Production of Copper as a Complex Mining and Metallurgical Processing System in Polish Copper Mines of the Legnica-Głogów Copper Belt

Jerzy Malewski

1 Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Na Grobli 15, 50 421 Wrocław, Poland
jerzy.malewski@pwr.edu.pl

Abstract. Geological and technological conditions of Cu production in the Polish copper mines of the Legnica-Głogów Copper Belt are presented. Cu production is recognized as a technological fractal consisting of subsystems for mineral exploration, ore extraction and processing, and metallurgical treatment. Qualitative and quantitative models of these operations have been proposed, including estimation of their costs of process production. Numerical calculations of such a system have been performed, which allow optimize the system parameters according to economic criteria under variable Cu mineralization in the ore deposit. The main objective of the study is to develop forecasting tool for analysis of production efficiency in domestic copper mines based on available sources of information. Such analyses are primarily of social value, allowing for assessment of the efficiency of management of local mineral resources in the light of current technological and market constraints. At the same time, this is a concept of the system analysis method to manage deposit exploitation on operational and strategic level.

1. Introduction

There are two faces of mineral industry: the technological and the social. Technology reflects an actual scientific and technical development level as well as environmental and economical limitations. The social side appears desirable at the local or central government level because of profits coming from employment, taxes, and other goods originated from exploitation of local mineral resources (Table 1). Therefore, the public interest is to maximize the life cycle of the mine and use the resources for a long time, as opposed to the interest of the mining operator, which is to maximize profits from ore deposit exploitation. At the same time, mining means environmental degradation of the mined areas as well as future costs of revitalization of the post-industrial regions and rebuilding of the local economy, which, as shown in the international practice, is largely attributed to the state and to local community.

Ore deposits in Poland belong to the state, and therefore are a common good. They are provided by the state administration for economic use under certain conditions, among which is the condition of the so-called rational economy of mineral deposits. There is no precise definition of this term. In short, it means extensive exploitation of resources at a certain acceptable level of profitability.
In any case, if there is a conflict with stakeholders’ interests, we are dealing with an optimization problem. In this case, it means looking forward to maximum production value of the exploitation system under the actual economic and environmental constrains.

At the level of planning, another important mining and metallurgical problem appears, namely the design of a so-called geo-metallurgical model of the ore deposit, i.e. recognition and aggregation of the deposit fields with similar parameters of mineral composition and metals concentration. This is also a problem how to optimize the ore extraction, processing and smelting operation parameters to maximize final profit of production.

At the operational level, production management is reduced to maintaining the production process parameters in the optimum range of values. Process automation makes this task easier, yet it does not replace production planning and production optimization in qualitative, quantitative and economic contexts.

On the other hand, the situation in the raw materials markets and the technological and economic competitiveness of the industry are driving factors in the strategic management of the enterprise and clearly translate into the process of operational management having a major impact the company's investment policy in the R&D sector.

The answer to these issues can be given by complex technological and economic analyses using advanced simulation tools. This paper attempts to design a rough model for such studies based on the idea of analysis of a complex system given by White and Simmons [2]. The method was successfully used and developed in our research on quarrying technology and later adapted to the domestic copper mining technology [3, 4, 5]. An advantage in this field of study was discovering the fractal nature of mineral technology, and this idea became particularly useful for mining technology modelling [4, 6].

Our proposal goes towards recognition of the production process as a complex set of technological operations, including their economic evaluation. Copper production is a series of operations, such as exploration, mining, processing and smelting (Figure 5). The main parameter that controls production efficiency is the exploitation gate, which is strongly correlated with reserves and cost of ore extraction, lithological structure of the ore, metal concentration in the ore, efficiency of processing, and revenues from the sale of copper concentrates or metals on the world market of non-ferrous metals.

Table 1. KGHM PM SA, 2015 payments for local government/community [adopted from ref. 1]

| Income                        | Mln USD (1 $=3.5 PLN) |
|-------------------------------|------------------------|
| From PIT tax                  | 57.14                  |
| From CIT tax                  | 38.57                  |
| Real estate taxes             | 38.86                  |
| Royalty                       | 18.57                  |
| Land taxes                    | 2.49                   |
| Environmental charge          | 2.34                   |
| Waste deposition charge       | 0.74                   |

2. Brief description of the copper deposit
Polish copper mining is well known in the world because of Poland’s share in the global metals market as the 6\(^{th}\) world producer of copper and silver. Operation is carried out by the KGHM company in the 200 km area called the Legnica-Głogów Copper Belt (LGCB) [Figure 1], which employs 18,000 workers and produces over 718 Kt/y of Cu, 1283 t/y of Ag, and 2703 kg/y of Au [1,4,8].

