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The methodological approach to determining the environmental and economic efficiency of processing of man-made mineral formations

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Relevance. The importance of ensuring environmental safety makes actual the development of environmental measures in the mining and metals sector. The processing of man-made mineral formations is essential in solving this problem. At the same time, the role of ferroalloy industry wastes plays a great role in the overall structure of technogenic resources, the processing of which is largely determined by improving the development of technological potential of the industry.
The purpose of the work is to develop a methodological approach to determining the environmental and economic efficiency of processing of man-made mineral formations.
Results. This paper systematizes the basic technologies for producing man-made products based on slags of ferroalloy industry. The volumes of formation of ferroalloy slag, dust, and sludge in Russia are specified. There was a decrease in industrial waste of various classes of hazard within the territory of the Sverdlovsk region, including slag from ferroalloy industry as a result of their partial processing. This paper notes the need to develop a methodological approach to assessing the environmental and economic efficiency of involving ferroalloy industry in waste production taking into account the assessment of the strategic flexibility of technological decisions made. Within the framework of this task, the main approaches are presented and systematic indicators for assessing the economic efficiency of waste recucling taking into account the environmental factor are presented. A scheme is presented that reflects the main stages of implementation of the methodological approach for assessing the environmental and economic efficiency of processing of man-made mineral formations of ferroalloy industry including strategic flexibility. The relevance of applying the real options methodology is justified; the feasibility of calculating the proposed real options using the Black-Scholes model is emphasized. The classification of possible options in the field of processing ferroalloy industry wastes is developed; a general view of the binary event tree for projects in this area is given.
Conclusions. The proposed provisions of the author's methodological approach allowed forming a methodological toolkit for assessing the environmental and economic efficiency of waste of mining and smelting industry, which can be successfully used in practice.

Keywords: ferroalloy industry, waste, man-made mineral formations, "dome products", performance evaluation, real options, the best available technologies.

Introduction

The problem of pollution of the atmosphere and water bodies with harmful substances, land occupation by industrial waste is one of the most urgent issues today. The main source of environmental complications in Russia is the mining sector, including the production of energy resources, chemical and metallurgical production, extraction and processing of natural resources, etc. Within the framework of metallurgical production, the main sources of environmental pollution include ferroalloy industry along with non-ferrous metallurgy. The level of development of ferroalloy industry determines the qualitative development of metallurgy as a whole. Globally, about 40 million tons of ferroalloys are produced per year today. In Russia, the annual production of ferroalloys is more than 1.73 million tons [1], while the share of the Urals is more than 53% (Fig. 1).

It should be noted that there are discrepancies in the volumes of ferroalloys produced in the Russian Federation in the review materials and statistical books. Thus, according to the Federal State Statistics Service, in 2018, the melting volumes of ferroalloys in Russia were estimated at 2.1 million tons (Table 1). The structure of production of the main ferroalloys in the Urals Federal District and Russia as a whole is quite diverse. Large-capacity ferroalloys include ferro- and silicomanganese, ferrochrome, ferrosilicon. Ferroalloys of the small-capacity group are necessary for the development of special metallurgy. These include alloys based on vanadium, molybdenum, niobium, titanium, nickel, etc.

In the Sverdlovsk region, the structure of ferroalloy industry also includes ferroalloys of large and small-capacity groups (Table 2).

The mineral raw material base is characterized by limitedness, which often acts as a deterrent when design planning of production. At the same time, it is advisable to adopt a resource-saving policy, within which a special role is given to the use of man-made mineral formations. The involvement of man-made resources in production is becoming one of the most promising directions for the development of ferroalloy industry. Such waste acts as a new source of raw materials, and in addition, its processing can reduce the burden on the environment. This direction of technological development not only expands the raw material base but is also the first step towards the formation of a closed-loop economy [2].

The Ecology national project approved by the Presidium of the Presidential Council for strategic development and national projects (Minutes No. 16 of December 24, 2018) has 11 Federal projects, including the implementation of the Best Available Technologies (BAT) project. This project provides preparation industry-specific methods for assessing the costs of transitioning to BAT principles at the end of the year 2022. Until 2023, it is expected to create a production base (taking into account the constructed and reconstructed equipment) of environmental engineering. Over the next year, this production base should be sup-

