# Increasing the efficiency of secondary resources in the mining and metallurgical industry

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**Synopsis**

**An improved methodology is presented for assessing the economic feasibility and effectiveness of recycling industrial waste. The methodology is based on the break-even control mechanism, but at the same time provides for the introduction of new evaluation criteria such as the threshold of conditionality and the degree of ore substitution. Based on an improved analysis, it becomes possible to more precisely predict recycling efficiency. A more refined determination of the lower limit of concentration of recoverable metals, at which technogenic waste can be assigned the status of secondary raw materials and processed profitably, leads to a significant expansion of the secondary raw material base suitable for recycling. The potential for recycling manganese-containing dust from the production of ferrosilicomanganese, dehydrated sludge from the hydro separation of slags, and cake from the production of electrolytic manganese dioxide at the Chiatura mining enterprise is used as an example. It is shown that with a threshold of –24% Mn content, the highest recycling efficiency can be achieved by the production of low-phosphorus manganese slag and conversion to ferrosilicomanganese using the above waste to replace 40-60% grade III and IV manganese concentrates in the feed.**

**Keywords**

**industrial waste, secondary raw materials, efficiency of recycling, coefficient of conditionality, ore substitution index.**

## Introduction

Mining and metallurgy are major sources of industrial waste accumulation (BRGM, 2001). In this industry, on average, no more than 25% of the mined mineral resources, ends up in the final product. The remaining 75% constitutes industrial waste (Butorina, and Butorina, 2018).

According to Reuter and Kojo (2012), iron and lead undergo the highest degree of recycling – 47% each – followed by aluminum, copper, zinc, and nickel with indices of 40, 38, 36, and 34%, respectively. It is obvious that most metal-containing wastes are not included in the recycling stream and are stored indefinitely, which increases the risk of environmental pollution and other disasters (Bagrov, and Murtazov, 2010; Bolshina, 2012). Despite this, the appropriate management of metal-containing waste is still not given due attention, neither from the point of view of nature conservation, rational use of energy and natural resources, nor from the economic perspective. Global demand for metals is growing and will continue to grow due to the high rate of industrialization in developing countries (UNEP, 2013; Kaza *et al.*, 2018). Accordingly, in the short term, the rate of production of metal-containing industrial wastes will increase. Based on the current situation, the effective management of industrial wastes and secondary resources of the steel industry will remain relevant and of practical importance, both for environmental and economic reasons.

### Overview of the problem and setting the goal of the study

A survey of the literature shows that in the modern world there is already a consensus on the importance of solving problems of optimizing the use of primary (natural) resources and increasing the efficiency of recycling of wastes and secondary resources in the mining and metallurgical industry (Hogland *et al.*, 2014; NEA, 2019; Chernousov, 2011; Jishkariani *et al.*, 2012; Chernousov *et al.*, 2016; Sausheva, 2017; Allesch, and Brunner, 2015; Reuter, and Schaik, 2016; Brunner *et al.*, 2017; Ndlovu, Simate, and Matinde, 2017; Matinde, Simate, and Ndlovu, 2018). Modern technologies for recycling and processing secondary resources create new opportunities for sustainable development. However, the focus to date has been mainly on technological solutions. Less emphasis has been placed on improving the organizational and economic aspects of waste management, which is also important or increasing recycling efficiency (Abramov, 2009; van Schaik, and Reuter, 2016).

The need to improve the management of the waste in the mining and metallurgical industry is especially apparent when considering the problems involved in the efficient processing of resources with a relatively low content of valuable elements, such as tailings and metal oxide by-products (dust from electric furnaces, dehydrated sludge, slag). These materials are currently used mainly in the construction industry (Berdzenishvili, 2008; Tang *et al*., 2019; Romanova, and Begunov, 2016; Bolshakov *et al*., 2016; Needomskiy, Chernishev, and Chernishov, 2017), but this practice is irrational since they can be more effectively used as metallurgical raw materials (Rao, 2006; Norval, and Oberholster, 2011; Jandieri, 2012; Jandieri *et al*., 2012, 2015; Kojamuratov *et al*., 2017; Corte, Bergmann, and Woollacott, 2019).

According to the United Nations Environment Programme and International Solid Waste Association (UNEP/ISWA, 2015), one of the main priorities is to establish an effective, integrated system of management for recycling, utilizing, and neutralizing metal-containing wastes. This will include improving the tools for assessing the resource potential of industrial waste.

An analysis of improvement opportunities shows that a new approach should be based on the break-even concept (Cherniy, Kudriavskiy, and Golev, 2007), with the addition of fundamentally new evaluation criteria such as the concentration thresholds (allowable lower limits) of the recoverable elements and the degree of ore substitution. According to the break-even concept, a conditional resource will be understood to mean a technogenic resource with a metal content equal to or greater than the break-even point of the selected processing route. By establishing the concentration threshold of conditionality and the ore substitution index, it will be possible to predict the effectiveness of metallurgical processing of the secondary resource, which in turn will lead to a more accurate assessment of the feasibility of recycling and the scale at which it can be done. This can significantly expand the secondary resource base suitable for processing in the mining and metallurgical industry. As a result, the usage of expensive primary ore resources will decrease, harmful anthropogenic impacts on the environment will be reduced, and the inefficient and unsafe use of resources suitable for ferrous metallurgy in the construction industry will decrease.

Based on the above analysis, the development and practical implementation of the selected approach to improving the organizational-economic management system, an indicator for assessing the recycling efficiency can be derived (Abramov, 2009):

$$I_{er} = F\,(E_r,\ E_c,\ Q_j) \qquad [1]$$

where

$E_r$ - is an indicator of the economic efficiency of recycling

$E_c$ - an indicator of the environmental significance of recycling

$Q_j$ - an indicator of the scale of recycling.

