

Effectiveness of mineral waste management

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Abstract: Mineral waste is a side effect of mineral industry activity. In the case of metal industry, flotation waste generated during ore treatment and slag produced in metallurgical processes are large in quantity. Implementation of effective methods for utilization of waste is one of priorities, leading to measurable economic and environmental effects. Taking these facts into consideration, four effectiveness models were proposed and analyzed in terms of waste management in current processes as well as waste utilization in new products. Calculation algorithms for all models have been developed.

Keywords: waste management; landfill mining; economic assessments

Introduction

Mining and further processing of ores is accompanied by waste generation and their disposal on the Earth's surface or in mine workings. The footprints of this are visible in the form of heaps, dumps or ponds. Often, the wastes constitute an unnatural landscape element, usually creating objects of various shapes and heights or artificial water reservoirs. The waste take up agricultural and forest land and create hazard due to a risk of landslide. At the same time, the waste has a negative impact on water and soil. Sometimes, it is still visible even after land reclamation.

In the copper industry the waste is produced in the mining process and ore treatment consisting of crushing, grinding, flotation and dewatering. The tailing of flotation is usually disposed in the so-called settling ponds. An analysis of available worldwide publications on possible beneficiation of flotation waste indicates that the copper ore waste can be used in ceramics production because in combination with other components, brown and black pigments for ceramic glaze can be obtained. It has also been established that addition of flotation waste to ceramic mixtures causes reduction of shrinking of final products and elimination of water absorption [13, 14]. Another method of reduction of the amount of

copper industry waste is to use it for production of various abrasive material, cutting tools and devices and special-purpose tiles [4]. The flotation waste can also be a source of iron compounds useful for production of hydraulic binding agents in the cement production, road construction or backfilling the mined out spaces [1, 2, 9].

Many types of waste are also generated in metallurgical processes including shaft furnace slag, electric furnace slag, gas scrubbing and converter sludge, and dusts. The shaft furnace slags are used as aggregate or surface working reclamation material while granulated slag is applied as abrasive material or as a component of hydraulic fill. Lead-bearing dusts and sludge, usually accompanying copper production, are processed into crude lead. Desulfurization waste is used as a flux in metallurgical furnaces and what is left is stored, after neutralization, in special chambers within the metallurgical plant areas.

Considering a large amount of waste produced worldwide, it is necessary to find a solution for the raw materials treatment with zero waste option (Figure 1). Innovative technologies, leading to recovery of all components from raw materials, will be helpful for this purpose.