The ore deposit is of sedimentary rocks type. It starts from the vicinity of Legnica at the depth of approximately 500 m and extends to the north-west sinking to the depth of 1,200 m and more (Figure 1). The ore body consists of three lithological type of rocks: sandstone, carbonate and shale. Petrographic and mineralogical properties of the ore influence ore beneficiation and metallurgical treatment processes.
The average copper content falls within the range between 1.0 and 2.0%. The main copper minerals are chalcocite (Cu₂S), bornite (Cu₅FeS₄), chalcopyrite (CuFeS₂), and rarely covellite (CuS). The Cu resources are estimated at 22.7 million tons (Proven & Probable), 44.4 million tons (Measured & Indicated) and 8.7 million tons (Inferred). These reserves provide mining production for the next 30 to 40 years [8,9].

The deposit quality (Cu, Ag, Au grading) is varied. Shallower resources have poor copper mineralization, which improves with the resources depth. Cu mineralization depends on the type of rock. Shale has the best mineralization (4-16% Cu), while carbonate and sandstone rocks lag behind (0.5-1.5% Cu).

Each mine exploits the deposits in various fields by several divisions with different mining capacity, so there is a possibility of ore averaging to maintain the required average grade of the ore fed to concentrators. Figure 3 shows a typical distribution of Cu minerals in the profile of ore body.
The production process at KGHM Polska Miedź S.A. is fully integrated, wherein the end product of one stage is the feed to another stage. Ore mined at the Lubin, Rudna and Polkowice-Sieroszowice mines are processed in three separate concentrators, the products of which are a feed to metallurgical smelting and refinery plants: Legnica, Głogów I and Głogów II.

Table 3. Concentrating and smelting performance [8]

| Concentrators Smelters and refinery (Głogów+ Legnica) |
|------------------------------------------------------|
| Throughput 31 Mt/y of ore cont. of ~0.5Mt/y of Cu     |
| Capacity 580 kt/y refining Cu                        |
| Electrolytic Cu production (2013) 564 kt/y           |
| Metallic silver 1152 t                               |
| Metallic gold 1066 kg                                |
| Concentrate production, Mt/y 1.9 Mt/y                |
| Technology Flash furnace, electrorefining             |
| Copper output grade 24%                              |
| Silver grade 625 g/t                                 |
| Full list products Cu, Ag, Au, Pb, Zn, Se, Re, NiSO4, H2SO4 |

3. Technology and model of Cu production system

Mining production technology can be represented by a series of technological operations/subsystems:
1. exploration and determination of mineral resources,
2. mining and transport of the ore (deposit exploitation),
3. mineral processing (beneficiation),
4. metallurgical treatment and refining.

Each of these macro-operations (stages of production) may have its own more or less advanced technological structures, depending on the level of technological and economic development. Generally, the structure of technology may be embraced in the form of a technological fractal as in Figure 6. The production system can be extended or reduced to a structure suitable to the level of identification of technological and economic processes. The information model of the technological operation is a zero-dimensional object shown in Figure 7.
Exploration means qualitative-quantitative identification of resources as well as distribution of metals concentration in the profile of deposit. The result of exploration is the description of geological and geotechnical features of the deposit in the three-dimensional geographic space. At this stage of the study, basic information will include the type of rocks and their mineralization.

Mining is extraction of the part of the deposit that has economic value (reserves) and technical availability (industrial reserves). This stage includes the means of transporting ore to the processing plant. The cost of mining and transportation in underground mines depends on the deposit depth, thickness and environmental conditions (water, temperature, rock mechanics, ventilation).

Processing is enrichment of ore in useful minerals, in our case production of copper concentrates. The standard Cu content of concentrates is 24%. The cost of enrichment depends on ore Cu content and efficiency of enrichment operations, which is influenced by a number of major and auxiliary enrichment operations.

Treatment means smelting and refining of metals. The effectiveness of metal production depends mainly on the quality of concentrates, including their mineral and lithological compositions, which affect the energy efficiency of metal smelting processes [12,13].

The efficiency of mining, processing and treatment operations as a whole can be measured in a variety of ways; yet of practical significance is information on profit, that is the difference between the selling price and the cost of production of the final product. The mining industry has slight impact on the market prices of metals, therefore the only way to achieve profit is to reduce the unit cost of production. One can influence the cost by lowering the intensity of material production or by increasing efficiency of enrichment operations, and also by extracting richer parts of the deposit. Unfortunately,
the latter may result in significant yet short-lived economic benefits, inevitably leading in the long run to accelerated consumption of geological resources and shortening the mining project life cycle. All in all, this is a problem of optimization of sustainable use of domestic mineral resources controlled by technical, economic and environmental factors.