## Theoretical research and analysis methodology

In order to solve the problem, we adapt the economic-mathematical model of breakeven (Cherniy, Kudriavskiy, and Golev, 2007) to the organizational-economic features of the system of industrial recycling, after which we obtain the model of break-even of recycling:

$$E_p \geq 0 \Rightarrow \sum_{j=1}^{n}\left(I_{\text{mj}}M_j K_{\text{rj}}\left(P_{\text{mj}} - C_{\text{mj}}\right) \cdot 10^{-2} + C_{\text{ej1}}\right) \geq \sum_{j=1}^{n} C_{\text{ej2}} I_{\text{mj}} M_j \qquad [2]$$

where

$E_p$ - is the expected income from the processing of technogenic resources ($).

$I_{mj}$ - the content of the *j*-th target component in the resource (%)

$M_j$ - the total mass of the recycled resource (t)

$K_{rj}$ - the coefficient of extraction of this component

$P_{mj}$ - the market value of the *j*-th component ($ per tont)

$C_{mj}$ - costs of recovery and extraction ($ per ton)

$C_{ej1}$ and $C_{ej2}$ - specific environmental costs before and after recycling ($ per tont)

$n$ - the number of extracted components.

In our case, the break-even point of recycling is the lower critical boundary of the content of the extracted component, $I_{\min}$, at which the selected process does not violate the margin threshold condition. Based on this, determination of the concentration threshold of conditionality of the resource can be determined from the following expression:

$$I_{\min} \geq \left(\left(C_m - C_{e1} + C_{e2}\right)/P_m\, K_{\text{vpm}} K_r\right) \times 100\% \qquad [3]$$

where $I_{min}$ is the permissible lower limit of the content of the target component in the resource (%), and $K_{vpm}$ is the coefficient of variation of the market price.

The ratio of the actual content of the target component, $I_{ac}$, to the calculated threshold content of that component, $I_{\min}$, will be called the coefficient of conditionality of the technogenic resource, $K_k$:

$$K_k = I_{\text{ac}}/I_{\min} \qquad [4]$$

The resource will considered as secondary raw material if $K_k \geq 1$.

To estimate the amount of primary concentrate that can be substituted by the raw materials, we introduce the ore substitution index, $I_{os}$:

$$I_{\text{os}} \leq 1 \Rightarrow K_{r2}\, I_{\text{ac}}/K_{r1}\, I_{\text{oc}} \qquad [5]$$

where

$I_{ac}$ is the concentration of the target component in the secondary resource (%)

$I_{oc}$ - the concentration of the target component in the primary concentrate (%)

$K_{r1}$ - the coefficient of extraction of the target component from primary concentrate

$K_{r2}$ - the coefficient of extraction of the same component from the secondary resource (established experimentally).

The norm of consumption of secondary raw materials of threshold conditionality ($I_{\min}$) in the production of a product with a given content of the extracted component ($I_{\text{met}}$) is equal to:

$$N(I) = I_{\text{met}}/I_{\min}\, K_{r2} \qquad [6]$$

In turn, the consumption norm of secondary raw materials differing in content from the calculated concentration threshold will be equal to:

$$N(I_{\text{ac}}) = N\,(I_{\min})/K_k = I_{\text{met}}\, k_k/I_{\min}\, K_{r2} \qquad [7]$$

It is noteworthy that although the profitability of the production of the target product when using secondary raw materials with an extremely low content of the recoverable component may be zero, the total profitability of the enterprise itself, *R*, will still increase due to the decrease in consumption of expensive primary raw materials, *i.e.* reducing the cost of normalized working capital:

$$R = V_p/(P_{cfa} + P_{vnwc}) \times 100\% \qquad [8]$$

where

$R$ is the profitability of the enterprise (%)
$V_p$ - annual production output ($)
$P_{cfa}$ - the cost of fixed assets ($)
$P_{vnwc}$ - the average annual value of normalized working capital ($).

Since the average annual cost of normalized working capital is a function of the saving indicator of the main ore raw materials $P_{vnwc}=f(E)$, it can be determined by calculating the reduction in the consumption norm of this raw material, $N_{\Delta q}$:

$$N_{\Delta q} = N_{qi} - \frac{N_{qi}N_{qj}}{W_1 N_{qi} + W_2 N_{qj}} \qquad [9]$$

where
$N_{qi}$ - is the norm of consumption of the ore raw materials per unit of finished product (t)
$N_{qj}$ - the norm of consumption of secondary raw materials approved by the technological regulations, (at $N_{qj}=N(I_{ac})$ $N_{qi}=0$) (t)
$W_1$ - the norm of waste generation during the processing of the raw materials (kg/t)
$W_2$ - the norm of formation of waste during recycling (kg/t).

In this case, taking into account the quantitative saving of the main raw materials $\Delta Q_i = Q_i N_{\Delta q}$ and its purchase price $P_i$, the expected cost savings $E_p$ on the purchase of ore raw materials can be calculated:

$$E_p = P_i Q_i \left( N_{qi} - \frac{N_{qi}N_{qj}}{W_1 N + W_2 N_{qj}} \right) \qquad [10]$$

As a result, the known functional dependence (Equation [1]) for evaluating the recycling efficiency index takes the following form:

$$I_{er} \leq 1 \Rightarrow \frac{\left(K_1(E_p+E_s)+K_2(C_{e1}-C_{e2})\right)K_3 Q_j}{C_m - C_{e1} + C_{e2}} \qquad [11]$$

where
$K_1$, $K_2$, $K_3$ - are the weighting factors that determine the importance of the economic, environmental, and scale components of the recycling process, which are determined experimentally
$E_s$ - revenues from the sale of secondary by-product silicate waste, as a suitable material for the construction industry.