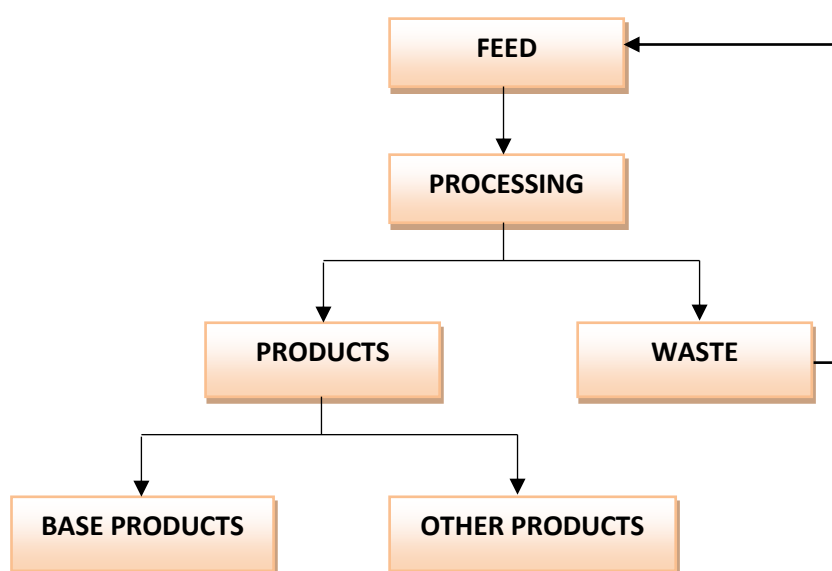


Fig. 1. Raw materials treatment with zero waste approach

Waste originating from the Polish copper industry creates also environmental problems due to its large volume and some toxicity. The flotation tailing of copper sulphide ore mined in Poland represents about 94% of the mass of the run-of-mine ore (Table 1). The ore is of sedimentary origin and the tailing consists of quartz, dolomite and clay minerals with some sulphides and accessory minerals. Until now, about 800 million tons (million megagrams, 10^6 Mg) of copper flotation tailing has been deposited in the Legnica-Glogow region and 28 million Mg is added every year. The flotation tailing, besides copper minerals, contains also minerals of other valuable metals, and new studies show that they can be recovered by hydrometallurgical methods [8, 12].

Table 1. Average chemical composition of flotation waste produced by Polish copper industry [10]

	Lubin	Polkowice	Rudna
SiO ₂ , %	57.24	19.67	53.27
CaO, %	11.87	24.85	13.88
MgO, %	4.23	6.19	5.25
Al ₂ O ₃ , %	4.17	3.25	3.84
Cu, %	0.15	0.19	0.21
Pb, %	0.04	0.02	0.02
Ag, ppm	10	6	8
As, ppm	50	30	20
Co, ppm	52	18	12
Zn, ppm	90	60	60
Fe, %	0.82	0.54	0.52
Na, %	0.23	0.28	0.24
K, %	1.24	1.18	1.14

The best approach to waste management is creation of technical and technological conditions to process it further. Considering the present state of technology and science, it is usually possible to find a quite well operating technical system with its negligible impact on environment, but such system very likely will be expensive, while economics of waste processing is very important. The cost of getting social acceptance of waste beneficiation also increases the financial outlay of the selected way of treatment. Therefore, many elements of waste management create difficulties [6, 7]. Such a complex system can be analyzed by multi-criteria decisive methods which are based on mathematic tools enabling to evaluate waste

management. These tools are able to perform objective evaluation of waste management system, replacing intuition evaluations based on expert's opinions. They also allow evaluating the system in conformity with requirements of environment management even in the case of change of regional conditions.

The aim of the paper is to present and evaluate four effectiveness models of waste management in different applications. Calculation algorithms for all models were developed.

Waste management and methods of environment damage estimation

Wastes that can be effectively utilized are divided into two categories: containing recoverable useful components and used for other applications. The waste disposal is usually associated with environmental degradation and considerable financial burden [5, 15, 16]. The quantity of waste generated during ore upgrading process can be calculated using the following formula:

$$\gamma_o = \frac{\beta - \alpha}{\beta - g} \cdot 100\% \quad (1)$$

where γ_o stands for the waste yield expressed in %, β for content of useful component in the concentrate in %, α content of useful component in the feed in % and g content of useful component in the waste in %.

Taking Polish copper ore as an example, for which roughly $\beta = 30\%$, $\alpha = 2\%$ and $g = 0.2\%$, the value of $\gamma_o = 94\%$ is obtained. When the amount of processed ore is $6 \cdot 10^6$ Mg annually, as in the case of the Polish copper ore, the amount of generated waste is $6 \cdot 10^6$ Mg $\cdot 0.94 = 5.64 \cdot 10^6$ Mg.

Most often the mineral waste can be managed through:

- utilization in the currently applied technology, for instance as hydraulic fill in the mine workings or for manufacture of new products
- reprocessing for useful component recovery
- other processes.

The waste management leading to the useful component recovery does not solve the problem of its disposal because the waste volume is not significantly reduced. The essential factor influencing the necessity of seeking other solutions is possible damage caused by the

waste to the land and water environment, more specifically to agriculture, woodland, water resources, parks, people, housing, industrial plants, roads, railways and territorial development.

Estimation of damage is a complicated and responsible task requiring expert's knowledge and experience. Among the damage estimation methods, restitution, substitution and index methods can be distinguished.