3.1. Information model of a technological operation

Any mineral technology operation has two products – the desirable and the undesirable called waste. Both products are the components of the operation’s feed. In this case any mineral technology can be considered as a system shown in Figure 6. This technology has all features of a fractal if its elements are presented as separation operations. The fractal information model is presented in figures 7, 8, where the output vector \( y \) depends on variables \( x \) and operation parameters \( p \). Symbol \( T \) stands for transition function or algorithm to transform \( x \) to \( y \).

Complexity of the \( T \) operator depends on quality of needed output information and system dimensions (fractal’s scale). Such formal description of geotechnology makes modelling process very convenient for programming and computing because efficiency of each operation (or system) may be represented by two equations

\[
\varepsilon(\text{operation}) = f(\alpha, \beta, p, Q) \\
K(\text{operation}) = f(\varepsilon, p, Q)
\]

where (Figure 8):
- \( \alpha \) - Cu content in the feed,
- \( \beta \) - Cu content in the main product,
- \( \varepsilon \) - recovery of the Cu from the feed to the main product,
- \( Q \) - flow intensity (capacity),
- \( p \) - a set of operation parameters,
- \( K \) - operation costs (fixed + running).

Regardless of the operation which we are dealing with, it always results in two products, the less and the more valuable one, and the extraction process of the desired ingredient is characterized by some efficiency which affects technological and economic results of the operation.

The work [6] shows that an increase/reduction of the geotechnological fractal is described by the function, depending on the stage of the process

\[
y = A \cdot x^D = A \cdot (e')^D,
\]

where \( A \)- function’s amplitude, \( x \)-fractal’s size \( e' \)- scale of technology, \( s \)-technology stage/stadium, \( D=\ Dim-d, \ Dim- \) object’s geometric dimension (0 to 3, here dimension of operator \( T \) in Figure 7 is equal to 0), \( d \)- fractal’s factor of self-similarity.

Using this function, it is possible to forecast different characteristics of technology, production costs, energy consumption etc. In the case of the Cu technology, product prices may be projected with \( d=-2.3 \). Then, starting from \( s=0 \), i.e. Cu market price at 4500 $/t it can be obtained from (2) \( A = 4500 \) $/t and at the stages of \( s=\{1-\text{metallurgy}...5-\text{exploration}\} : y = 4500e^{2.3s}=\{4500,450,45,4.5,0.45\} \). Thus, the metallurgical product is worth $ 4500/t Cu, and mining production about $ 500/t of concentrate (or about
$ 50/t of ore). This value, depending on the mine, corresponds to the KGHM PM data, i.e. $40-65/t of ore [14].

3.2. Exploration stadium

The geological structure of LGCB deposits and the nature of the distribution of the metal concentration in the deposit profile (Figures 3,4,9,10) allow for describing this distribution with a functions:

\[ \alpha_w = \frac{1}{H_c} \sum_w h(w) \cdot \int_0^{h(w)} \lambda(x,w) \cdot dx \]  
(3)

\[ H_c = \sum_w h(w) \]  
(4)

where \( \lambda(x,w) \) is Cu grade distribution in the deposit profile in layer of thickness \( h(w) \), \( H_c \) - exploitation gate, \( w = (\text{shale, carbonate, sandstone}) \).

\[ \sum_w \int_0^{h(w)} \lambda(x,w) \cdot dx = 0 \]  
(5)

\[ H_c = \sum_w h(w) \]  

It was shown [5] that the distribution of copper concentration in the cross-section of the geological deposit can be described by the power distribution model for each lithological layer with corresponding values of distribution parameters:

\[ \lambda(x,w) = A(w) \cdot x^{B(w)} + C(w) \]  
(5)

where \( x \)-exploitation gate axis, \( A(w), B(w), C(w) \) parameters dependent on rock types: \( w = (\text{shale, carbonate, sandstone}) \).

Studies conducted by Pactwa [5] showed that parameters \( A(w) \) and \( B(w) \) are correlated with the thickness of the shale layer and copper concentration in that layer. Figure 10 shows an example of such approximation for the actual Cu distribution in the exploitation gate profile.

In turn, Figure 11 shows that this model allows to calculate the reserves and their parameters, i.e. the concentration of metal in the products of this operation and the size of the operation gate, or the concentration of Cu in the deposit for given exploitation gate.
3.3. Model of ore mining stage

Separation of ore with the given boundary parameters for Cu is an operation which is performed with a certain efficiency smaller than 100%. Therefore, in the mining product (ore) we have decreased content of metal in the ore (a so-called ore depletion). We are currently unable to provide a model of such an operation. Assuming this efficiency as perfect (100%), we get the result as in Figure 11.