For an accurate quantitative assessment of the reserves of target components contained in the secondary resource, we use the expression:

$$Q_j = Sh \sum_{j=1}^{n} I_{acj} \gamma_{mj} I_{osj} / K_{kj} \times 100\% \qquad [12]$$

where
$S$ - is the area of the accumulated secondary resource (km$^2$)
$h$ - the thickness of this accumulation (m)
$I_{acj}$ - the content of the $j$-th target component in the recycled secondary resource (%)
$\gamma_{mj}$ - the specific gravity of the $j$-th component (t/m$^3$)
$I_{osj}$ - ore substitution index of the $j$-th resource
$K_{kj}$ - the coefficient of conditionality of the $j$-th resource
$n$ - the amount of target components.

Based on the calculated indicator of the recycling efficiency index, provided that $I_{er} \leq 0.5$, the feasibility of further intensification of recycling processes and the maximum possible extraction of valuable components can be investigated by encouraging innovative developments and the introduction of high-performance energy-saving technologies. If this involves significant investments, the expected effectiveness of these investments needs to be assessed. For this we use the forecast indicator of the profitability index $I_i$:

$$I_i = \frac{\sum(M_{in} - M_{out})}{K_t} \qquad [13]$$

where
$M_{in}$ and $M_{out}$ - are the expected cash inflow and outflow
$K_t$ - project investment capital
$T$ - project implementation period (months, years).

In turn, as an indicator of the expected effectiveness of developed or implemented innovative technologies, we can to apply the integrated efficiency coefficient of the use of technogenic resources, $K_i$, which is used to determine the ratio between the volumes of recycling before and after applying innovative technologies to the total amount of secondary raw materials in need of processing:

$$K_i = \sum_{i,j=1}^{n} \frac{\sum(V_{ri} - W_{ni})}{\sum(V_{rj} - W_{nj})} \cdot \frac{1}{Q_{rj}} \qquad [14]$$

where
$K_i$ - is the coefficient of useful use of secondary material
$V_{ri}$ - consumption of secondary raw materials after the application of innovative technology (t)
$V_{rj}$ - consumption of raw materials before the application of innovative technologies (t)
$W_{nj}$, $W_{ni}$ - inevitable repeated technological losses before and after the application of innovative technology (t)
$Q_{rj}$ - the total quantity of accumulated secondary resources (t).

Taking into account the predicted indicators of the useful use of secondary raw materials and the investments required for this, the mathematical expression (Equation [11]) for a comprehensive assessment of the recycling efficiency can be written as:

$$I_{er} = \sum_{i,j=1}^{n} \frac{\sum_{i=1}^{i}(V_{ri} - W_{ni})}{\sum_{j=1}^{j}(V_{rj} - W_{nj})} \cdot \frac{\sum_{t=1}^{T}(M_{in} - M_{out}) \cdot (K_1(E_p + E_s) + K_2(C_{e1} - C_{e2}))K_3 Q_j}{K_t Q_{rj}(C_m - C_{e1} + C_{e2})} \rightarrow 1 \qquad [15]$$

If internal recycling is not possible or expedient, which may be due to poor technical and economic indicators of the main production process and, accordingly, to a high concentration threshold of conditionality and ore substitution, it may be possible to market the accumulated secondary resource to other, more technologically flexible enterprises. In this case, the outcome is given by the following expression:

$$E_r = Q_{rs} \cdot \left[ P_p - \left( \sum_{j=1}^{n} \frac{C_{cdj} + C_{cpj}}{I_{os} \cdot K_{wj}} + E_n I_{sp} \right) \right] \qquad [16]$$

where
$P_p$ - is the sale price of the base ton of secondary raw materials ($ per ton)
$C_{cdj}$ - costs of collecting the $j$-th type of recyclable materials ($ per ton)
$C_{cpj}$ - preparation costs for the sale of this raw material ($ per ton)
$Q_r$ - the volume of raw materials sold (t)
$I_{os}$ - ore substitution index
$K_{wj}$ - correction coefficient of the degree of external clogging
$E_n$ - the normative coefficient of comparative economic efficiency of capital investments ($E_n = 0.16$)
$I_{sp}$ - specific capital investment for the processing of 1 t. of secondary raw materials ($).

If necessary, for a separate assessment of the expected environmental effect of recycling, Equation [17] can be used to calculate the savings on environmental costs, depending on the reduction of the negative environmental impact:

$$E_e = M_v \cdot S_a \cdot K_e \cdot K_{eh} + \sum_{j=1}^{n} P_{ej} \cdot M_j \qquad [17]$$

where

$M_v$ - is market value of land adjacent to the enterprise ($ per km²)

$S_a$ - the land area saved from pollution (km²)

$K_e$ - the coefficient of ecological and social significance of this area

$K_{eh}$ - coefficient of environmental hazard of a polluting metal

$P_{ej}$ - state duty for the accumulation and landfill of metal pollutant ($ per ton)

$M_j$ - the mass of metal recovered during recycling (t).

## Analysis and discussion of results

The technical-economic indicators of different enterprises, even those producing the same product, differ significantly, depending on numerous technical, technological, and organizational-economic factors, including differences in mineralogical characteristics, physicochemical properties, and the cost of basic and auxiliary raw materials. Therefore, calculations for each specific enterprise must be carried out individually, for local conditions of industrial recycling. As an example, we investigated the possibility of recycling manganese-containing secondary resources at Georgian Manganese LLC, which comprised the Chiatura mining enterprise, Zestafoni ferroalloy plant, and Varcikhe hydroelectric power station.