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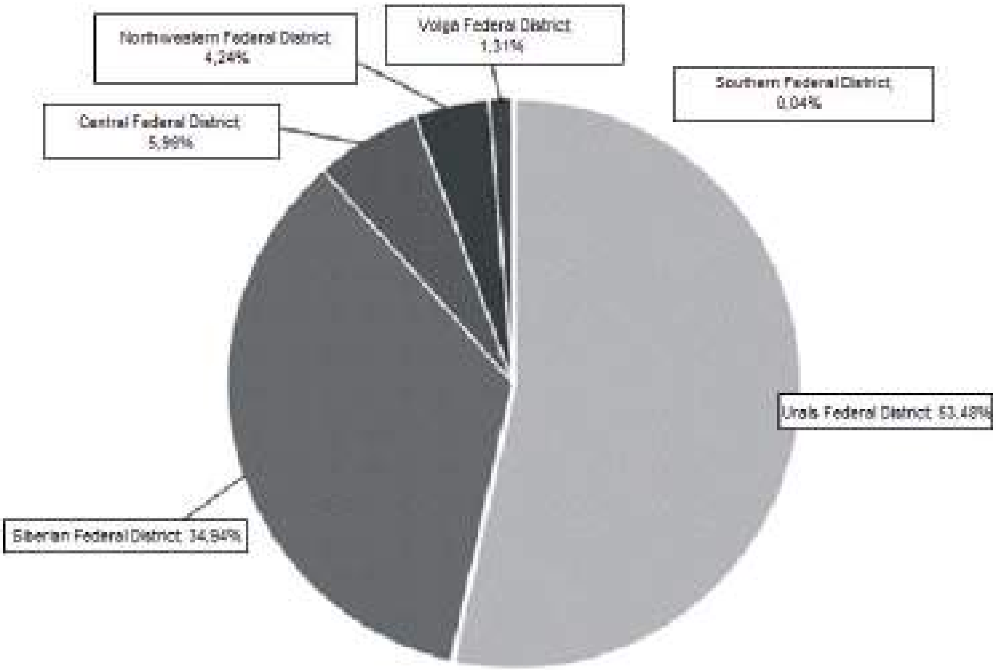

Figure 1. Shares of federal districts (FD) in the production of ferroalloys in Russia in January – February 2018, %[1]. ***According to some analysts who study markets for raw materials, metals and metal products International Metallurgical Research Group.***
Рисунок 1. Доли федеральных округов (ФО) в производстве ферросплавов в России в январе–феврале 2018 г., %[1]. ***По данным группы аналитиков по изучению рынков сырья, металлов и продукции из них «International Metallurgical Research Group».***

Table 1. Production of main products in physical terms, tons.
Таблица 1. Производство основных видов продукции в натуральном выражении, т.

Product	Year					
	2017	2018	2019			
	January-December	January-December	January	February	March	April
	Administrative-territorial facility (Russian Administrative-Territorial Division Classification)					
	Russian Federation					
Ferroalloys	2 024 000	2 112 490.00	184 420.00	170 530.0	187,830.0	179 530.0
Including:						
ferrosilicium	840 765	932 068.55	78 965.95	72 056.8	75 466.5	67 258.3
silicomanganese	52 095	48 396.00	4347.00	3875.0	4037.0	4167.0
ferromolybdenum	4856	3072.16	364.00	397.0	386.0	418.0
ferrovanadium	12 588	11 313.75	864.15	962.5	997.0	940.5
vanadium oxide	56 917	53 738.00	4931.00	4265.3	4831.9	3838.8
ferrochrome	436.280	337 390.58	34 612.30	30 215.9	35 676.4	32 779.7
ferrochrome silicon	80 923	89 997.00	7835.00	7208.0	8117.0	7294.0
ferrosilicon manganese	292 000	305 000.00	22 800.00	22 400.0	23 700.0	27 200.0
ferromanganese	167 000	262 200.00	22 000.00	20 200.0	27 600.0	28 900.0
	Ural Federal district					
Ferroalloys	1 155 000	1 113 290.00	101 340.00	92 120.0	99 320.0	92 540.0
Including:						
ferrosilicium	202,769	236 471.35	19 273.75	17 481.4	17 224.9	12 143.1
ferrovanadium	147	144.75	17.15	21.5	8.0	23.5
vanadium oxide	45 402	42 290.00	3860.00	3398.3	3768.9	3173.8
ferrochrome	359 542	255 984.58	29 022.30	24 358.9	29 243.4	27 120.7
ferrochrome silicon	80 923	89 997.00	7835.00	7208.0	8117.0	7294.0
ferrosilicon manganese	292 000	305 000.00	22 800.00	22 400.0	23 700.0	27200.0
ferromanganese	104 000	127 300.00	11 200.00	8700.0	10 600.0	9100.0

According to the Federal state statistics service.
По данным Федеральной службы государственной статистики.

[1] The share of the Southern Federal District in the analyzed period was 0.04%, which did not allow reflecting it on the diagram.
Доля Южного ФО в анализируемый период составляла 0,04 %, что не позволило отразить её на диаграмме.

Table 2. Change in production volumes of the main ferroalloys in the Sverdlovsk region,%.
Таблица 2. Изменение объемов производства основных ферросплавов в Свердловской области, %.

