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The influence of concentrate's quality on the economic efficiency of multi-plant mining and metallurgical company

Key words

Copper ore enrichment, process optimization, mathematical modeling, mineral economics

Abstract

KGHM P.M. S.A. is the example of multi-plant enterprise, where the whole copper production process, from extracting the ore to electrolytic copper production, takes part in one company. In the article, the model describing the operating of company, taking into consideration characteristic of ores' selectivity, total drawn-costs of mining, processing, and metallurgical process and also the way of concentrates' distribution to specific copper smelters, was presented.

Solution of model enable us to maximize company's profit by steering of the quality of concentrates processing in processing plants, taking into consideration properties of ores and the level of metal prices on world metal exchanges.

Chosen modeling results, on the basis of which we can assume that the optimal quality of concentrates, assuring the highest possible profit at given conditions, mainly depends on metal prices on world metal exchanges and in a minor degree on processing costs, are presented in the article.

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Introduction

Issues presented in the article, concerning the influence of the concentrate's quality on the effective operating of processing plant, were taken into consideration on the basis of KGHM "Polish Copper" S.A. It is one of the world leading company producing copper and silver, and it mainly consists of:

— three mining plants (Lubin, Polkowice and Rudna),
— three processing plants (OZWR Lubin, OZWR Polkowice, OZWR Rudna),
— three copper smelters (Legnica, Głogów I, Głogów II).

Copper production process is multistage one, what causes that the most favorable technological results of processing plant not always are coherent with technological demands of copper smelters and they do not agree with the most profitable company's economic results in the whole copper production system. It is necessary, however, searching of methods improving the work efficiency of the company, in order to keep up the competitiveness of the polish copper industry. The effective method for improving the economic results of the company is the optimization of concentrates' quality, understood as shaping their quality in dependence on technological and economic conditions. The problem of optimization can be considered from the viewpoint of profit maximization, what causes, that the decision concerning the quality of enriched concentrates should take into consideration following factors:

— selectivity of ore,
— prices of copper and silver on world metal exchanges,
— metallurgical and processing costs.

In order to achieve that, a suitable model was built (Grabowski 1982), while it's verification was made with using of optimizational software GAMS (Brook 1992) (General Algebraic Modeling System).

1. Assumptions for building the model

In order to describe the operating of KGHM plant, the appropriate set of equations was used, which determine both the quantitative and qualitative mass flows among individual plants' units, and costs of the process on each production stage (mining, processing and metallurgical). During building the model, it is necessary to characterize many parameters (concerning costs, technology and exchange prices), which should well reflect the real situation and external conditions. The optimisational criterion is the profit of the company (P) defined as the difference between total incomes (I) from selling of copper and silver, and total production costs (C)

$$P = I - C \tag{1}$$

where:

P, I, C — total company's profit, income and costs, respectively (in monetary units).

In order to maximize the profit (P), two conditions should be fulfilled: firstly – a specified amount of the concentrate with determined percentage content of copper in it (β) must be produced, and secondly – the proper composition of concentrates' mixtures being the feed to copper smelters should be selected. The optimisational task then consists in the determination of the quality and quantity of enriched concentrate in each OZWR district, and the determination of concentrates' mixture sending to individual copper smelter. Also technical and technological limitations, properties of processing ore as well as the situation on world metal exchanges should be here taken into consideration.

For the reason, that during the enrichment process silver passes into concentrate together with copper, no other additional costs, connected with the silver production, have to be considered. The recovery of silver and copper also runs together in major part of metallurgical process. The silver and other precious metals are concentrating in metalliferous products coming from intermediate stages of the metallurgical process. Just in the final production stage – the electrolytic refining – is obtained the slime, from which the silver recovery is possible.

2. Technological and organizational conditions

2.1. Description of dependencies between content of copper in the concentrate and it's weigh recovery (the yield)

The amount of produced concentrate is one of crucial parameters directly influencing on the company's incomes and costs (Cramer 2001). It is then justified to find the direct dependence between the yield of the concentrate (γ) and it's quality (β). The dependence is a significant component of econometric model describing the company's profit, and it's precise description influences in a large part on modeling results. On the basis of experiments in the field of copper ore enrichment led in Non-Ferrous Metals Institute in Gliwice, Poland, it was proved that a well approximation in description of the dependence between the quality of concentrate and it's yield is the exponential function (Sprawozdanie IMN 6257/05):

$$\beta = c\gamma^{d} \tag{2}$$

where:

c and d — parameters.

