit (target function of model) for each stage in technological process, which was dependent conditional on the β value (content of copper in the concentrate). Such form of the model describes demands for energy of given enrichment technology in dependence on the quality of produced concentrate.

1. INTRODUCTION

For each company a measurable efficiency measure is the long term profit (P), which consists of a difference between long term incomes (I) and cost of production (C). In non-ferrous metals enrichment industry the income is determined by the value of metals sold by the company on the world metal exchanges, the plant therefore has practically no influence on the exchange price and the income resulting from that price. It is however possible to optimize the enrichment process in order to limit the cost of ore processing.

The aim of the article is therefore the presentation, that the costs of enrichment, and particularly costs of electrical energy consumption, are not the fixed values, but they depend on the course of enrichment process as well as enrichment results (the quantity and quality of enriched concentrate).

Ore enrichment processes are energy-consuming ones. Total consumption of electrical energy in the enrichment process exceeds 35% and in comminution operations is amounts up to 70-80% in dependence on the type of ore (Saramak 2006). That tendency is common for the whole non-ferrous metals enrichment industry, for example in zinc and lead enrichment industry total energy consumption cost equals about 30% of the whole enrichment cost. Due to the fact, that the costs of energy make up in total technological cost of production so large part, this component of costs will be taken into consideration both in analysis of the enrichment costs and in the assessment of efficiency of work for copper enrichment plants. In order to build a suitable model describing the work the KGHM, there should be first made the analysis of enrichment costs, with special respect to the costs of electrical energy on the enrichment stage in the whole process of copper production.

2. THE SYSTEM OF COSTS RECORD AND THE ENRICHMENT COST-ANALYSIS

The most common system of cost record in industrial company is generic cost system. Costs in that arrangement are divided into homogeneous components of costs which, from the viewpoint of plant, are the straight elements of process of work. We can distinguish following costs: amortization, consumption of materials and energy, labour, other services, repairs and other costs. In whole production process costs can be also recorded according to places of their formation (Mokrzycki 2001). Combination of these two arrangements of costs record, that is the record of costs in generic system for each stage in process of production is called accounting costs record, and costs of enrichment in KGHM being analyzed below are just in such arrangement.

In KGHM Polska Miedź S. A. costs grouped according to place of their formation are defined for following stages of the enrichment process:

– the preparation of ore to grinding,
– grinding and classification,
– flotation,
– the pumping station of down waters,
– the utilization of sulphuric acid,
– installation to chemical modification,
– dewatering
– flotation tails treatment

For each stage in technological copper enrichment process costs are recorded in generic system. The costs according to this classification are divided with regard on their kinds (the economic content) making up simple homogeneous components of costs. In KGHM in generic system there are distinguished following kinds of costs:

– labour costs
– materials costs
– energy costs
– amortization charges
– cost of repairs
– common costs
– other costs

The percentage participation of individual components of costs are presented in the fig 1.

In the Table 1 there are presented both the participation of electrical energy consumption costs for individual stages of the process, and the participation of costs of individual stages in the whole technological cost of enrichment process.

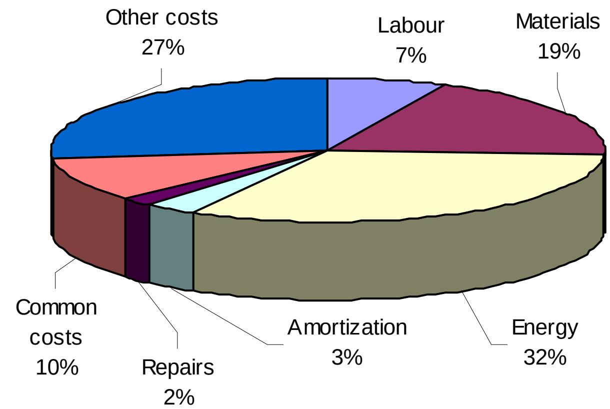

Fig. 1. A percentage participation of individual types of costs in technological enrichment cost

Table 1 Percentage combination of energy consumption costs as well as total technological operating cost of enrichment for individual stages.

The stage in enrichment process	Energy cost [%]	Total cost [%]
preparation of ore to grinding	4,08	10,53
grinding and classification	67,45	37,80
flotation	17,59	15,58
pumping station of down waters	1,21	0,52
utilization of sulphuric acid	0,41	1,53
dewatering	3,91	12,06
flotation tails treatment	5,34	21,98
Total	100,00	100,00

On the ground of introduced data it is possible to notice, that the key stages of enrichment process both with regard on amount of energy consumption cost and with regard on participation of cost in total operating cost are following: grinding and classification, flotation tails treatment as well as flotation (Saramak 2006).