Product	2014 by 2013	2015 by 2014	2016 by 2015	2017 by 2016
Ferrosilicium	86.9	61.7	17.4	By 4.2 times
Ferrochrome silicon tradeable	124.7	By 1.6 times	70.0	111.3
Low-carbon ferrochrome	90.9	73.7	129.9	147.4
High-carbon ferrochrome	103.4	61.0	87.5	
Metal chrome	113.9	100.8	115.6	N/a
Vanadium oxide, tradable	103.9	107.1	104.3	108.4
Ferrotitanium	140.3	94.5	141.2	110.3
Ferroboron	103.9	89.3	36.6	By 1.7 times

According to the statistical books of Sverdlovskstat: «Sverdlovsk region: production of main types of products " for 2015–2018.
По данным статистических сборников Свердловскстат: «Свердловская область: производство основных видов продукции» за 2015–2018 гг.

plemented by the commissioning of instrumentation engineering. Moreover, within the framework of the project, it is planned to update 51 information and technical reference books on BAT by 2024. For these purposes, from 2019 to 2024, 27.3 billion rubles will be allocated from the federal budget and 2400 billion rubles from non-government sources.

The processing base for the development of the closed-loop economy in the metallurgical industry takes into account such areas as recycling of blast-furnace gas, the use of pulverized coal fuel, and refocusing to the use of coal-ore briquettes in both blast-furnace process and steel industry. The development of these areas will reduce the volume of harmful emissions into the atmosphere by an average of 60%, reduce the cost of metal products by more than 25%. At the same time, the carbon footprint from ferrous metallurgy enterprises should be reduced by 2–3 times [3]. The philosophy of the closed-loop economy takes into account the formation of the market for "dome products"[1].

The main man-made resources of ferroalloy industry include slags, sludges, screenings of crude ore and ferroalloys. About 30% of ferroalloy slag is processed. They are mainly used for the production of materials used in construction, including crushed stone (carbon ferrochrome), the production of mineral fertilizers (from the finely-ground ferroalloy), and in steelmaking. For example, slags from the aluminothermic production of ferroalloys are used as raw materials in the production of aluminous cement and ultrahigh early-strength cement; slag from production of ferrochrome is used for deoxidation and alloying of steel [4]. For direct alloying of steel, slag of high-carbon ferromanganese and metallic manganese are also used. Slag powders are used for liming acidic soils, household chemicals, and materials of construction [5]. There is almost no accounting for slag, sludge, and dust from enterprises of ferroalloy industry which makes their quantitative assessment difficult. Nevertheless, on the basis of the known values of smelting of ferroalloys, data on the slag rate and the calculation of the specific amount of dust and sludge per 1 ton of ferroalloy, the volumes of formation of ferroalloy slag can be identified. For example, at the Institute of Metallurgy of the Ural Branch of the Russian Academy of Sciences, the calculation of volumes of formation of ferroalloy slags, dust and sludges within the framework of the domestic ferroalloy complex was performed (Tables 3, 4).

Dust and sludge belong to a higher class of hazard than slag in general; their collection is also much more difficult, which leads to additional energy and labor costs.

Table 3. Volumes of formation of ferroalloy slag in the Russian Federation for 2017, tons/year.
Таблица 3. Объемы образования ферросплавных шлаков в РФ за 2017 год, т/год.

Type of alloy	Volume of ferroalloys production, th.t	Slag ratio (average)	The mass of slag, th.t
Siliceous alloys	839	0.1	84
Chromium alloys	436	1.0	436
Silicomanganese	291	1.2	349
Ferromanganese	167	1.4	233
Total	1733	–	1102

According to the Ural Department of Economics of the Russian Academy of Sciences.
По данным Института экономики УрО РАН.

Table 4. Volumes of dust and sludge formation in the Russian Federation for 2017.
Таблица 4. Объемы образования пыли и шламов в РФ за 2017 год.

Type of alloy	Production volume, thousand tons/year	Air slack		Sludges		Total, thousand tons/year
		Output, kg/ton	Mass, thousand tons	Output, kg/ton	Weight, thousand tons	
Silicon	839	120	100.7	N/a	N/a	100.7
Chrome	436	150	65.0	N/a	N/a	65.0
Manganese	458	10	4.6	100	45.8	50.4
Total	1733	–	170.3	–	–	216.1

According to the Ural Department of Economics of the Russian Academy of Sciences.
По данным Института экономики УрО РАН.

[1]"Dome products" are production wastes generated at one enterprise; they can serve as a factor in production at another enterprise.

The main waste from ferroalloy industry is slag. In Russia, the annual volume of formation of such slags is more than 1100 thousand tons/year. Technologies for producing "domed" products based on ferroalloy slags take into account:

1. The proposed methods and units used to separate metal shots (given their weak magnetic properties):

– an x-ray radiometric method for the separation of slags from aluminothermic production (reduction) is used at the Klyuchevsk ferroalloy plant;

– Ukraine uses the pneumatic separation method (Nikopol Ferroalloy Plant);

– the use of jigging chambers, classifiers, as well as some special units.