Exemplary selectivity curves obtained from equation (2) for ores processing in three O/ZWR districts: Lubin, Polkowice and Rudna are presented in the Figure 1. For all obtained dependencies the correlation coefficient r is not lower than 0.98.

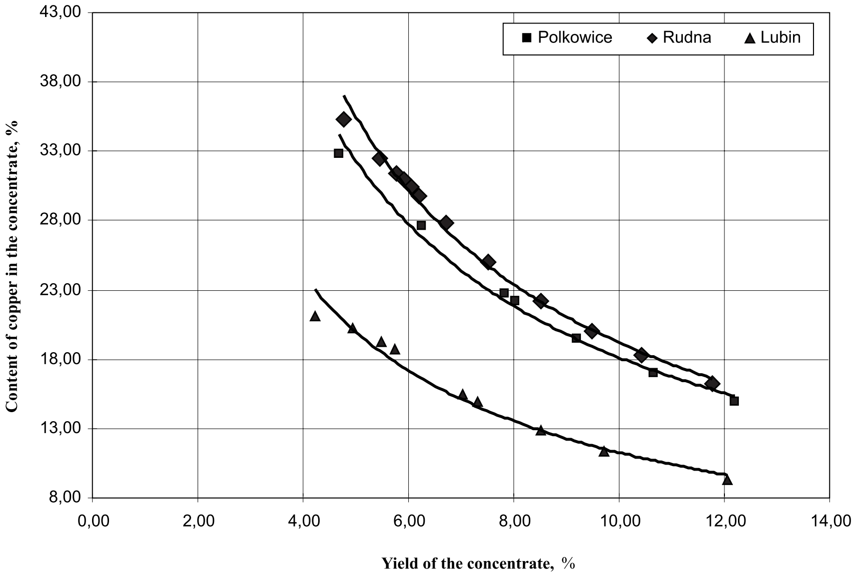

Fig. 1. Dependencies between the yield and content of copper in the concentrate for ores processing in Rudna, Polkowice and Lubin

Rys. 1. Zależność wychodu od zawartości miedzi w koncentracie dla rudy przerabianej w Rudnej, Polkowicach i Lubinie

2.2. Relationship between the recovery of copper and silver

Investigations over selectivity of copper and silver for ores processed in individual districts (Sprawozdanie IMN 5035/94 1994; Bortel i in. 1987; Wieniewski i in. 1994) are carry out quite a long time ago. It results from them, that the recovery of silver in the concentrate is, as a rule, only somewhat lower than the recovery of copper. It is the effect of similarity in properties of both minerals, as weel as izomorphous substitutions of silver in cupriferous minerals. Laboratory analysis over copper and silver selectivity shows, that for given ore, the linear dependency between the content of copper and content of silver in enrichment products exists. It can be denoted as follow

$$\beta_{Ag} = a\,\beta + b \tag{3}$$

where:

β_{Ag} — percentage content of silver in the concentrate,
β — percentage content of copper in the concentrate,
$a,\ b$ — coefficients.

The relationship for ores processed in Lubin, Polkowice and Rudna districts are presented in the Figure 2. For all obtained dependencies the correlation coefficient r is not lower than 0.99.

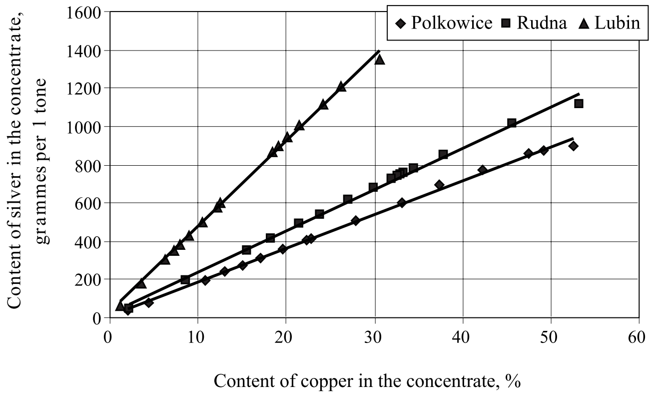

Fig. 2. The relationship between the content of silver and copper in concentrates obtained from laboratory flotation

Rys. 2. Zależność między zawartością miedzi srebra w koncentratach uzyskiwanych w warunkach flotacji laboratoryjnej

