TEKHNOGEN-INVEST SOFTWARE PROGRAM FOR ASSESSING THE EFFECTIVENESS OF RECYCLING TECNOGENIC FORMATIONS OF THE FERROALLOY PRODUCTION. PART 2

O. A. Romanova,¹ D. V. Sirotin,² L. I. Leont’ev,³ V. I. Zhuchkov,² and O. V. Zayakin⁴ UDC 338.2

Under contemporary conditions of social development, it is necessary to rethink the role of waste produced due to economic activity and, in particular, industrial formations of the ferroalloy industry. In order to evaluate the expediency of involving industrial formations in the production process and substantiate the efficiency of design solutions in the field, a functional approach was proposed and its algorithm created in the Tekhnogen-Invest software. This article continues a study aimed at assessing the efficiency of processing industrial formations of the ferroalloy industry. In this part, the developed software was tested using data from the production of high-carbon ferrochrome. The relevance of the applied methodology for assessing the ecological and economic efficiency associated with processing industrial formations of ferroalloy production is confirmed, taking into account the strategic flexibility of projects. The conducted testing the developed Tekhnogen-Invest software produced positive results. The algorithm used in the software allows the cost of implementing an investment project for processing industrial formations of high-carbon ferrochrome production under current conditions of the Urals to be evaluated and the feasibility of its implementation under changing market conditions to be substantiated. The obtained results demonstrate a high potential for producing marketable products from ferroalloy industry waste, confirming the economic efficiency and feasibility of processing industrial formations.

Keywords: metallurgy, ferrous metals, ferroalloys, industrial formations, circular economy, estimation of ecological and economic efficiency, slag.

Introduction

The Ural Federal District occupies a leading position in the Russian Federation in terms of ferroalloy production [1, 2]. Three large ferroalloy enterprises in the Urals including JSC “Serovsky Ferroalloy Plant”, JSC “Chelyabinsk Electrometallurgical Combine,” and PJSC “Klyuchevsky Ferroalloy Plant” [3–5] comprise the main facilities of the Russian Federation for producing chrome ferroalloys (apart from LLC “Tikhvin Ferroalloy Plant”) [6–8]. The production of each ton of finished products results in the formation of over a ton of industrial waste, mainly in the form of slags [9–13].

Wastes of ferroalloy production are currently considered either as industrial formations or as by-products. In the former case, the high costs of waste disposal force enterprises to occupy vast areas for their burial.
In the latter, the economic expediency of selling wastes is determined by comparing with the costs of their disposal. Although there are individual regulations, no unified methodological approach to assessing the efficiency of processing industrial formations has been proposed.

In order to expand the range of instruments used for improving the efficiency of management solutions in this field, a methodological approach forming the basis of the Tekhnogen-Invest software (License No. 2021666084, date of registration 07.10.2021) was developed to assess the environmental and economic efficiency of processing industrial formations with due regard for the strategic flexibility of projects. Testing of the developed software was carried out conditionally by involving data from one of the Urals industrial plants in order to assess the efficiency of using waste from the production of chrome ferroalloys. During the evaluation, the expediency of involving slags formed during the smelting of high-carbon ferrochrome (HCFC) in the economic turnover was evaluated. The period of the project implementation was determined to be ten years.

The processing of HCFC slag by using crushing and gravitational preparation methods yields crushed stone and sand having a grain size of 5–40 mm, provided to construction organizations [14, 15]. The slag ratio equals 1.0. Such processing provides 182 thousand tons of finished industrial product, i.e., crushed stone, per year with 4.2% of slag lost (filtered) along with the grind. The price of crushed stone obtained from industrial raw materials established by the plant amounts to about 100 rubles/ton.

Slag processing is carried out using equipment existing at the plant; therefore, investments, including only the costs of transportation and auxiliary equipment purchased in the period preceding the commencement of the project, amounted to 5,500 thousand rubles. The profit-to-investment ratio was taken as 15% (estimated as the ratio of increment in profit to the total of investments). The operating expenses of the preparation for sales of 1 ton of industrial raw materials comprised 52 rubles. Including the above data, the annual economic effect obtained by the plant from selling processed industrial waste amounted to 8,736 thousand rubles. The calculation tools were based on the results of the works [16–20].

The environmental efficiency of the project comprises the total of prevented damage as a result of its implementation (Fig. 1). As of prices in 2021, the estimated specific environmental damage from the degradation of soils and lands of the Sverdlovsk region due to the burial of 190 thousand tons of slag (1.8 ha) amounts to 456.6 thousand rubles (253.7 thousand rubles/ha of this type of land, considering the coefficient of natural and economic significance). Since high-carbon ferrochrome slag belongs to hazard class IV, its coefficient value being equal to one, the prevented damage from land pollution with chemicals amounts to the damage from their degradation.