As to the operation cost, it can be related to the size of the exploitation gate. Siewierski [15] showed the dependence of relative mining costs on the size of the exploitation gate (Figure 12). We propose to express that relationship with the equation (6):

$$rC = k_1 1.5 * H^{-1.05} + k_2 0.04H^4$$

where

$$x = \frac{H}{3}; \quad k_1 = 1 \text{ and } k_2 = 0 \text{ if } H \leq 3; \text{ or } \quad k_1 = 0 \text{ and } k_2 = 1 \text{ if } H > 3$$

Knowing the function (6) and the dependence of copper grade in the mining product on the size of the gate, one may associate the quality of the ore with the cost of its extraction.

3.4. Mineral processing operation

Under the qualitative and quantitative calculations of yield of the main component (Cu), depending on efficiency of the beneficiation operations, we can use a relationship that is well-known in the processing technology [16], and which is derived from the mass balance of the processing operation:

$$\varepsilon(w) = \frac{\beta(w)}{\alpha(w)} \cdot \gamma(w)$$

where $\alpha(w)$ is a metal (Cu) content in the feed, $\beta(w)$ is a metal (Cu) content in the main product of specified type of rock $w=$(shale, carbonate or sandstone).

The second relationship (7) is useful for further calculations and will be the empirical hypothesis of a relationship between Cu recovery and the desired concentration of that metal in the concentrate [6]:

$$\varepsilon(w) = 1 - \left[ \frac{\beta(w) - \alpha(w)}{\beta_{\text{max}}(w) - \alpha(w)} \right]^{\gamma(w)}$$
where $A = f(\pi, z, t, w)$ is a function of current values of the operation parameters $\{\pi\}$, environmental variables $\{z\}$ and duration of the beneficiation operation $t, \beta(w)_{\text{max}}$ – limit of the metal (Cu) content in processed minerals, $\alpha(w), \beta(w)$ – as in (1); $\gamma_i$ is relative amount of concentrate.

Thus, Cu recovery to the concentrate is dependent on the type of rock, and one needs to know the relationship $\alpha(\beta) = f(\lambda, w)$, that is the type of processed rocks, and calculate the operation according to its share in the feed flowing to the concentrator. An example of such calculation is given in Figure 15.

The key production problem of the mine is to maintain the quality and quantity of the ore at an appropriate level for the processing plant. The problem arises due to variation of lithological composition of the ore, which is a mixture of many ore streams coming from different divisions, where lithological structure of the deposit is also varied. In such a case, the average Cu content in the concentrator’s feed is expressed by the following formula

$$\alpha \leq \overline{\alpha} = \frac{\sum_{i=1}^{n} \lambda_i \cdot P_i}{\sum_{i=1}^{n} P_i}$$

$$Q \approx \sum_{i=1}^{n} P_i$$

, where:

$\alpha$ - Cu content in ore to be mined

$\lambda_i$ – Cu ore content from i-mine division


\[ \bar{\lambda} \] - mean Cu grade obtained from n-mine divisions
\[ P_i \] – production of i-mine division
\[ Q \] – contracted ore input to the concentrator plant

Conveying ore from mine divisions to concentrators is done by means of conveyor systems and shafts. During transport the ore is crushed and mixed in aggregate points and storing silos. Thus, the data obtained from the forecast calculations, as in Figure 15, are in principle an important source of information only for longer planning periods, since in practice the real distribution of metal concentration in the ore is the same as in Figure 16. Nowadays, some efforts have been undertaken to control this process on the path from ore extracting operations (mine divisions) to the concentrator’s bin, by tracking some information species added to the ore streams [17]

3.5. Smelting and refining stage
Mineral and lithological compositions of copper concentrates produced from different sources are varied [18]. That is why the smelting mills mix these concentrates in a way suitable for their own smelting technology. Planning and optimization of feed to metallurgical process is possible if we can predict the mineral and lithological composition of rocks as shown in Figure 15. Reversing the problem, we can also formulate qualitative and quantitative criteria for design of geo-metallurgical blocks of deposit classifying them according to block parameters to provide fairly stable characteristics of the feed for metallurgical processes.