2.3. Limitations

2.3.1. Smelters' capacities

The mass of processed concentrate must be no bigger than copper smelters' capacities and must fulfill technological requirements as regards mixtures of concentrates processed in individual processing plants. We can then denote

$$(\gamma_R\, Q_R + \gamma_P\, Q_P + \gamma_L\, Q_L)10^{-2} < H_L + H_{GI} + H_{GII} \tag{4}$$

$$H_{GI} \geq (Q_{RGI}\,\gamma_R + Q_{PGI}\,\gamma_P + Q_{LGI}\,\gamma_L)10^{-2}$$

$$H_{GII} \geq (Q_{RGII}\,\gamma_R + Q_{PGII}\,\gamma_P)10^{-2}$$

$$H_L \geq (Q_{RL}\,\gamma_R + Q_{LL}\,\gamma_L)10^{-2}$$

where:

γ — yield of the concentate, %;
Q — mass of ore processed in processing plants, Mg;
H — capacity of the copper smelter, Mg.

2.3.2. Distribution of concentrates to smelters

The structure of concentrate's distribution to copper smelters mainly results from the qualities of processed concentrates as well from the technology of metallurgical processing.

The description of concentrate's distribution is presented below. Concentrates from processing plants are the feed to both copper smelters, according to formula (5)

$$\frac{\sum_{j=1}^{3}\sum_{k=1}^{2}\gamma_j Q_{jk}\cdot r_{jk}}{\sum_{j=1}^{3}\sum_{k=1}^{2}\gamma_j Q_{jk}} = 1 \tag{5}$$

where:

$\sum_{j=1}^{3}\sum_{k=1}^{2} r_{jk} = 1,$

r_{jk} — fraction of the whole concentrate processed in processing plant number j, transported into copper smelter number k, k = 1, 2, 3.

The five below dependencies define the fixed range proportions of concentrate mixtures transported to smelters. To smelter number 1 concentrates are transported according to following proportions:

$$0.3 \le \frac{\gamma_1 Q_{11}\cdot r_{11}}{\sum_{j=1}^{3}\gamma_j Q_{j1}} \le 0.4 \quad \text{for processing plant 1}$$

$$0.6 \le \frac{\gamma_2 Q_{21}\cdot r_{21}}{\sum_{j=1}^{3}\gamma_j Q_{j2}} \le 0.7 \quad \text{for processing plant 2}$$

To copper smelter number 2 are sending concentrates according to following proportions:

$$0.15 \le \frac{\gamma_1 Q_{12}\cdot r_{12}}{\sum_{j=1}^{3}\gamma_j Q_{j2}} \le 0.2 \quad \text{for processing plant 1}$$

$$0.3 \le \frac{\gamma_2 Q_{22}\cdot r_{22}}{\sum_{j=1}^{3}\gamma_j Q_{j2}} \le 0.6 \quad \text{for processing plant 2}$$

$$0.2 \le \frac{\gamma_3 Q_{32}\cdot r_{32}}{\sum_{j=1}^{3}\gamma_j Q_{j2}} \le 0.35 \quad \text{for processing plant 3}$$

3. Optimizational model of work for KGHM

Final optimizational model with the target function defined as maximization of profit is presented below (Skorupska, Saramak 2005):

$$Z_2 = \left(\sum_{i=1}^{3} \sum_{j=1}^{3} \sum_{k=1}^{2} M_i \cdot \gamma_{jk} \cdot \beta_{jk} \cdot \varepsilon_k \cdot P_{\mathrm{Cu}} + \sum_{i=1}^{3} \sum_{j=1}^{3} \sum_{k=1}^{2} M_i \cdot \gamma_{jk} \cdot (a_j \beta_{jk} + b_j) \cdot \varepsilon'_k \cdot P_{\mathrm{Ag}} \right) - \quad (6)$$

$$- \left(\sum_{i=1}^{3} M_i \cdot MC_i + \sum_{i=1}^{3} \sum_{j=1}^{3} M_i \cdot \gamma_j \cdot \beta_j \cdot PC_j + \sum_{i=1}^{3} \sum_{j=1}^{3} \sum_{k=1}^{2} M_i \cdot \gamma_{jk} \cdot \beta_{jk} \cdot HC_k \right)$$

where:

- i — number of mines in the whole copper production system,
- j — number of processing plants,
- k — number of copper smelters,
- M_i — mass of ore extracted in mine number i,
- γ_j — yield of the concentrate produced in processing plant number j,
- β_j — content of copper in the concentrate produced in processing plant number j,
- ϑ_{j} — content of copper in tails obtained from enrichment of individual ores.
- γ_{jk} — yield of the concentrate produced in processing plant number j, altered in copper smelter number k,
- β_{jk} — content of copper in the concentrate produced in processing plant number j, and altered in copper smelter k,
- ε_k — metallurgical recovery of copper for copper smelter number k,
- ε'_k — metallurgical recovery of silver for copper smelter number k,
- P_{Ag} — price of silver in metal exchange in London,
- P_{Cu} — price of copper in metal exchange in London,
- MC_i — mining cost per mass unit,
- PC_j — processing cost per mass unit,
- HC_k — metallurgical cost per mass unit,
- a_j, b_j — coefficient from formula (3) obtained experimentally.

The income of KGHM is strictly dependent on the processing of the ore. Production of the lower quality concentrates is always connected with the bigger recovery of metal weight – what, in general, positively influences on the total income. Total costs are also dependent from the weight of produced concentrate. Decrease in quality of produced concentrate causes the increase in total processing costs. Total company's profit (formula (6)) is then directly connected with both the value of income and the level of total costs.

4. The results analysis

Model was solved with using the GASM software for several scenarios, taking into consideration processing costs, prices on world metals exchanges, and selectivity of ores. For each scenario, the optimal content of copper as well the yield of individual concentrate were obtained, and then the maximum profit at these optimal parameters was calculated. Basic data for calculations were accepted on the basis of productive results of KGHM, obtained in the first half of the year 2004

4.1. The influence of exchange prices of copper and silver on shaping the optimal quality of concentrates

As a result of application of the model for determining the optimal contents of copper (and simultaneously silver) in concentrates it was proved, that exists a significant influence of exchange prices on such optimal contents of metals in these concentrates, which optimize company's profit. For calculations, the range of exchange copper and silver prices during the years 2003–2005 was accepted. Average monthly copper prices (settlement) varied during that period from 1650 UDS per tone (I quarter of 2003) to 4000 UDS per tone (IV quarter of 2005). During that period also prices of silver raised, however the dynamics of the growth was not as large as in the case of copper. Prices of silver varied from 140 USD per kilo (III quarter of 2003) to 270 USD per kilo (December, 2005).

4.1.1. The influence of copper exchange prices

Results of calculations, in which the influence of copper and silver exchange prices on optimal quality of concentrates are shown in the Figures 3 and 4. The rise of prices –

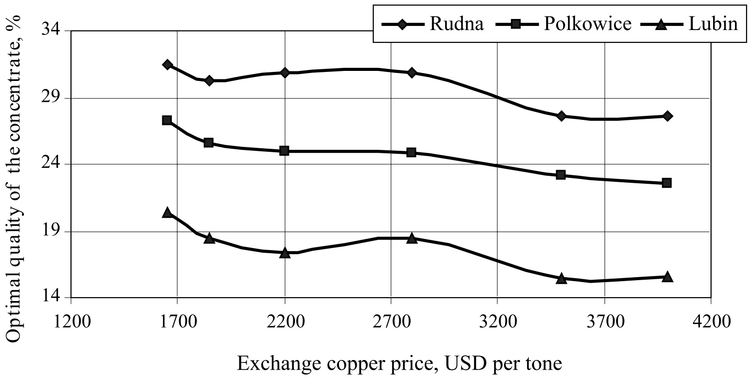

Fig. 3. The influence of copper exchange price on optimal qualities of concentrates processing in Rudna, Polkowice and Lubin districts

Rys. 3. Wpływ ceny giełdowej miedzi na optymalne jakości koncentratów produkowanych w rejonach Rudna, Polkowice i Lubin especially for copper, which is the base metal in ore – significantly influences on the decrease in optimal quality of concentrate. Obtained results confirm that, and in the range of copper prices change from 1650 USD per tone to 4000 USD per tone, the optimal quality of concentrate changes as follow:

— for Rudna district – from 31.5% – to 27.6%,
— for Polkowice district – from 27.2% – to 22.7%,
— for Lubin district – from 20.4% – to 15.6%.