The avoided costs for the waste disposal and burial from the HCFC production in one year amounted to 5,700 thousand rubles. The annual effect obtained by replacing primary raw materials with industrial waste is appraised at 631 thousand rubles. Although the development of waste dumps is beyond the scope of this project, fewer than all possible economic and environmental benefits being taken into account, the value of the absolute efficiency of using industrial raw materials is over 1 (1,037), indicating that the integral annual ecological and economic effect exceeds the total costs associated with the implementation of the project.

With an inflation rate of 7.4% (for 2021), the discount rate calculated by the cumulative method is estimated at 9.6%. The low level of the rate reflecting the investor's financial losses from investments having guaranteed income can be explained by the difficult economic situation against the background of the ongoing coronavirus pandemic.

Considering all the conditions noted above, the commercial and fiscal performance of the project is evaluated as positive. Net present value (NPV) from the project implementation amounted to 43,652 thousand rubles over 10 years with a payback period of 1.5 years. The ecological and economic efficiency of using industrial raw materials by the enterprise (NPVee) exceeded the NPV by almost two times—86,086 thousand rubles (Fig. 2). It is worth noting that the balance of the flow of economic activity is comparable to that of the environmental flow.
The NPV of the budget amounted to 42,495 thousand rubles due to tax revenues for the federal budget (at no cash flows to the budget at the regional level) of the Russian Federation throughout the entire period (Fig. 3). The integral efficiency of processing and using HCFC slag (NPV) is estimated at 128,582 thousand rubles. The risks driven by the turn of the market are envisaged in the requirements of the implementation of the investment project.

With the help of a strategic planning toolkit built into the Tekhnogen-Invest software, it is possible to evaluate a number of project solutions, whose implementation will allow the project to be continued under market uncertainty, while maintaining its investor appeal [21]. For this purpose, a number of real options were developed, three of them being the most advantageous.

1. The option to scale down the production stipulates conditions when the plant reduces the output of high-carbon ferrochrome and hence the reduction of the annual slag formation to 130 thousand tons, the volume of
crushed stone produced being 122.5 thousand tons per year. The price of the industrial product and the volume of investments remain unchanged. The volatility of basic assets (construction crushed stone) in market prices is assumed to be equal to 1.28%. The cost of such a real option is estimated at 83,297 thousand rubles.

2. The option for product flexibility of the project is driven by the turn of the market, forcing the plant to refocus on the production of small crushed stone, having a size of 2–5 mm. The price and the volume of the production of the industrial product remain unchanged. The economic effect is enlarged by the difference in the cost of mineral and industrial products. The effect of replacing sand of mineral origin with industrial sand amounted to 2,451 thousand rubles. The volatility of prices for the small crushed stone of the defined size (basic asset) based on monthly data for the last four years is taken as 3.39%. The cost of the product flexibility option is estimated at 135,334 thousand rubles.

3. The option to expand the resource base involves additional low-carbon ferrochrome (LCFC) slag, obtained at another factory workshop. Following processing, the LCFC slag can be reused as an additive in the smelting of this ferroalloy [22]. Following the project conditions, it is possible to sell the recycled LCFC slag, while maintaining the full-scale production of crushed stone from the HCFC according to the basic scenario. One disadvantage is the decomposition of highly basic slags formed during low-carbon ferrochrome productions, which, having no effect on the technological process, adversely affects the environment not only at the industrial site but also tens and hundreds of kilometers around the enterprise [23]. The conventional production of such ferroalloys yields highly basic slags having a high content of dicalcium silicate, which crumbles into a fine powder when being cooled. A scheme of smelting LCFC to obtain stabilized slag by partial replacement of the $\text{SiO}_4^{4-}$ anion of dicalcium silicate with boron anions was developed [24–26]. Like HCFC slag, this waste undergoes mechanical separation, followed by crushing to a size of 5–40 mm and separation from metal inclusions in an aqueous medium by gravity method. The project provides for the production of 124 thousand tons of such a slag, processed using its own resources with additional investments of 5,500 thousand rubles. The volatility of average prices for low-carbon ferrochrome in the domestic market is determined at the level of 4%.

The cost of the real option amounted to 218,300 thousand rubles (Fig. 4) (the software limits the number of options to 20 within one investment project). The expected investment costs are minimal when exercising
the first and second options; to activate the option to expand the resource base, the costs include the purchase of additional transport and auxiliary equipment (5,500 thousand rubles). The value of the project increased by 436,932 thousand rubles due to the inbuilt flexibility tool, including the above three real options, the NPV of the project being equal to 565,514 thousand rubles, indicating the feasibility of the project even under current market instability.