Figures 1 and 2 give details of the types of manganese ore beneficiation wastes in the Chiatura mining enterprise, their qualitative and quantitative characteristics, and the annual amounts of oxidic waste generated from ferrosilicomanganese smelting at the Zestafoni ferroalloy plant. Each year an additional 500 000 t of slime (10-11% Mn), 250 000 t of so-called agglomeration grade (14-16% Mn), and 350 000 t of intermediate product (15-16% Mn) are generated (Jandieri, Sakhvadze, and Raphava, 2020; Sasmaz, Sasmaz, and Hein, 2021).

It is possible to process waste (hydrometallurgical sludge, -30±3% Mn) from the production of electrolytic manganese dioxide together with the indicated technogenic resources to produce either low-phosphorus manganese slag suitable for the production of standard ferrosilicomanganese (FeMnSi18, ISO 5447, 1980) or ferrosilicomanganese (FeMnSi28, ISO 5447, 1980) for smelting medium- and low-carbon ferromanganese (FeMn90C20, ISO 5446, 2017).

Figure 3 illustrates the dependence of the coefficient of conditionality, $K_k$, on the calculated concentration threshold of conditioalityn $I_{min}$ and the actual manganese content in secondary manganese-containing raw materials. Figure 4 shows the change in the quantitative indicator of ore substitution, $I_{os}$, depending on the manganese content in the secondary manganese-containing raw material, when substituting manganese concentrates of grades I, II, III, IV. Figure 5 illustrates the dependence of the norm of consumption of secondary raw materials on the concentration of manganese in the final product.

As regards the practical application of the results, it is especially important to consider the trends in Figures 4 and 5. From Figure 4 it is seen that a secondary resource that contains 24-27% manganese (for example, electric furnace dust, dehydrated sludge) can replace manganese ore concentrate grade I (48% Mn) by 28-40% grade II (42% Mn) by 35-45%, grade III (36% Mn) by

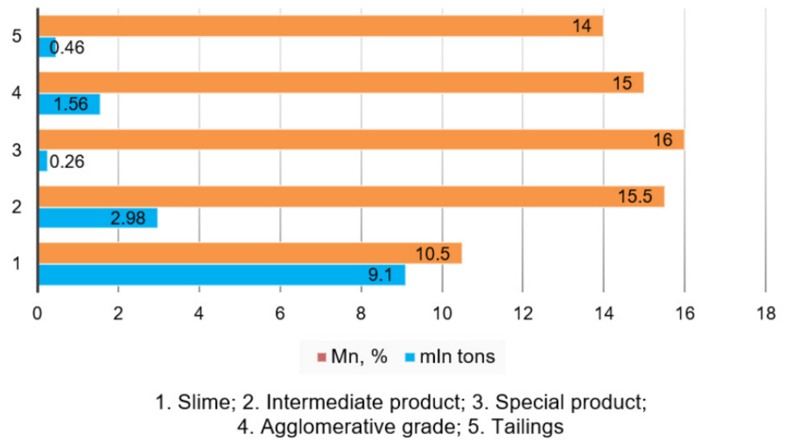


**Figure 1—Types of manganese ore-beneficiation wastes at the Chiatura mining enterprise and their qualitative and quantitative characteristics**

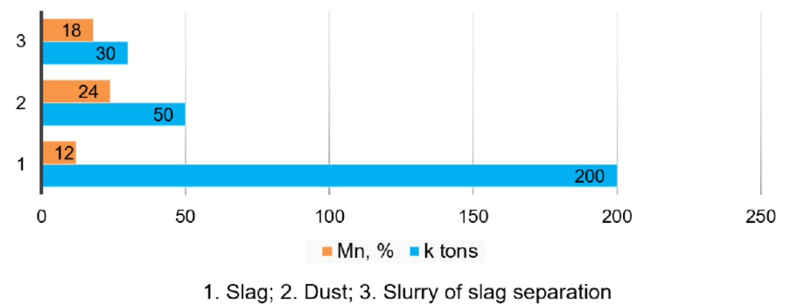


**Figure 2—Annual production of solid oxidic waste from ferrosilicomanganese smelting in the Zestafoni ferroalloy plant**

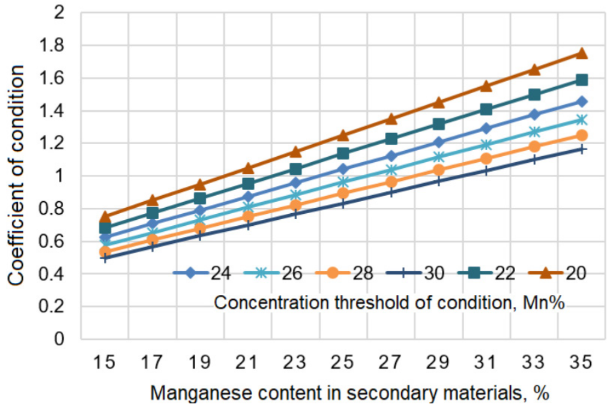


**Figure 3—Change in coefficient of condition depending on the concentration threshold and manganese content in the secondary raw material**