4.1.2. The influence of silver exchange prices

The silver in next metal generating the income of KGHM. Changes in prices of silver influence on the company's income in lower degree than in the case of copper, for the reason of lower content of this metal in concentrate. However, that influence is also significant, especially at lower exchange prices of copper. Modeling results are presented in the Figure 4. In general, increase in silver exchange prices also causes the decrease in optimal quality of the concentrate. For fixed price of copper 1650 USD per tone and changeable price of silver (from 130 to 300 USD per kilo) the optimal quality of the concentrate was changing as follow

— for Rudna district – from 33.7% to 29.8% – ($\Delta\beta$ = 3.9%),
— for Polkowice district – from 28.0% to 26.3% – ($\Delta\beta$ = 1.7%),
— for Lubin district – from 23.0% to 18.4% – ($\Delta\beta$ = 4.6%).

The biggest decrease takes place for concentrate produced in Lubin district – 4.6%. It is consistent with expectation, for the reason that in Lubin the ore with the biggest content of silver is processed. That is why the influence of silver on technological and economic

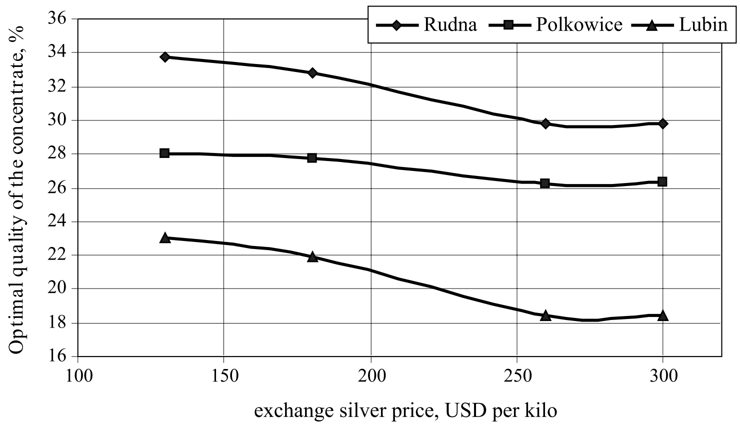

Fig. 4. The influence of silver exchange price on optimal qualities of concentrates processing in Rudna, Polkowice and Lubin districts

Rys. 4. Wpływ ceny giełdowej srebra na optymalną jakość koncentratów produkowanych w rejonie Rudna, Polkowice i Lubin indexes is the largest. Changes in silver prices affect not in a large degree, if so, for shaping of optimal quality of concentrate at high prices of the base metal generating company's income, namely the copper.

4.2. The influence of processing costs on shaping the quality of concentrate

For the reason that metallurgical and processing costs depend on quality of concentrates, we can state that change of such costs caused either by external factors (i.e. change of energy or material prices) or by internal ones (i.e. change of labor costs) both influences on the change of optimal quality of concentrate. The problem of costs influence on shaping the quality of concentrate was considered for four different levels of unit metallurgical costs as well as for three levels of processing costs. The initial level of costs was their close-to-real value from the year 2004. For processing cost it was 220 PLN per tone of concentrate and for metallurgical – 1450 PLN per tone of copper. The next values were increased or decreased respectively, in comparison to the base value.

The increase in both processing and metallurgical costs has directly proportional influence on the change of economically optimal quality of concentrate (it also increases). The dependence for metallurgical costs is presented in the Figure 5, where we can notice mainly growing trend.

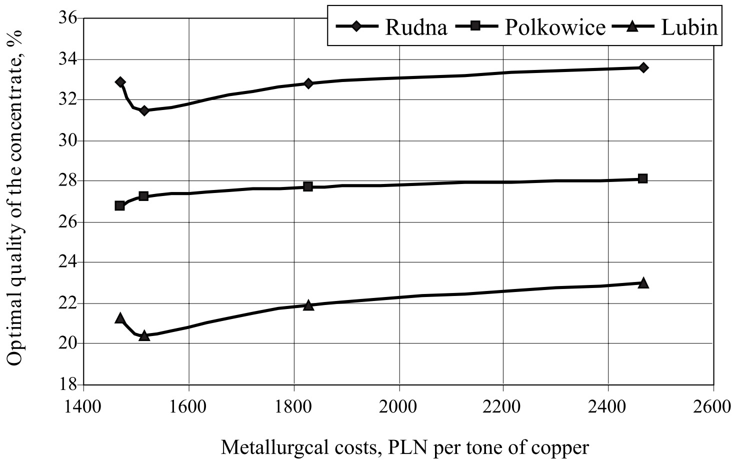

Fig. 5. The influence metallurgical costs on the optima quality of concentrate

Rys. 5. Wpływ kosztów hutniczych na optymalną jakość koncentratu

The increase in processing costs influences on the increase in optimal quality of copper in concentrate in not a large degree, owing to the smallest participation of these costs in total cost of copper production. Then we can omit them in further analyses and it will not be a larger error.