The principal assumption of the restitution method is that the losses caused by environmental contamination, conversion or pollution are equal to the expenditure to be incurred on their liquidation and restoration of environmental balance. The loss estimation consists of calculating the necessary investment expenditures and operating costs of equipment used to reduce or eliminate the losses, including the restoration of the environment to its previous state. A disadvantage of this method is that estimation is isolated from the real losses.

The substitution method is used when there is a loss of a specific element or value of the environment. The cost is equal to the cost of acquiring the lost element in a different place or costs of the construction and operation of facilities able to fulfil the same function as the lost element of the environment.

The index method relies on establishing indices based of experience and empirical studies followed by appropriate generalization. The estimation of losses is performed using the direct calculation method for appropriately selected regions or trial areas. The results of these calculations constitute a base for calculating losses in other places.

Cost-effectiveness of waste management

Three aspects of waste minimization can be examined: profitability of useful components recovery, management methods and profitability-of investment expenditure. To evaluate the

cost-effectiveness of waste management, Net Present Value (*NPV*) can be apply. It represents the difference between the present cash inflow and outflow. *NPV* is used in capital budgeting to analyze the profitability of the investment. A positive *NPV* indicates that the projected earnings generated by a project exceeds the anticipated costs. Another indicator is Earning Before Interest and Tax (*EBIT*), being an operating profit criterion. The formulas of *EBIT* and *NPV* can be found in publications on the economic assessment of industrial projects [3, 10, 11, 17]. For the purposes of this work, the numerical values used for calculations of *EBIT* and *NPV* in the formulas regarding raw materials have been modified accordingly taking into account characteristics of the mineral waste. Four effectiveness models were analyzed:

- a) cost-effectiveness of waste management in a current process technologically linked with mineral components recovery
- b) cost-effectiveness of waste management in current process without mineral components recovery
- c) cost-effectiveness of utilization of waste in new products technologically linked with mineral components recovery
- d) cost-effectiveness of utilization of waste for making new products, without mineral components recovery.

The numerical values used in this paper are typical for the copper industry. They are hypothetical and do not refer to a specific case study.

Case 1. Cost-effectiveness of waste management in basic process technologically linked with mineral components recovery

Non-investment variant

The cost-effectiveness of waste management is assessed according to the operating profit criterion, which is described by the following formula:

$$EBIT = 0.01 \cdot \mathcal{G} \cdot \varepsilon \cdot Q(p - c) \pm P \cdot \Delta c_p + Q \cdot c_o. \quad (2)$$

For $z=Q/P$ Eq. 2 assumes the form

$$EBIT = Q \left[0.01 \cdot \mathcal{G} \cdot \varepsilon (p - c) \pm \frac{\Delta c_p}{z} + c_o \right]. \quad (3)$$

where $EBIT$ is operating profit with waste utilization in current production linked with mineral components recovery in USD/year, \mathcal{G} content of useful mineral components in waste in %, ε recovery of mineral components in technological processes specified by decimal number, p price of mineral components recovered in USD/Mg, c cost of acquiring mineral components from waste in USD/Mg, z coefficient specifying the ratio of annual amount of utilized waste to annual current production, Q amount of waste managed in Mg/year, P annual basic production in Mg/year, Δc_p decrease (+ sign) or increase (– sign) in costs of current production caused by waste management in USD/Mg, c_o payment for waste disposal in USD/Mg.

Investment variant

The cost-effectiveness of mineral waste management in the investment variant is described by the following formula:

$$NPV = NCF \frac{(1+WACC)^T - 1}{WACC(1+WACC)^T} - IC_1 - IC_2 \quad (4)$$

where

$$NCF = Q \left[0.01 \cdot \mathcal{G} \cdot \varepsilon (p - c + dep) + c_o \pm \frac{\Delta c_p - \Delta dep_{cp}}{z} \right], \quad (5)$$

and $T = 100/dep\%$,

where NPV is updated net value of waste management project in USD, NCF annual net cash flow in USD/year, T calculated period corresponding to average period of fixed asset depreciation in years, $WACC$ annual average cost of capital, IC_1 initial investment expenditures for technologies associated with mineral waste recovery in USD, IC_2 initial investment expenditures for technologies associated with waste management in USD, dep cost of fixed asset depreciation in current production following waste management in USD/Mg, Δdep_{cp} depreciation cost saving in basic production caused by waste management in USD/ Mg of basic production, $dep\%$ share of depreciation costs in total costs encompassing mineral waste recovery and waste management in %.