For the estimation of costs of metallurgical treatment operations, a cost deduction formula used in calculation of Net Smelting Revenue (NSR) may be applied as follows

\[
NSR = \left[ \sum \left( \beta_i \cdot \delta_i \cdot p_i \right) - (MC + DC) - P + B \right] \cdot \gamma_i
\]

(11)

\[
MC = \sum_{i} \left( \beta_i \cdot \delta_i \cdot RC_i \right) + TC
\]

(12)

, where:
\( NSR \) – net smelter revenue measured in $ per 1 ton of ore,
\( \beta_i \) – share of i-component (metal) in the main product (concentrate),
\( \delta_i \) – payable part of metal in the concentrate,
\( p_i \) – price of the i-component in the open market,
\( MC \) – metallurgical charge in $ per 1 dry meter ton 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),

Figure 16. Example of feed and operation product grade recorded in 435 sequenced workshifts

![Figure 16](image-url)
γ₁ = I - γ₂ – yield of the concentrate in the feed (ore), where γ₂ – yield of tailings, and γ₀ = I – amount (unit) of feed (ore).

Formula (11) may additionally introduce costs of chemical analyses (quality testing) and other contractual limitations.

Variable costs of metallurgy depend on the quality and quantity of the ore, i.e. copper concentrates. The dependence of metallurgical costs on concentrate quality manifests itself at the stage of metal smelting. Further operations, such as primary metal refining and precious metal metallurgy, depend only on the deposit quality. However, the costs of smelting will depend not only on the metal content of the processed concentrates, but also on the lithological composition of the concentrates, since the energy balance of the metallurgical process (especially shaft furnace) is more favourable to carbonate concentrates and less favourable to sandstone concentrates. There is even a practice of rationalizing the furnace charge due to type of rocks of the processed concentrates. Control over that process is possible only if we calculate the lithological structure of these concentrates. That option exists in the proposed calculation method for a long-term planning only.

4. Numerical example of system analysis

Unfortunately, due to great complexity of the metallurgical process [12], it is rather impossible to design a metallurgical model like it was proposed for the preceding operations. This type of study was undertaken in the work of Waluk [3] based on the uncertain statistical formulas of Stepinski [13] describing the influence of metal content in concentrates on the costs of metallurgical process. A much reliable approach to the problem would be to combine NSR estimation with mining costs in the following formula

\[
\text{Profit} = \text{NSR} - \text{Mining Costs}
\]  

In this formula the mining cost is the sum of costs of exploration, mining and processing. Figure 20 presents a probable result of formula (13) and numerical calculations made for hypothetical data of a deposit with parameters corresponding to the LGCB geology. In this example, the average mining cost is equal to 56.32 $/t. This cost is a sum of extracting and processing costs. Extracting costs consist of fixed costs (assumed at 50%) and variable costs (50%) which
depend on the actual exploitation gate and which change according to formula (6). Other initial data are presented in Table 4. Thus, if we control the exploitation gate that influenced the Cu content (α) in the extracted ore, which in turn has an impact on the concentrate value (mine revenue, Figure 19), the profit of Cu production will be varied as in Figure 20.

5. Conclusions

Copper mining technology may be examined as a technological fractal and described as interrelated equations (1). Identification of these equations is a challenge for science and technology.

The copper ore deposit in the Legnica-Glogow Copper Belt has a lithological structure specific for sedimentary rocks. The main rocks are carbonates, clayey organic-rich shale (Kupferschiefer), and sandstones. The Cu (and Ag, Au) content of these rocks varies. The Cu content variation in the layer’s profile is proposed to be described by a simple power distribution function with parameters that depend on the parameters of the shale layer and its location in the deposit field. This approach allows to establish a dependency between the size of operation gate and Cu content in the ore. Mining practice [15] shows that the operating costs depend on the size of the exploitation gate. Thus, it is possible to link the ore extraction operation volume and Cu content with production costs. Processing operations efficiency depends on the quality of the ore. It is possible to link the lithological composition of the ore and metal content in ore with efficiency of enrichment and grading of concentrates. However, this dependency can only be used for long-term planning because of the inability to control the content of metals in individual lithological layers as a result of their mixing in transport processes. Effectiveness of metallurgical processes depends on the quality of copper concentrates and their mineralization. At present, only a heuristic cost model can be proposed.

Analysis of effectiveness of the whole production system is possible in two ways: by controlling the quality and quantity of the operations and the cost of their production throughout the production cycle, or by calculating the profit of the mine as a subtraction of mining costs from income (NSR). The second approach is presented in the paper as a numerical example of the ability to control the profit by changing mining operation parameters. This approach seems to be more fruitful for the time being.

The presented method and models have certain value as the analytical tool for strategic planning of the deposit economy. Also, they are valuable for determination of geo-metallurgical properties of the deposit. Their also have social value because the enable the stakeholders to learn how internal factors (corporate production policy) and external factors (world market prices) influence the economy of domestic mineral resources exploitation.

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