2. The use of ferrosilicon slag as a flux for the production of high-carbon ferrochrome or charge-chromium (52–55% Cr) in ore-reducing electric furnaces.

3. Methods and units for the use of small fractions of ferroalloys from ladle slag, "cakes" and dump slag.

4. The use of boron-containing materials for the processing of slag of low-carbon ferrochrome having self-levelling properties.

5. The use of manganese varnishes in the production of slag stone products.

6. Technologies associated with the use of wastes from enrichment of chromium and manganese ore, which in their chemical composition are not inferior to man-made wastes of ferroalloy industry.

According to the data for the end of 2017, the volume of accumulated waste in the Sverdlovsk region amounted to 9.37 billion tons, which is almost 75 million tons more than in the previous year. At the same time, the share of commercial-grade waste in the total waste in 2017 amounted to 99.2% (9.291 billion tons). There was a decrease in the volume of production waste from 194.2 to 166.9 million tons within the territory of the region for the period from 2013 to 2017 (waste of classes of hazard I – IV was estimated at 6.25 million tons (3.7%), which is 11.4% less than in 2016 [6].) The main reason for the decrease in the generation of waste from these classes is their partial processing. First of all, these are slags of ferroalloy industry, slags of steel, copper, and copper concentrates, coke, etc. Enterprises that process production wastes have received expert opinions on the compliance of the products with state Sanitary-Epidemiological Requirements and Rules; they have also developed the necessary technical conditions.

Today for the development of ferrous metallurgy in the Sverdlovsk region, the rational use of additional sources of expanding the raw material base of industrial enterprises is of paramount importance. The efficiency of metallurgical production largely depends on the complexity of processing mineral raw materials. Since the creation of the most promising, large-scale mining and metallurgical complexes is costly, the search for alternative ways of obtaining raw materials for steelmaking and ferroalloy production remains a live issue today. Based on the assessment of the raw materials available in the Urals, ores can be considered scarce; the main elements include manganese, boron, niobium, molybdenum, copper, etc. Today in the Urals, a fairly large market of man-made raw materials has formed. However, only a small part of it is used as raw material for further processing. Nevertheless, we can talk about the presence of successful experience in processing these resources in the region.

Results

Ecological and economic efficiency of processing of man-made mineral formations of the ferroalloy industry. The solution to the problem of reducing waste from ferroalloy industry is possible through the implementation of areas such as reducing their quantity due to the development of production technologies; minimization of waste release into the environment as a result of increased measures for their collection; processing of formations into technogenic products. Today there are no technologies of completely non-waste production in metallurgy. The use of accumulated waste as man-made raw materials contributes to maximizing the saving of natural resources and improving the environmental situation, as well as dumps clearance [7]. To make a decision on the use of technogenic products in one direction or another, a system of criteria is necessary that takes into account their chemical and mineral composition, environmental characteristics, and reactivity. Depending on the type of ferroalloy and the application of slag, the processing of waste from ferroalloy industry is different. The ways of processing most ferroalloy slags are based on crushing and (or) granulation, magnetic and air separation, screening, etc. [8, 9].

The estimation of the cost of design decisions can be carried out by various methods, including the method of capitalization of income, the Olson method, the method of a company-peer or capital market, the method of net assets, etc. But to assess the economic efficiency of implementation of the investment project on the use of man-made mineral formations, we can distinguish three main approaches: comparative assessment, taking into account the comparison of a technogenic product with a traditional one; valuation of discounted cash flows (DCF), including the value of cash flows expected in the future; assessment of conditional requirements based on the real options method.

The calculation of the present value of the expected cash flows takes into account their discounting. The discount rate reflects the risk of future cash flows. In this case, the calculation of cash flows depends on the chosen strategy, which takes into account the disposal or use of ferroalloy production wastes in a particular area. The formulas necessary for determining the indicators of environmental and economic efficiency are systematized in Table 5.

When assessing the net environmental income, the calculation formula of which is given in Table 5, the sum of environmental results takes into account the cost expression of the prevented environmental damage resulting from the processing of waste, contributing to the release of the land they occupy and reducing the impact on the land of harmful substances contained in the waste. The amount of environmental costs includes the cost expression of the environmental damage caused by additional emissions of pollutants into the atmosphere and from pollution of surface water bodies.

The main methodological principle for determining the environmental and economic feasibility of involving ferroalloy industry waste in production is the analysis of environmental results (inflows) and costs (outflows) of the project in money. The calculation of the environmental component of net present value (present value of expected cash flows) in the *t*-th year is carried out according to the formula:

$$\text{ЧПД}^t_{\text{эл}} = \frac{\text{ЧД}^t_{\text{эл}}}{(1+r)^t}.$$

Table 5. Indicators of environmental and economic efficiency of recycling and use of ferroalloy waste.
Таблица 5. Показатели эколого-экономической эффективности утилизации и использования ферросплавных отходов.