Calculation example

Flotation waste from copper ore treatment have been used for backfilling mine workings as a substitution of filling sand. Mineral components are recovered from the flotation waste in technological processes before using them as a backfill.

Data: $\mathcal{G} = 0.20\%$, $\varepsilon = 0.7$, $p = 6,000$ USD/Mg Cu, $c = 4,000$ USD/Mg Cu, $dep = 2,000$ USD/Mg Cu, $\Delta c_p = 100$ USD/Mg, $\Delta dep_{cp} = 50$ USD/Mg Cu, $dep\% = 20\%$, $c_o = 75$ USD/Mg,

$Q = 150.000 \text{ Mg/year}$, $P = 100,000 \text{ Mg Cu/year}$, $WACC = 0.1$, $IC_1 = 20 \cdot 10^6 \text{ USD}$, $IC_2 = 15 \cdot 10^6 \text{ USD}$, $z = 1.5$, $T = 5 \text{ years}$.

Non-investment variant: $EBIT = 21,660,000 \text{ USD/year}$. Investment variant: $NCF = 17,085,000 \text{ USD/year}$ and $NPV = 29,732,000 \text{ USD}$.

Case 2. Cost-effectiveness of waste management in current processes without mineral components recovery

Basing on formulas (3), (4) and (5) and omitting the segment specifying the cost-effectiveness of current waste recovery, the economic result of mineral waste management can be described by appropriate formulas.

Non-investment variant:

$$EBIT = Q \left(c_o \pm \frac{\Delta c_p}{z} \right). \quad (6)$$

Investment variant:

$$NPV = NCF \frac{(1+WACC)^T - 1}{WACC(1+WACC)^T} - IC_2 \quad (7)$$

where

$$NCF = Q \left(c_o \pm \frac{\Delta c_p - \Delta dep_{cp}}{z} \right). \quad (8)$$

Calculation example (Data as in Case 1)

Non-investment variant: $EBIT = 21,250,000 \text{ USD/year}$. Investment variant: $NPV = 46,425,000 \text{ USD}$ and $NCF = 16,250,000 \text{ USD/year}$.

From a comparison of the calculation examples presented as Case 1 and Case 2, it follows that the waste management without mineral components recovery is more advantageous.

Case 3. Cost-effectiveness of utilization of waste for making new products technologically linked with mineral components recovery

Non-investment variant

The cost-effectiveness of the non-investment variant of waste management is described by the following formula:

$$EBIT = 0.01 \cdot \vartheta \cdot \varepsilon \cdot Q(p - c) + NP(p_{np} - c_{np}) + c_o \cdot Q.$$

(9)

For $NP = Q \cdot \gamma$ and after substituting and arranging the following formula is obtained:

$$EBIT = Q[0.01 \cdot \vartheta \cdot \varepsilon(p - c) + \gamma(p_{np} - c_{np}) + c_o] \quad (10)$$

where symbols ϑ , ε , Q , p , c and c_o are parameters given earlier and NP is quantity of new product made from waste in Mg/year, γ yield of new product from waste, p_{np} price of new product in USD/Mg and c_{np} is the cost of making and selling new product from waste in USD/Mg.

Investment variant

The cost-effectiveness of waste management in the investment variant is described by the following formulas:

$$NPV = NCF \frac{(1 + WACC)^T - 1}{WACC(1 + WACC)^T} - IC_1 - IC_2 \quad (11)$$

where

$$NCF = Q[0.01 \cdot \vartheta \cdot \varepsilon \cdot (p - c + dep) + \gamma(p_{np} - c_{np} + dep_{np}) + c_o] \quad (12)$$

while dep_{np} means depreciation cost for making new product (in USD/Mg).