4.3. The influence of ore selectivity

Ore selectivity (understood as ability to enrichment), depends on a number of physiochemical properties of materials contained in ore as well the lithologic composition of ore. Such properties, with connection to other parameters characterizing the flotation process (density of flotation pulp, number of flotation reagents, duration of process), affect on efficiency of enrichment process in a way, which can be described by formula either $\gamma = f(\beta)$ or $\beta = f(\gamma)$.

For modeling calculations three levels of ore selectivity were used. The selectivity was characterized by parameters from equation (2). These parameters were obtained experimentally on the basis of flotation analyses. Results of modeling are presented in Table 1. The influence of ore selectivity is very significant, and at fixed values of other parameters (unit processing costs for individual production stages, exchange metal prices) causes a considerable change of the optimal quality of concentrate. When exchange prices are decreasing, the optimal quality is increasing.

TABLE 1

The influence of ores' selectivity on the optimal quality of the concentrate at high and low exchange prices

TABELA 1

Wpływ wzbogacalności poszczególnych rud na optymalną jakość koncentratu przy wysokich oraz niskich cenach metali

Ore selectivity	Exchange metal prices					
	High			Low		
	Lubin	Polkowice	Rudna	Lubin	Polkowice	Rudna
	Optimal quality of concentrate			Optimal quality of concentrate		
Easy	16.5	30.0	26.4	20.1	30.0	30.6
Average	18.4	25.0	30.9	23.0	28.1	33.6
Difficult	18.6	25.7	27.6	23.0	30.0	32.3

Summary

Presented in the article solutions, leading to determining the optimal contents of copper in concentrates processing in three processing plants in KGHM, are based on mathematical models taking advantage of selectivity curves for copper and silver. Relationships $\gamma = \gamma(\beta)$ and $\beta_{Ag} = f(\beta_{Cu})$ are changeable in time, together with both the progress of exploitation process and changes of deposit's quality. Specific results, obtained with using the model

and proper computational methods, should be attributed to specific operating conditions of processing plants as well as to the ore characteristic. Practical application of presented optimizational techniques consist in multi-variant solutions, enabling us to determine the border solutions and to plan satisfying work conditions (that is targets of work for processing plants). Methods of realization of such aims (accepting specific technological condition of the process) lies in hands of managerial staff of individual processing plants.

Obtained solution can be then described as strategic ones, as they determine general principles of enrichment processing courses. For the reason of random and unstable character of deposits (content of useful minerals in ore), and due to not finally specified course of processing and metallurgical processes, calculation have an approximate character.

The situation in the company integrating three stages of electrolytic copper production process, presented at the beginning of the article, is a challenge to work out a comprehensive model of organization and management strategy or mining and processing industry.

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WPŁYW JAKOŚCI KONCENTRATU NA EFEKTYWNOŚĆ EKONOMICZNĄ WIELOZAKŁADOWEGO PRZEDSIĘBIORSTWA GÓRNICZO-HUTNICZEGO

Słowa kluczowe

Wzbogacanie rud miedzi, optymalizacja procesów, modelowanie matematyczne, ekonomika

Streszczenie

KGHM „Polska Miedź" S.A. jest przykładem wielozakładowego przedsiębiorstwa, gdzie całość produkcji od wydobycia rudy po produkcję miedzi elektrolitycznej odbywa się w ramach jednego przedsiębiorstwa.

W artykule przedstawiono model działalności przedsiębiorstwa uwzględniający charakterystykę wzbogacalności rud przerabianych w zakładach wzbogacania, koszty ciągnione procesu górniczo-przeróbczo-metalurgiczne oraz sposób dystrybucji koncentratów do hut.

Uzyskane rozwiązanie zezwala na zmaksymalizowanie zysku przedsiębiorstwa poprzez sterowanie jakością koncentratów miedzi produkowanych w poszczególnych zakładach wzbogacania, głównie w zależności od właściwości przerabianych rud oraz poziomu cen metali nieżelaznych na rynkach światowych.

W artykule przedstawiono wybrane wyniki modelowania, na podstawie których można stwierdzić, że optymalna jakość koncentratu gwarantująca najwyższy, w danych warunkach, zysk przedsiębiorstwa zależy głównie od cen metali na rynkach i własności przerabianych rud, a w mniejszym od kosztów przeróbki i metalurgicznych.