3. MODEL OF WORK EFFICIENCY FOR PROCESSING PLANTS IN KGHM

On the ground of the size of contained costs in generic system and in accounting cost record it has been possible to propose the model estimating the efficiency of work of enrichment plant, in dependence on quantity of energy consumed for two time periods: T1 and T2, representing two chosen years. The energy consumption costs are the one, being taken into consideration, due to their crucial participation in technological copper enrichment cost (Table 1). The consumption of energy is recorded in model in natural units (that is in kilowatts – kWh), but with regard to impossibility of publishing real data, the agreed units (u) of energy consumption instead of concrete values, expressing the consumption of energy, were introduced. The agreed units were calculated on the ground of real productive data suitably. Agreed units describe the consumption of energy on production the unit of the mass of concentrate with the quality ß (percentage content of copper in the concentrate), from the ore with percentage content of copper α, for main stages of copper ore enrichment process. During building of the model, the costs of energy consumption in following stages of the process were taken into consideration:

a) preparation of ore to grinding
b) grinding and classification
c) flotation
d) dewatering
e) flotation tails treatment

Total energy consumption cost on individual stage of enrichment process will be the multiplication of agreed units of energy consumption and the calculated mass of useful component (the copper) coming through the individual enrichment stage. Through the enrichment stages mentioned above there are coming following masses of metal:

$$\begin{array}{ll} \text{a) preparation of ore to grinding:} & Q \cdot \alpha \\ \text{b) grinding and classification:} & Q \cdot \alpha \\ \text{c) flotation:} & Q \cdot \beta \\ \text{d) dewatering:} & Q \cdot \gamma \cdot \beta \\ \text{e) flotation tails treatment:} & Q \cdot (100-\gamma) \cdot \vartheta \end{array} \qquad (1)$$

where:

Q: the mass of the feed (ore) steered from the mine to the enrichment plant;

γ: the yield of the concentrate;

α,β,ϑ: average contents of copper in the feed, in the concentrate and in tails, respectively.

3.1 Target function of the model

The target function in the model will be the measure of efficiency of work (E), understood as unit energy consumption on production of tone of the copper concentrate with average content of copper ß. The quality of concentrate ß is the basic variable, of which the results of modeling will depend on. The target function will then be denoted by the equation (2)

$$E(\beta) = u_p \cdot Q\alpha + u_c \cdot Q\beta + u_f \cdot Q\beta + u_d \cdot Q\gamma\beta + u_t \cdot Q(100-\gamma)\vartheta \qquad (2)$$

where:

u_p: agreed unit of energy consumption in preparation stage,

u_c: agreed unit of energy consumption in grinding and classification stage,

u_f: agreed unit of energy consumption in flotation stage

u_d: agreed unit of energy consumption in dewatering stage,

u_t: agreed unit of energy consumption in floatation tails treatment stage,

Q, α, ϑ: the same denotations like in formula (1)

In the model there are following variables:

γ, β: the same denotations like in formula (1)

3.1 Limitations

Except of the target function, in the model there exist following limitations, which more precisely settle in realities the enrichment process:

$$\beta < \beta_t$$
$$\upsilon \ll \beta \qquad (3)$$
$$\gamma \cdot \frac{\beta}{\alpha} \le 100\% \qquad (1)$$

as well as boundary conditions:

$$\beta > \alpha$$
$$\upsilon < \alpha$$
$$\alpha > 0$$
$$\upsilon > 0$$

$$\gamma \cdot \frac{\beta}{\alpha} \geq 0$$

The $ß_t$ index equals 67,73% and it was calculated based on the stechiometric content of copper in cupriferous sulphides, included in enriched concentrate (Chodyniecka and others 1993).

Due to mathematical formula the introduced model is non-linear one. Additionally variable γ, expressed by the formula

$$\gamma = \frac{\alpha - \vartheta}{\beta - \vartheta} \cdot 100\% \tag{4}$$

is a function of two variables: namely β and ϑ (under the assumption that α is fixed value). Such problem isn't easy to verify, with regard on number of variables occurred in model the as well as insufficient quantity of equations describing the connection among them (Tumidajski, Saramak 2002). It is possible however, with quite high precision, to make the γ function dependent conditional on only one variable, namely from β. In the papers (Tumidajski, Saramak 2002, Saramak 2003, Saramak 2004) there was used a hyperbolical function describing dependence between γ and β. Calculations presented by author show quite high convergence of modeling results with real ones, and justify an adoption of such function. In analyzed time periods for our processing plant formula will be as follow

$$\gamma = \frac{a}{\beta} + b \tag{5}$$

where:
a, *b*: parameters dependent on the ore type.