Calculation example

Flotation waste from copper ore treatment has been used for the production in combination with mineral components recovery from the waste.

Data: $\vartheta = 0.20\%$, $\varepsilon = 0.7$, $p = 6,000$ USD/Mg Cu, $c = 4,000$ USD/Mg Cu, $p_{np} = 37.5$ USD/Mg, $c_{np} = 12.5$ USD/Mg, $Q = 150,000$ Mg/year, $\gamma = 2.0$, $WACC = 0.1$, $dep = 2,000$ USD/Mg Cu, $dep_{np} = 5$ USD/Mg, $c_o = 75$ USD/Mg, $IC_1 = 20 \cdot 10^6$ USD, $IC_2 = 7.5 \cdot 10^6$ USD, $dep\% = 20\%$, $T = 5$ years.

Non-investment variant: $EBIT = 19,170,000$ USD/year. Investment variant: $NPV = 52,220,000$ USD and $NCF = 21,090,000$ USD/year.

Case 4. Cost-effectiveness of utilization of waste for making new products without mineral components recovery

Basing on given earlier formulas and after omitting the segment specifying the cost-effectiveness of mineral component recovery, the economic result of mineral waste management can be described by the given below formulas.

Non-investment variant:

$$EBIT = Q \cdot [\gamma \cdot (p_{np} - c_{np}) + c_o] \quad (13)$$

Investment variant:

$$NPV = NCF \frac{(1 + WACC)^T - 1}{WACC(1 + WACC)^T} - IC \quad (14)$$

where

$$NCF = Q \cdot [\gamma \cdot (p_{np} - c_{np} + d_{np}) + c_o]. \quad (15)$$

Calculation example (Data as in Case 3)

Non-investment variant: $EBIT = 17,750,000$ USD/year. Investment variant: $NPV = 69,045,000$ USD and $NCF = 20,250,000$ USD/year.

From the comparison of the calculation examples in Case 3 and Case 4 it follows, that the waste management without mineral components recovery from the waste is more advantageous.

Sensitivity analysis

For the purpose of assessing profitability of waste treatment, a sensitivity analysis should be performed. For parameters of Case 2, a sensitivity analysis of the operating profit was made to accomodate any change of the fee for landfilling in a surface repository (Fig. 2). In this

model, the waste is used to backfill post-mining excavations. Underground waste location allows the investor to reduce fee for using the landfill. Such activity also generates a positive factor in the profit and loss account of the enterprise.

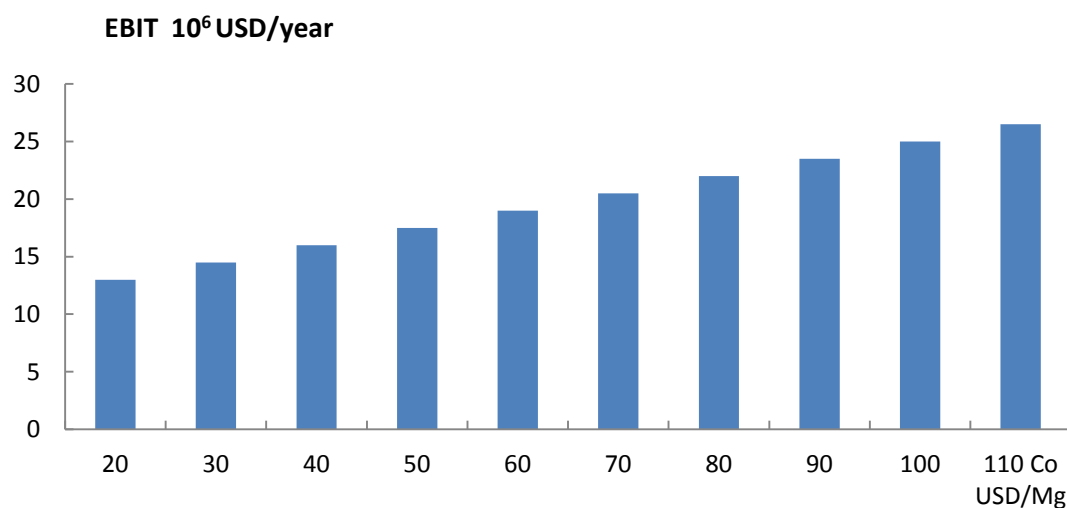


Fig. 2. Sensitivity of annual operating profit (EBIT) to changing the fee for landfilling (c_o)