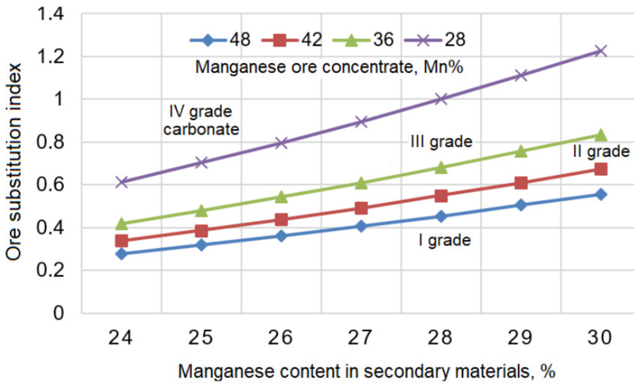


**Figure 4—Dependence of the ore substitution index on the manganese content in the secondary raw materials and the quality of the substituted ore concentrate**

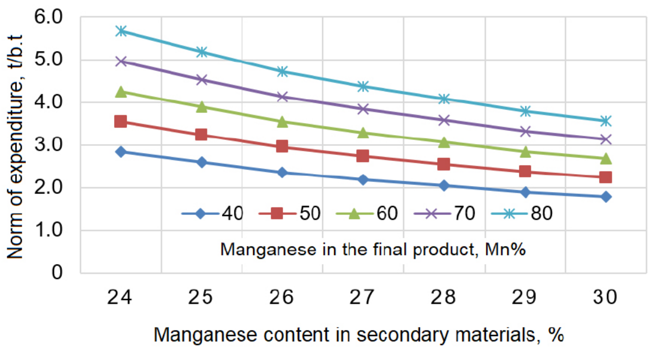


**Figure 5—Effect of the manganese content in the secondary raw materials and in the product smelted from it on the consumption of secondary raw material**

42-60%, and grade IV (28% Mn) by 62-90%. Secondary raw materials that contain 27-30% Mn (for example, sludge from the production of electrolytic manganese dioxide, slag from the production of carbon ferromanganese) can replace grade I manganese concentrate by 40-58%, grade II by 50-65%, grade III by 60-82%, and grade IV by >90% (*i.e.*, 800-1100 kg of the secondary material can be substituted for 1 t of grade IV concentrate).

At the Zestafoni ferroalloy plant, when smelting special low-phosphorus slag (38-40% Mn), the concentration threshold for conditionality of manganese-containing secondary raw materials is 24% Mn, for which the consumption of manganese secondary raw materials is 2.6-2.8 t per base ton of product. At a manganese content of 26% in secondary raw materials, the consumption decreases to 2.2-2.4 t per base ton product. For the production of ferrosilicomanganese (FeMnSi28, 57-60% Mn), secondary raw materials with a manganese content of 28% can be used – the consumption of such secondary material will be 2.9-3.1 t per base ton. Recycled materials containing 30% manganese and with an acceptable phosphorus level can be used in the production of ferrosilicomanganese (FeMnSi18, 65-70% Mn) or ferromanganese (FeMn75C80, 75-80% Mn), with a consumption of 2.8-3.2 t. and 3.4-3.6 t per base ton respectively (data from Figure 5).

An analysis of the results shows that the highest recycling efficiency index can be achieved by maximizing the environmental and large-scale components, *i.e.* The purpose of combining resources of various types is to obtain secondary raw materials with a threshold content of the target component. For example, mixing relatively Mn-rich sludge from the production of electrolytic manganese dioxide (27-30% Mn) with sludge (slag sand) from the hydro separation of ferrosilicomanganese slag (18% Mn) in a ratio of 1:0.5 yields an intermediate product with a threshold manganese content of 24-25%. According to Figure 4, such secondary material can reduce consumption of grade IV manganese concentrate by 60-70%, and that of grade III by 40-50%, in the smelting of low-phosphorus slag (40% Mn) or ferrosilicomanganese (57% Mn) respectively. If it is necessary to completely omit the use of grade III and IV manganese concentrates, it will be necessary to utilize 2.8 t and 3.6 t of these combined raw materials, respectively (Figure 5). An additional benefit in the processing of these secondary raw materials is the high content of silicon dioxide ($SiO_2$ 45 ± 5%). This can also lead to a decrease in the consumption of quartzite (96% $SiO_2$) by an average of 30%.

It should be noted that the above approach to improving recycling efficiency can be especially effective for recycling metal-containing secondary resources, with the stability of internal and external economic factors that significantly affect production indicators. For example, recycling efficiencies, from an economic point of view, can be significantly affected by fluctuations in the market prices of the main and auxiliary raw materials (manganese concentrate, coke, electrode materials *etc.*), for energy resources (electricity, natural gas), or for the products. The significance of this problem is quite clearly emphasized in the generalized study (Carrera, Bastourre, and Ibarlucia, 2010). Recycling efficiencies may also fluctuate due to unplanned downtime of main production furnaces and auxiliary units. According to Equation [3], in such cases there will be a consequent deviation in the value of the conditionality threshold of the recyclable resource (the break-even point of the recycling process will change). This, in turn, will affect the coefficient of conditionality (Equation [4]), ore substitution index (Equation [5]), and the norm of consumption of secondary raw materials (Equations [6] and [7]).

It is also important to note that with an increase in the cost of ore concentrates and other charge materials, or a decrease in the price of manufactured products, enterprises that are dependent on imported raw materials, by developing their own system of internal recycling/processing of accumulated production waste (replacing expensive purchased ore with cheaper secondary resources) will be more competitive, economically more stable, and less sensitive to external economic factors. In the case of external recycling (transfer or sale of secondary resources to other processing enterprises, recycling efficiency will decrease due to margins on logistics services (Equation [16]). According to Equation [15], the maximum recycling effect is achieved by maximizing the efficiency index $I_{ermax} = 1$.