For ore processed in analyzed plant for the period T1 values of both coefficients equal respectively $a = 0{,}0205$ and $b = -0{,}0099$ and for the period T2: $a = 0{,}0198$, $b = -0{,}0096$. Other proposals of approximation the dependence $\gamma = \gamma(\beta)$ were presented in the work (Skorupska, Saramak 2005).

The model presented with using formula (1) will be then in following form

$$Z(\beta) = u_p \cdot Q\alpha + u_c \cdot Q\beta + u_f \cdot Q\beta + \\ + u_d \cdot Q\left(\frac{a}{\beta} + b\right)\beta + u_t \cdot Q\left(100 - \left(\frac{a}{\beta} + b\right)\right)\vartheta \tag{6}$$

where:
a,b: parameters, other denotations like in formulas (1) and (2)

4. MODELING RESULTS OBTAINED FOR DIFFERENT VARIANTS OF ENRICHMENT PROCESS, THE DISCUSSION OF RECEIVED SOLUTIONS

The verification of model depends on determination of energy consumption costs in dependence on quality of enriched concentrate. For both analyzed periods T1 and T2 the following production variants of processing plant were accepted:

Variant I: $\beta = 20\%$
Variant II: $\beta = 22\%$
Variant III: $\beta = 25\%$
Variant IV: $\beta = 28\%$
Variant V: $\beta = 30\%$

For the period T1 and T2 the efficiency of processing plant work for every of variants, defined as the amount of energy consumed on the enrichment process, were determined. Results are presented in Table 2.

Table 2 Computed values of γ and ϑ for accepted variants of concentrate enrichment

time period	Values of indexes	I	II	III	IV	V
T1	β [%]	20	22	25	28	30
	γ [%]	9,25	8,32	7,20	6,33	5,84
	ϑ [%]	0,197	0,217	0,247	0,277	0,296
T2	β [%]	20	22	25	28	30
	γ [%]	8,93	8,03	6,95	6,11	5,63
	ϑ [%]	0,191	0,210	0,238	0,267	0,286

Because the content of copper (ß) is a variable in the model, then together with changing of the β value the efficiency of processing plant work (E) will be changing too. In order to verify that, suitable calculations were executed. Results are presented in Table 3.

Table 3. Modeling results of energy consumption for accepted variants for analyzed time periods (in agreed units (u))

T1	Variant I	Variant II	Variant III	Variant IV	Variant V
E(β)	17,31	19,03	21,61	24,19	25,91
T2	Variant I	Variant II	Variant III	Variant IV	Variant V
E(β)	17,29	19,01	21,60	24,17	25,89

On the ground of the results it is possible to notice that the growth of energy consumption per copper mass unit in enrichment process is proportional to the growth of quality of enriched concentrate (percentage content of copper β in concentrate). The yield of the concentrate diminishes together with growth of it's quality as well as the content of useful component in tails also increases (Table 2), what means that losses grow.

The efficiency of work of individual stages in technological enrichment process for different qualitative variants of enriched copper concentrate changes also. Only on the stage of preparation of ore to the enrichment process, costs of energy do not change with the change of content of copper in enriched concentrate. On remaining stages of ore enrichment the consumption of energy is dependent on the content of copper in concentrate in following way: for grinding and classification, flotation and flotation tails treatment stages, with an increasing in concentrate quality the energy consumption increases together with, however for stage of dewatering the dependence is inverse (together with an increasing in the quality of the concentrate, the energy consumption decreases). It is easy to interpret such course of individual dependences. In the processes of grinding and classification the extension of grinding time leads to more fine comminution of ore, and in consequence to easier liberation of cupriferous sulphides in next stage of process, namely flotation. The longer process of grinding joins with enlarged energy consumption. Similar situation occurs in flotation process. Namely, longer course of the process raises it's precision, and the quality of concentrate as a result. The production of richer concentrate causes the production of smaller mass of concentrate, then it increases the yield of tails and the content of copper in tails respectively. That causes an increase in energy consumption for the stage of flotation tails treatment. The smaller mass of richer concentrate requires smaller energetic expenditures on the process of dewatering, therefore the consumption of energy with growth of content of copper in concentrate decreases itself for the processes of dewatering.