Similarly, for the parameters of Case 4, the sensitivity analysis of the operating profit to a change in the price of the new product was performed (Fig. 3). Depending on the importance of the new product on the market, this venture becomes a profitable investment.

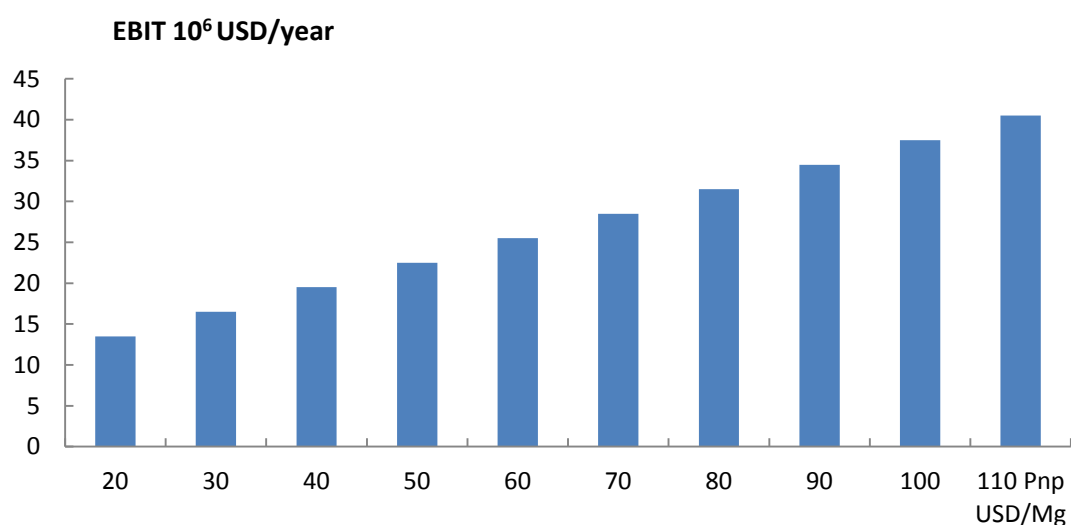


Fig. 3. Sensitivity of annual operating profit (EBIT) to changing the price of a new product (p_{np})

Summary

Management of waste generated during ore beneficiation, especially of copper ore mining, is an important issue in the pro-environmental activities of mining companies. However, the waste can be a source of valuable metals which are partially recover of using new more economical hydrometallurgical technologies. The paper presents methods of effectiveness of waste management estimation using different approaches. The effectiveness of the waste management was examined as: profitability of useful components recovery, management methods and as profitability of investment expenditure. In the case of the cost-effectiveness of waste management in a current processes, it is more profitable to apply the option without mineral components recovery. This solution increases *NPV* about 56%. In the case of the cost-effectiveness of utilization of waste for making new products it is more profitable to run the process without mineral components recovery. Then, the difference in the *NPV* values is about 32%. Basing on this example it can be concluded that the waste management is more advantageous without mineral components recovery. In the considered in this paper cases, this is due to a small content of copper (0.2%) in the waste.

The waste management can be technologically linked with the recovery of mineral components contained in the waste. When it is advantageous to manage and process the mineral waste without reducing its amount, then waste dumps become anthropogenic in their character. In practice, the waste is usually managed without the recovery of mineral components contained in it.

This work confirmed the profitability of the proposed solutions of the waste management. The results of the analyzed four cases revealed positive economic indicators of the offered approaches.

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