Formula	Explanation
$ЧПД = \sum_{t=1}^{t=n} \frac{ДП_t}{(1+r)^t}$	ЧПД – NPV – net present value of an asset; *n* is the life of the asset; ДП – CF – cash flows for the period *t*; *r* is the discount rate [10]
$Э_{ут} = \left(\frac{n_1}{a}\right)(C_1 + n_2C_2 - C_3)$	$Э_{ут}$ – E_{rec} – economic effect of materials recovery of the ferroalloy industry; C_1,*C*3 – cost of materials from traditional and recycled materials, respectively; C_2 – annual maintenance costs for dumps; n_1 – coefficient that reflects the share of costs of this type of material in the total costs of raw materials; n_2 – coefficient that reflects the partial or complete elimination of dumps (0.3 <*n* <1); *a* is the specific consumption of recycled materials per unit [11]
$Э_{исп} = \frac{(Ц - С)Д}{К_к}$	$Э_{исп}$ – E_{use} – economic efficiency of using ferroalloy industry wastes, rub.; Ц – P is the selling price of a unit based on waste, rubles; C is the cost of a unit based on waste, rub.; Д –D – the projected annual volume of waste production of ferroalloy industry, units; $K_к$ – capitalization ratio, share units [12]
$\Delta P_о = \sum_{i=1}^{n} \left[Ц_{оi} - (C_{оi} + D_i)\right] A_{оi}$	$\Delta P_о$ – increase in the company's net profit as a result of the integrated use of ferroalloy industry wastes, rubles; $Ц_{оi}$ – P_oi – selling price of the final product, in the production of which the replaced resource *i* was used, rubles; $C_{оi}$ – cost of production of a unit of similar products obtained using waste, rub.; D_i – total deductions to the budget, taking into account benefits for the use of man-made raw materials, rubles; $A_{оi}$ – volume of sold products in physical terms obtained using waste [4]
$\Delta У = \Delta У_в + \Delta У_б$	$\Delta У$ – effect of reducing environmental damage; $\Delta У_в$ – reduction of damage from the development of dumps; $\Delta У_б$ – reduction of damage to water and other types of economy [4]
$ЧД^t_{эл} = P^t_{эл} - З^t_{эл}$	$ЧД^t_{эл}$ – NI – net environmental income received in the *t*-th year; $P^t_{эл}$ – sum of the environmental results obtained in the *t*-th year; $З^t_{эл}$ – amount of environmental costs incurred in the *t*-th year [13]

In this case, the discount rate *r* shows the expected profitability of the project. The *r* indicator can be determined on the basis of the universal capital asset pricing model (CAPM) adapted to the real conditions of the project. Thus, the CAPM model has the form:

$$r = r_0 + \beta\,(R_p - r_0),$$

where r_0 is the risk-free rate of return; R_p – market profitability of processing waste into the final product; β - an indicator of the volatility of the price of the final product on the market (reflects the riskiness of investment in relation to the market).

Then the formula of the integrated environmental and economic net discounted income for the duration of the project (NPV$_{ee}$) will take the form:

$$ЧПД_{ээ} = \sum_{t=1}^{n} ЧПД^t_{эн} + \sum_{t=1}^{n} ЧПД^t_{эл},$$

where $ЧПД^t_{эн}$ is the economic component of net present value in the *t*-th year.

The competitiveness of ferroalloy production and industry as a whole is significantly affected by the stimulation of innovation and the promotion of new technological solutions. Such decisions should take into account the requirements of the modern economic system, ecology and resource conservation, as well as contribute to achieving a high level of quality of manufactured products. Previous studies have made it possible to justify the need for a methodological tool, the implementation of which takes into account the strategic flexibility mechanism. As part of assessing the economic efficiency of new technological solutions in metallurgy (in ferroalloy industry, in particular), which meet the criteria of the best available technologies, the real options method has shown good results [14]. With this in mind, the methodological approach to valuating the environmental and economic efficiency of processing man-made mineral formations of ferroalloy industry can contain three stages (Fig. 2).

I stage. Preliminary evaluation of the effectiveness of the use of technogenic formations.
- Integral economic effect
- Ratio of costs and the expected effect of use
- Simple rate of return
- Payback period

II stage. Economic justification of the effectiveness of the project on the use of technogenic entities.
- Commercial performance indicators
- Environmental and economic efficiency
- Integral efficiency

III stage. Evaluation of strategic project flexibility.
- Choice of option pricing method (Black-Scholes model, Cox-Ross-Rubinstein binomial model, etc.)
- Formation of the base of the main real options taken into account by the investment project
- Development of an investment project valuation algorithm (in the form of a binary event tree)