It is also possible to determine how the energy consumption increases when the content of copper in concentrate raises at one percentage. To make that, there should be solved regression equations, in which the energy is dependent variable, and the variable independent is the content of copper in concentrate β. Table 4 presents results. The value of coefficient *r* in both cases is very high.

Table 4. The regression equations for the models of work of O/ZWR Polkowice for time periods T1 and T2

T1 time period	T2 time period
$E = 0{,}860\ \beta + 0{,}103$	$E = 0{,}859\ \beta + 0{,}097$

On the ground of the results it is possible to assume, that in both cases the increase in content of copper in concentrate at 1 percentage point generates the increase in energy consumption in the enrichment process at about 0,86 of agreed unit (u) per copper mass unit.

5. CONCLUSIONS

The presented model sets aside the influence of technology on the quality of enriched concentrate. Therefore presented dependencies have a linear course. However technological limitations cause that dependences between the quality of concentrate and energetic demand on it's enrichment in real conditions are linear only on sure section. When increasing in quality of the concentrate over standards, enrichment costs grow incommensurably high with achieved effects and the enrichment process becomes ineffective from economic viewpoint.

Presented model is not typical optimizational one (Saramak, Tumidajski 2004), due to the fact, that there are not directly considered technological limitations. The aim of the model is rather the presentation of dependence between the cost of energy and the quality of enriched concentrate, than finding the optimal quality of the concentrate. On the ground the presented results one may notice that the cost of energy is connected with the content of copper in the concentrate, the dependence is proportional (on sure section) to the quality of the concentrate. The article matters from the viewpoint of cost-analysis in the ore enrichment process. Assuming the cost of enrichment as parameter and treatment it as fixed per mass unit of enriched ore might be too large simplification. In case when the high precision of modeling is demanded, enrichment cost should be suitably tied with led process technology. Presented subject matter is in area of interest of investigative team, the member of which is the author (Tumidajski, Saramak, Skorupska 2007).

Comparing the modeling results with real ones one may claim, that the presented econometric model of work effects for O/ZWR Polkowice KGHM "Polish Copper" S. A. on received level of precision describes well the real conditions, in what the technology of copper enrichment is led in the plant. In order to build more detailed econometric model, there should be introduced additional dependences describing connections among individual units of processing plant as well as among processing plant and it's environments.

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REFERENCES

Chodyniecka L., Gabzdyl W., Kapuściński T. (1993). *Mineralogia i petrografia dla górników*. Katowice: Śląskie Wydawnictwo Techniczne.

Mokrzycki E. (2001). *Rachunek kosztów w zakładzie przeróbki węgla kamiennego*. Cracow: Wydawnictwo IGSMiE PAN.

Saramak D. (2003). Model ekonometryczny działalności KGHM „Polska Miedź" S.A. jako sposób optymalizacji procesów wzbogacania rud miedzi, *Mineral Engineering*, special issue no. 3, September.

Saramak D. (2004) *Optymalizacja uzysku metali w Zakładach Wzbogacania Rud w KGHM „Polska Miedź" S.A.*, doctoral thesis, Cracow.

Saramak D.(2006). Analiza efektywności wybranych grup operacji wzbogacania z uwzględnieniem ich kosztochłonności na przykładzie technologii wzbogacania rud miedzi. *Mineral Resources Management,* vol. 22, issue 1, pp. 23-33

Saramak D., Tumidajski T. (2004). Wpływ sterowania jakością koncentratu na efektywność procesu wzbogacania rud miedzi na podstawie OZWR KGHM „Polska Miedź" S.A. *Mineral Resources Management*, vol. 3, issue 20, pp. 55-65.

Skorupska B., Saramak D. (2005). Methods of determination the optimal quality of the concentrate according to chosen technological and economic criteria, *Mineral Resources Management*, vol. 21, issue 4, pp 5-20.

Tumidajski T., Saramak D. (2002). Wielowymiarowa analiza wskaźnika oceny przebiegu procesów inżynierii mineralnej opartych na prawie zachowania masy. *Mineral Resources Management,* vol. 18, issue 2, pp 77-90.

Tumidajski T., Saramak D., Skorupska B. (2007). Chosen indexes of technological assessment of mineral resources enrichment processes as a function of the concentrate's quality, *XII Balkan Mineral Processing Congress, Delphi, Grece.*