The algorithm for the practical implementation of the developed methodology for increasing recycling efficiency can be graphically illustrated in the form of a functional flow chart (Figure 6). The particulars of the functioning of the proposed algorithm are as follows: In the first instance, after determining the initial data on the metal content in the waste ($I_{ac}$) according to Equations [2] and [3], the break-even point and the corresponding threshold of conditionality of the waste ($I_{\min}$) are determined. If the metal content is greater than the minimum permissible ($I_{ac} > I_{\min}$), the resource is classified as a conditional secondary raw material and its technological characteristics ($K_k$), ($I_{oc}$), ($N (I_{\min})$) and ($N (I_{ac})$) are determined according to Equations [4]-[7]. If the metal content in the waste is below the threshold concentration, then in-house recycling will be inefficient. Provided that the waste is a conditional secondary raw material ($I_{ac} > I_{\min}$), then the consumption savings ($E_p$) for the main ore raw materials are calculated according to Equation [10]. Equation [12] is used to estimate the total resource (reserve) of secondary raw materials ($Q_j$), while the savings on environmental taxes ($E_e$) are determined by Equation [17]. Using the data obtained, Equation [11] provides for the preliminary assessment of the recycling efficiency ($I_{er}$). If the calculated efficiency is higher than 50% ($I_{er} \geq 0.5$), then recycling is efficient and can be carried out without any additional investment and/or using existing production capacities and infrastructure.

Alternatively, if the estimated efficiency is below 50%, then the recycling efficiency is considered to be low and an additional investment is required to increase it to $I_{er} \geq 0.5$. In this case, after determining the object or technology of additional investment, according to Equations [13] and [14], a forecast of the effectiveness of the planned investment ($I_i$) and ($K_i$) is made, after which the waste recycling efficiency ($I_{er}$) Equation [15]) is then re-evaluated. If the total recycling efficiency has increased to 0.5 or higher, then the metal-bearing secondary resource can be subjected to target processing after additional investments. Should the total recycling efficiency after possible additional investment still remain below 0.5, then in-house processing is uneconomic and not worth pursuing. It is thus recommended to consider the recycling and re-use of the metal-bearing wastes in alternative industries. In this case, Equation [16] is used to calculate the expected economic return from the direct sale of secondary raw materials ($E_r$). The improvement of the abovementioned technical, technological, economic and environmental performance indicators leads to an overall sustainable increase in recycling efficiency.

## Conclusion

Based on the results of the study, it can be concluded that by applying the proposed recycling efficiency improvement technique, the following practical problems can be solved:

- A qualitative and quantitative assessment of the appropriateness and scale of internal recycling of a secondary technogenic resource
- Calculation of the total conditional reserves of valuable components in the accumulated secondary resource
- Identification of the appropriate proportions for combining secondary resources of different types and conditionalities.

This will lead to a significant increase in the secondary raw material base suitable for profitable recycling and extraction of valuable components.

In particular, the recycling of manganese-bearing secondary resources at the Chiatura mining enterprise using the proposed algorithm will:

- Increase total manganese recovery from the current 50-55% to 75-80%
- Reduce manganese concentrate consumption by 25-30% with a corresponding increase in the service life of operating mines
- Reduce the cost of ferroalloy production by 10-15%.

The present solution to the problem of increasing recycling efficiency is universally applicable and can be particularly successfully used to improve the processing efficiency of secondary resources in the production of metal semi-finished products such as manganese, chromium and silicon ferroalloys, ligatures, and modifiers that are produced in bulk.

## References

Abramov, A.I. 2009. Evaluation of the effectiveness of recycling. *Bulletin of the St. Petersburg*. University of State Fire Service, vol. 4. pp. 36–38. https://vestnik.igps.ru/wp-content/uploads/V4/7.pdf [in Russian].

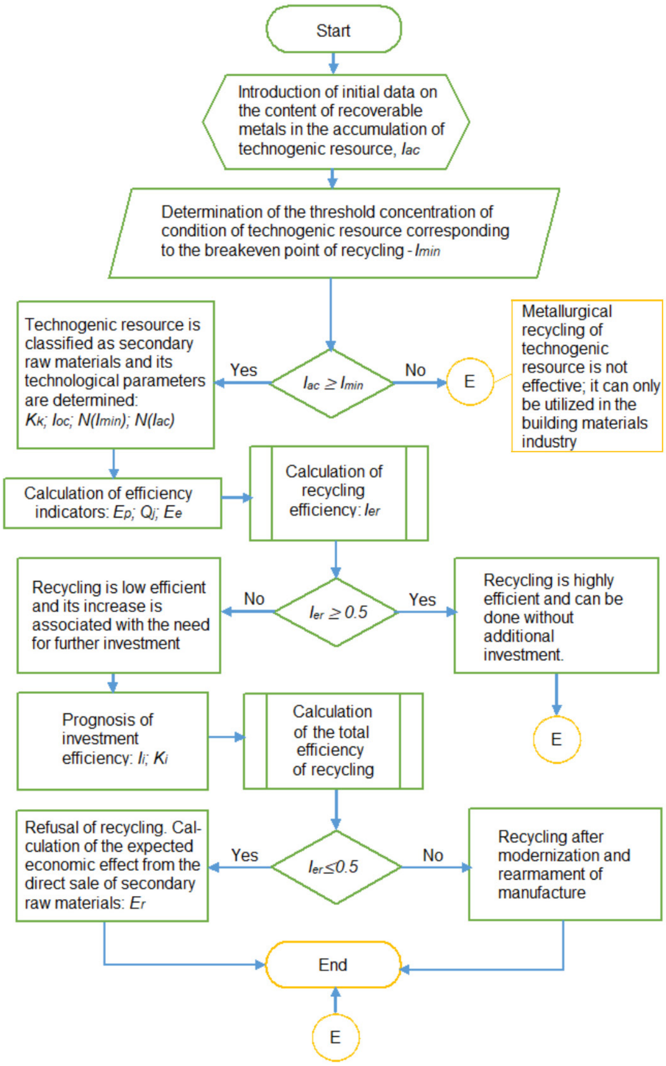


**Figure 6—Functional algorithm to increase the efficiency of recycling of secondary resources of the mining and metallurgical industry**