In conditions of environmental uncertainty, especially in some areas such as ferroalloy industry, investment design planning should take into account elements of strategic flexibility. In recent years, the largest industrial companies have increasingly used the real options method, which is considered to clarify the net present value, since it allows you to take into account the main risks of the project [15-17]. A real option shows the right, but not the obligation of its owner to perform any operations with assets in the future. The calculation of the value of a real option is carried out according to the Black–Scholes formula used to evaluate CALL financial options of the American and European types [18]. The application of the American option is possible at any time, but not later than the date of its exercise. In practice, they also use the formulas for the European option, which differs in the date of its exercise (it can be executed only on the specified date). To calculate the real American-style CALL option, it is advisable to take the Black-Scholes formula modified by R. Merton, taking into account the payment of dividends, which reduce the value of

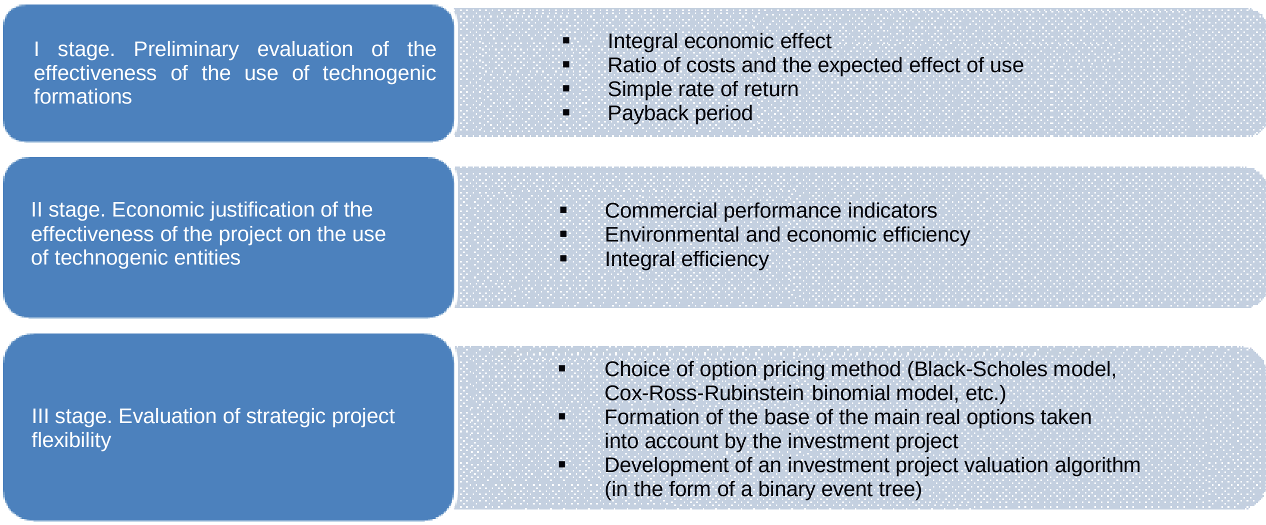

Figure 2. Stages of implementation of the methodological approach to valuating the environmental and economic efficiency of processing man-made mineral formations of ferroalloy industry taking into account strategic flexibility. *Made by the authors*.
Рисунок 2. Этапы реализации методического подхода к оценке эколого-экономической эффективности переработки техногенных образований ферросплавных производств с учетом стратегической гибкости. *Составлено авторами.*

the asset. For this, the system of model elements is supplemented with an indicator reflecting the value of y lost during the life of the option. In a modified form, the Black–Scholes formula has the following form:

$$C(t)=Se^{-yt}\Phi(z_1)-Xe^{-rt}\Phi(z_2)$$

where

$$z_1=\frac{\ln\left(\frac{S}{X}\right)+\left(r-y+\frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}}+\frac{\sigma\sqrt{t}}{2};$$

$$z_2=z_1-\sigma\sqrt{t};$$

$$\Phi(z)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{y}\mathrm{e}\left(-\frac{x^2}{2}\right)dx.$$

The decoding of the elements of the formula is presented in Table 6. To evaluate options in the field of processing of man-made mineral formations of ferroalloy industry, elements of the formula are adapted to the corresponding real sector of the economy.

The use of real options in projects for the processing of man-made mineral formations involves a change in design parameters in connection with the integration of flexibility elements designed to increase the overall effectiveness of the project. To identify these elements and determine their content, we systematize the main types of real options in the studied sector (Table 7).

Table 6. The ratio of the elements of the Black–Scholes model relative to financial and real options in the field of processing of man-made mineral formations of ferroalloy industry.
Таблица 6. Соотношение элементов модели Блэка–Шоулза относительно финансовых и реальных опционов в сфере переработки техногенных образований ферросплавных производств.