Allesch, A. and Brunner P. 2015. Material flow analysis as a decision support tool for waste management: A literature review. *Journal of Industrial Ecology*, vol.19, no. 5. pp. 753–764

Bagrov, A.I. and Murtazov, A.K. 2010. Technogenic systems and theory of risk. S.A. Yesenin Ryazan State University, Ryazan, Russia. 207 c. https://www.rsu.edu.ru/wp-content/uploads/users/m.mahmudov/Bagrov_Murtazov.pdf [in Russian]

Berdzenishvili, I.G. 2008. Utilization of electrolytic manganese dioxide production waste in silicate industry. *Proceedings of the 5th International Conference on Cooperation to Solve the Problem of Waste*, Kharkov, Ukraine. https://waste.ua/cooperation/2008/theses/berdzenishvili.html

Bolahsakov, V.I., Eliseeva, M.A., Nevedomskij, B.A., and Shcherbak, S.A. 2016. Building materials and products based on silicomanganese slags. *Bulletin of the Dnieper State Academy of Civil Engineering and Architecture*, vol. 5, no. 218. pp. 54. http://nbuv.gov.ua/UJRN/Vpabia_2016_5_9 [in Russian].

Bolshina, E.P. 2012. Ecology of metallurgical production. Novotroitsk, Russia, *NB NUST MISiS*. 155 pp. https://nmetau.edu.ua/file/ktemp_15502.pdf [in Russia].

BRGM. 2001. Management of mining, quarrying and ore-processing waste in the EU. 79 pp. https://ec.europa.eu/environment/waste/studies/mining/0204finalreportbrgm.pdf

Brunner, Ch., Schwelberger, J., Fleischanderl, A., and Ropke, A. 2017. Practice of recycling operations in iron direct reduction units. *Chernye Metally. Journal of Ore and Metals*, vol. 8. pp. 59–63. https://www.rudmet.ru/journal/1652/article/28375/

Butorina, I.V. and Butorina, M.V. 2018. Review of wastes utilization technologies in mining and metallurgical industry. *Chernye Metally, Journal of Ore and Metals Publishing House*, vol. 12. pp. 44–49. http://www.rudmet.ru/journal/1781/article/30433/

Carrera, J., Bastourre, D., and Ibarlucia, J. 2010. Commodity prices: Structural factors, financial markets and non-linear dynamics. Banco Central de la República Argentina, Investigaciones Económicas.

Cherniy, S.A., Kudriavskiy, Ju.P., and Golev, A.V. 2007. Complex criteria of break-even for industrial waste recycling technologies. *Advances in Current Natural Sciences*, vol. 11. pp. 72–76. http://www.naturalsciences.ru/pdf/2007/11/38.pdf [in Russian]

Chernousov, P., Saiadova, U., and Golubev, O. 2016. Econometric forecast of ferrous metal -recycling. LAP Lambert Academic Publishing. Saarbrucken, Germany. 93 pp. https://www.morebooks.de/store/gb/book/Эконометрический-прогноз-рециклинга-чёрных-металлов/isbn/978-3-659-95589-1 [in Russian]

Chernousov, P.I. 2011. Рециклинг. Recycling. Technologies for processing and utilization of technogenic formations and wastes in the ferrous metallurgy. *NUST MISiS*. 428 pp. https://www.twirpx.com/file/1005553/ [in Russian]

Corte C. da, Bergmann, C., and Woollacott, L. 2019. Improving the separation efficiency of Southern African haematite from slimes through selective flocculation coupled with financial markets and non-linear dynamics. *Journal of the Southern African Institute of Mining and Metallurgy*, vol.119. pp. 963–972.

Hogland, W., Kaczala F., Jani Y., Hogland M., and Bhatnagar A. 2014. Beyond the zero waste concept. *Proceedings of Linnaeus ECO-TECH´14*, At Kalmar, Sweden. Department of Biology and Environmental Science, Linnaeus University, pp. 2–10.

ISO 5446:2017. Ferromanganese - Specification and conditions of delivery. https://www.iso.org/standard/65346.html

ISO 5447:1980. Ferrosilicomanganese - Specification and conditions of delivery. https://www.iso.org/standard/11492.html

Jandieri, G. 2012. Electrothermal alloying of grey cast iron from iron-containing fine-dispersive technogenic waste. *Proceedings of the IX International Congress 'Machines, Technologies, Materials',* Varna, Bulgaria. vol. 1. pp. 5–8. https://mech-ing.com/journal/Archive/2013/1/3_Dzhandieri_ENG.pdf

Jandieri, G. and Sakhvadze D. 2013. Smelting of alumosilicomanganese from technogenic and secondary resources mining-metallurgical industry of Georgia. *Proceedings of the X International Congress Machines, Technologies, Materials*, Varna, Bulgaria. vol. 1. pp. 107–110.

Jandieri, G., Jishkariani, G., Sakhvadze, D., and Tavadze, G. 2012. Technologies of rendering harmless and regenerating solid and liquid inorganic industrial wastes. *Proceedings of Modern Technologies and Methods of Inorganic Materials Science*, Tbilisi, Georgia. pp. 304–319.

Jandieri, G., Sakhvadze, D., and Raphava, A. 2020. Manganese biomining from manganese-bearing industrial wastes of Georgia. *Journal of the Institution of Engineers (India): Series D*, vol. 102. https://doi.org/10.1007/s40033-020-00235-0

Jishkariani, G., Jandieri, G., Sakhvadze, D., Tavadze, G., Oniashvili, G., and Aslamazishvili, Z. 2012. Ecological problems related to mining-metallurgical industries and innovatory, energy-efficient ways of solving them. *Engineering*, vol.4, no.2. pp. 83–89. https://doi.org/10.4236/eng.2012.42011

Kaza, S., Yao, L.C., Bhada-Tata, P., and van Woerden, F. 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. World Bank, Washington, DC: https://elibrary.worldbank.org/doi/epdf/10.1596/978-1-4648-1329-0

Kojamuratov, R.U., Safarov, R.Z., Shomanova, J.K., and Nosenko, Yu.G. 2017. Utilization of ferroalloy wastes. *Proceedings of Global Science and Innovations 2017*, Bursa, Turkey. Bursa Technical University. pp. 201–213.

Matinde, E., Simate, G.S., and Ndlovu, S. 2018. Mining and metallurgical wastes: a review of recycling and re-use practices. *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 118. pp. 825–844.

Ndlovu, S., Simate, G.S., and Matinde, E. 2017. Waste Production and Utilization in the Metal Extraction Industry. CRC Press: Portland, OR. 512 pp. –http://library.sadjad.ac.ir/opac//temp/18652.pdf

NEA. 2019. 3R guidebook for industrial developments. National Environment Agency. Singapore. 52 pp. https://www.nea.gov.sg/¬docs/default-source/resource/3r-guidebook-for-industrial-developments.pdf

Nevedomskij, V.A., Chernoshov, A.V., and Chernishov, A.A. 2017. Nanotechnology for the production of stone material from fiery liquid technogenic waste to produce products. *Journal of ZSTU/Engineering*, vol. 2, no. 80. pp. 60–67. https://doi.org/10.26642/tn-2017-2(80)-60-67

Norval, D. and Oberholster, R.E. 2011. Further processing and granulation of slags with entrained metal and high metal compound content, with specific reference to present manganese slag dumps as well as additions due to daily production. *Proceedings of Southern African Pyrometallurgy*. Jones, R.T and den Hoed, P. (eds.). Southern African Institute of Mining and Metallurgy, Johannesburg. pp. 129–143.

ao, S.R. 2006. Resource Recovery and Recycling from Metallurgical Wastes. *Waste Management*, vol. 7. Elsevier Science & Technology, UK. 580 pp.

Reuter, M.A. and Schaik, van A. 2016. Strategic metal recycling: adaptive metallurgical processing infrastructure and technology are essential for a circular economy. *Responsabilité & Environnement*, vol. 2, no. 82. pp. 62–66.

Reuter, M.A. and Kojo, I.V. 2012. Challenges of metal recycling. *Materia*, no. pp. 52–57.

Romanova, I.P. and Begunov, O.B. 2016. Use of metallurgical waste in the construction industry as a way to save natural resources and reduce environmental tensions. *Territory of Science. Journal of Voronezh institute of Economics and Lawl*, vol. 2. pp. 53–57 [in Russian].

Sarukhanishvili, A.V., Shashek, L., Shapakidze, E.V., and Sarukhvanishvili, I.A. 1992. Waste materials from the production of electrolytic manganese dioxide in the glass-container industry. *Glass and Ceramics*, vol. 49. pp. 161–163. https://doi.org/10.1007/BF00676989

Sasmaz, A., Sasmaz, B., and Hein, J.R. 2021. Geochemical approach to the genesis of the Oligocene-stratiform manganese-oxide deposit, Chiatura (Georgia). *Ore Geology Reviews*, vol. 128. 103910. https://doi.org/10.1016/j.oregeorev.2020.103910

Sausheva O.S. 2017. Monitoring of the effectiveness of recycling: tasks and organization. *Journal of ITMO University, Series Economics and Environmental Management*, vol 4. pp. 102–109. https://cyberleninka.ru/article/n/monitoring-effektivnosti-retsiklinga-zadachi-i-organizatsiya/viewer [in Russian]

Suman Lata. 2018. Industrial Economics. Alagappa University, India. 286 pp. https://alagappauniversity.ac.in/uploads/files/MAEconomic-362%2014_Industrial%20Economics.pdf

Tang,C., Li, K., Ni, W.,and Fan, D. 2019. Recovering iron from iron ore tailings and preparing concrete composite admixtures. *Minerals*, vol. 9, no. 4. https://doi.org/10.3390/min9040232

UNEP. 2013. Metal Recycling: Opportunities, Limits, Infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M.A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., and Hagelüken C. (eds).Paris, France. 316 pp. https://wedocs.unep.org/handle/20.500.11822/8423

UNEP/ISWA. 2015. Global Waste Management Outlook. Osaka, Japan. 333 pp. https://www.uncclearn.org/sites/default/files/inventory/unep23092015.pdf

Van Schaik, A. and Reuter, M.A. 2016. Recycling indices Visualizing the performance of the circular economy. *World of Metallurgy – ErzmetallI*, vol. 69, no, 4. pp. 201–216.

Zhdanov, A.V., Zhuchkov, V.I., Dashevskiy, V.Ya, and Leontyev, L.I. 2015. Wastes generation and use in ferroalloy production. *Proceedings of the Fourteenth International Ferroalloys Congress: Energy Efficiency and Environmental Friendliness are the Future of the Global Ferroalloy Industry. Proceedings of INFACON XIV.* Kiev, Ukraine. pp. 754–758. https://www.pyrometallurgy.co.za/InfaconXIV/754-Zhdanov.pdf ◆