Model element name	The essence of the model element within the financial option	The essence of the model element in the framework of a real option in the field of processing of man-made mineral formations of ferroalloy industry
C(*t*)	The value of the CALL option for time *t* in selected units of time before exercise	Cost of accountability for strategic flexibility in the use of ferroalloy waste
S	The current price of the underlying asset	Current value of cash flows of an investment project for the processing of ferroalloy waste
r	Risk-free return (effective rate per unit of time with continuously compounded interest)	Risk-free return rate
X	Exercise price	Cost estimate associated with the processing of ferroalloy industry waste
[Xe]^(–*rt*)	Present value of asset strike price	Present value of the price of costs associated with the processing of ferroalloy waste
σ	The standard deviation of the return on the underlying asset for the period in question (with continuous compounding)	Uncertainty of the project cash flows due to the variability of market demand for the final product from technogenic raw materials
Φ(*z*)	Standard normal distribution function (cumulative)	Cumulative distribution function
y	The current value of dividends reducing the value of shares	The value lost during the life of an option

Made by the authors.
Составлено авторами.

Table 7. Real options in the field of processing of man-made mineral formations of ferroalloy industry.
Таблица 7. Реальные опционы в сфере переработки техногенных образований ферросплавных производств.

The name of a real option	Content
Bide time option	It makes it possible to choose the time for the start of the project, as well as the suspension of the project in the event of adverse external conditions and restarting it at a more convenient time. The use of this option in the framework of the project for processing of man-made mineral formations of ferroalloy industry can be justified, for example, by a decrease in demand for technogenic raw materials.
Growth option	It is used when the initial investment is a prerequisite for future development.
Scalable option	It allows a ferroalloy plant to optimize the development of dumps by changing the volumes of processed slag both upward or downward due to changes in environmental conditions
Sequential investment option	It is inappropriate due to the simplicity of the technology of slag processing
Input mix option	It gives the option holder the right to vary between types of slag acceptable for the production of the final product
Product flexibility option	It consists in the fact that, in the event of unfavorable market conditions, partially or completely redirect slag destined for the main product for recycling
Project rejection option	It becomes relevant in the event of adverse environmental conditions for the processing of slag and is applicable to reduce the associated losses. Depending on the progress of the project, cost recovery may be partial or full, accompanying the termination of the project

Source: made by the authors.
Составлено авторами.

Taking the Black-Scholes model as the basis for evaluating the value of options allows us to identify factors that have a significant impact on project efficiency. The evaluation algorithm of the investment project for processing of man-made mineral formations of ferroalloy industry using the real options method can be presented in the form of a binary event tree (Fig. 3). The key factor underlying the task of forming-up the tree of events is the creation of conditions for the development of the market for dome products of ferroalloy industry.

The event tree models the options for managerial decisions considered in the project, the adoption of which is advisable when the environmental conditions change. Each branch from the baseline scenario has its own real option valued according to the Black–Scholes model and adapted to the conditions of the real sector of the economy. Thus, the model evaluates the strategic value of the project. Acceptance of the terms of strategic flexibility based on real options increases the cost of the project in comparison

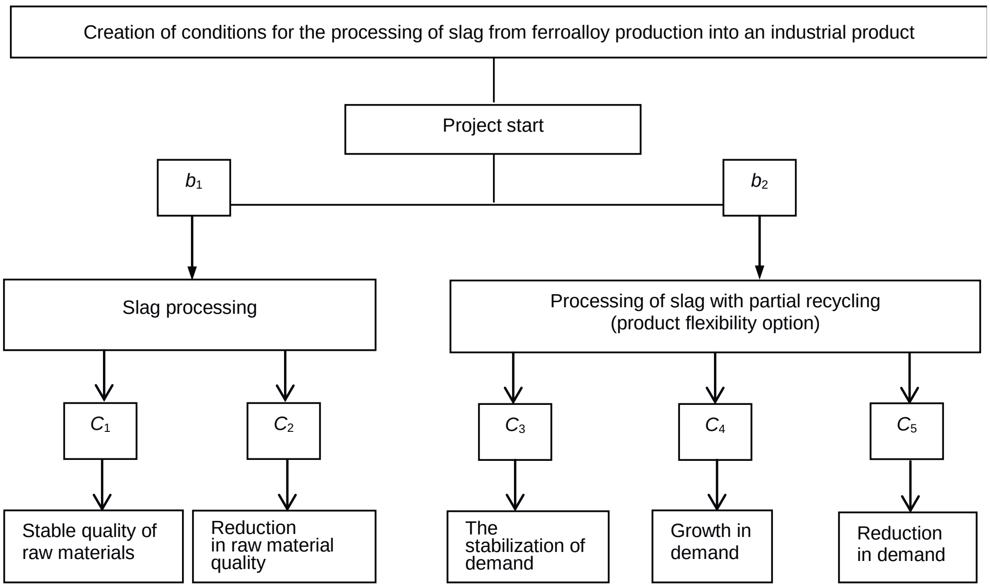

Figure 3. General scheme of the binary event tree for projects on the processing of man-made mineral formations of ferroalloy industry. a – the moment of the start of the project, when all the conditions for processing slag into an industrial product are created; b_1 – the basic version of the project; b_2 – implementation of the product flexibility option; C_1 – implementation of the basic version of the project; C_2 – implementation of the project in conditions of decreasing quality of slag / sludge; C_3 – stabilization of demand for industrial waste –implementation of the basic version of the project; C_4 – increased demand for industrial waste; C_5 – reduced demand for industrial waste – implementation of the bide time option or the option of rejecting the project. *Made by the authors.*

Рисунок 3. Общий вид бинарного дерева событий для проектов по переработке техногенных образований ферросплавных производств. а – момент начала проекта, когда созданы все условия для переработки шлаков в техногенный продукт; b_1 – базовый вариант реализации проекта; b_2 – реализация опциона продуктовой гибкости; C_1 – реализация базового варианта реализации проекта; C_2 – реализация проекта в условиях снижения качества шлаков/шламов; C_3 – стабилизация спроса на техногенные отходы – реализация базового варианта реализации проекта; C_4 – рост спроса на техногенные отходы; C_5 – снижение спроса на техногенные отходы – реализация опциона выжидания благоприятного времени, либо опциона отклонения проекта. *Составлено авторами.*

with the basic version of its implementation, nevertheless, in the conditions of a high degree of uncertainty in the global situation, this approach minimizes the risk of the project (allows you to take into account the main risks of the project).

Choosing the best option for working with waste, whether it is processing or recycling, can solve problems such as release of the land they occupy and the reduction of the impact on the land of the harmful substances contained in the waste, which alone determines income generation as a result of prevented environmental damage. The solution to the problem of expanding the raw material base is no less important. In addition, the adoption within the metallurgical industry of an industry-specific methodology for assessing the costs of transitioning organizations to BAT principles taken into account by the Ecology National Project, will allow relying on incentives in the form of tax benefits (deductions), accelerated depreciation of fixed assets, or use of funds spent on the implementation of BAT as a calculation for environmental damage.

Conclusion

The development of technologies for processing of man-made mineral formations allows us to expand the market for "dome products". So, for example, the possibility of mastering the technology of obtaining refractory materials from chrome ferroalloys from production wastes is being examined. The development of the technological base for the production of technogenic ferroalloy products will contribute to the formation of a new way of perceiving metallurgy as an environmentally friendly (greenfield).

The methodological approach proposed in this paper is intended to determine the environmental and economic feasibility of involving ferroalloy industry in the production of waste taking into account the strategic flexibility of technological decisions. Preliminary results of the study at the Institute of Metallurgy (Imet) and the Institute of Economics (IE) of the Ural Branch of the Russian Academy of Sciences confirm the feasibility of using the real options methodology. Further research in this direction will be focused on clarifying methodological features and carrying out further calculations in the field of environmental and economic efficiency of using waste products from the production of chromium, manganese and silicon ferroalloys.

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Методический подход к определению эколого-экономической эффективности переработки техногенных образований

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Актуальность. Важность обеспечения экологической безопасности окружающей среды актуализирует развитие природоохранных мероприятий в горно-металлургическом комплексе. Существенное значение в решении этой проблемы имеет переработка техногенных образований. При этом в общей структуре ресурсов техногенного типа велика роль отходов ферросплавного производства, переработка которых во многом определяется совершенствованием развития технологического потенциала отрасли.
Цель работы – разработка методического подхода к определению эколого-экономической эффективности переработки техногенных образований.
Результаты. В работе систематизированы основные технологии получения техногенной продукции на базе шлаков ферросплавного производства. Уточнены обьемы образования ферросплавных шлаков, пыли и шламов в России. На территории Свердловской области отмечено снижение обьемов образования промышленных отходов различных классов опасности, в том числе шлаков ферросплавного производства в результате их частичной переработки. В статье отмечена необходимость разработки методического подхода к оценке эколого-экономической эффективности вовлечения в производство отходов ферросплавного производства с учетом оценки стратегической гибкости принимаемых технологических решений. В рамках данной задачи приведены основные подходы и систематизированы показатели оценки экономической эффективности утилизации и использования отходов с учетом экологического фактора. Представлена схема, учитывающая основные этапы реализации методического подхода оценки эколого-экономической эффективности переработки техногенных образований ферросплавных производств с учетом стратегической гибкости. Обоснована актуальность применения методологии реальных опционов, подчеркнута целесообразность расчета предложенных реальных опционов с применением модели Блэка–Шоулза. Разработана классификация возможных опционов в сфере переработки отходов ферросплавного производства, приведен общий вид бинарного дерева событий для проектов в этой сфере.
Выводы. Предложенные положения авторского методического подхода позволили сформировать методический инструментарий оценки эколого-экономической эффективности переработки отходов горно-металлургического производства, который может быть успешно использован на практике.

Ключевые слова: ферросплавное производство, отходы, техногенные образования, «купольные продукты», оценка эффективности, реальные опционы, наилучшие доступные технологии.

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