At present, the business model used by ferroalloy enterprises dictates that the costs of processing the waste be included in the cost of the resulting industrial product. The money earned by selling industrial products is, as a rule, deducted from the cost of ores and concentrates purchased for the production of ferroalloys. Such a scheme simplifies the monetary and economic system of the enterprise, excluding, however, the environmental effect of implementing project opportunities. It should be anticipated that increasing industrial production will provide products considered not as a by-product, but as an independent, profitable production.

**CONCLUSION**

Under contemporary conditions of social development, it is necessary to rethink the role of waste produced due to economic activity and, in particular, industrial formations of the ferroalloy industry. In order to evaluate the expediency of involving industrial formations in the production process and substantiate the efficiency of design solutions in the field, a functional approach was proposed and its algorithm created in the Tekhnogen-Invest software.

The developed software was tested using data on the processing of slag produced at a high-carbon ferrochrome plant. The relevance of the applied method for assessing the ecological and economic efficiency associated with processing industrial formations of ferroalloy production is confirmed, taking into account the strategic flexibility of projects. The software is shown to be an effective decision-making tool. The algorithm used in the software allows the cost of implementing an investment project for processing industrial formations of high-carbon ferrochrome production under current conditions of the Urals to be evaluated and the feasibility of its implementation under changing market conditions to be substantiated. The obtained results show the high potential of producing marketable products from industrial waste of the ferroalloy industry, which, as a rule, is underestimated by enterprises under current conditions.

The study was supported by RFBR Grant No. 18-29-24027.
REFERENCES

1. Ferroalloys Market in Russia 2015-2021, Numbers, Trends, Forecast; https://tksolutions.ru/russia-rynok-ferrosplavov. 2022. Accessed 15.02.2022.
2. Ferroalloys Market in Russia and the CIS. Monopolization of the Market. Threats; https://www.urmcompany.ru/upload/iblock/b12/b127a6938b8f997af1abd0aed9fe157.pdf. Accessed 15.02.2022.
3. https://www.chemk.ru/products/ferrochromium. Accessed 17.02.2022.
4. http://sfap.ru/index.php?page_link=tech. Accessed 16.02.2022.
5. Ya. I. Ostrovsky, I. A. Veselovsky, V. I. Afanas'ev, et al., “Technology development for producing chrome ferroalloys using poor domestic chromium ore raw materials,” Stal’, No. 5, 40–43 (2013).
6. A. V. Pavlov, D. Ya. Ostrovsky, V. V. Aksenova, and S. A. Bishenov, “Current state of ferroalloy production in russia and cis countries,” Izv. vuzov., Chern. Met., 63, No. 8, 600–605 (2020).
7. V. I. Zhuchkov, O. V. Zayakin, L. I. Leont’ev, et al., “Main trends in the processing of poor chrome ore raw materials,” Russ. Metall. (Met.), 8, 709–712 (2008).
8. A. B. Esenzhulov, Ya. I. Ostrovskii, V. I. Afanas’ev, et al., “Russian chromium ore in smelting high-carbon ferrochrome at OAO SZF,” Steel Transl., 38, No. 4, 315–317 (2008).
9. T. Ochiai, Y. Inoue, and F. Tanimoto, et al., “Application of “Ferroform” to concrete pavement,” JFE Giho, No. 40, 51–56 (2017).
10. J. P. Beukes, N. F. Dawson, and P. G. Van Zyl, “Theoretical and practical aspects of Cr (VI) in the South African ferrochrome industry,” in: Proc. of the 12th Intern., Ferroalloy Congr., June 6–9, 2010, Outotec Oyj, Helsinki, Finland. (2010), pp. 53–62.
11. K. Midander, A. De Frutos, Y. Hedberg, et al., “Bioaccessibility of ferrochromium and ferro-silicon-chromium particles compared to pure metals and stainless steel – aspects of Human Exposure,” in: Proc. of the 12th Intern., Ferroalloy Congr., June 6–9, 2010, Outotec Oyj, Helsinki, Finland (2010), pp. 43–52.
12. H. Stockmann-Juvala, A. Zitting, I. Wailinder, et al., “Use of Read-Across in the Health Risk Assessment of Ferrochromium Alloys under REACH,” in: Proc. of the 12th Intern., Ferroalloy Congr., June 6–9, 2010, Outotec Oyj, Helsinki, Finland (2010), pp. 35–42.
13. O. Sariev, B. Kelamanov, Y. Zhumagaliyev, S. Kim, A. Abdrahi, and M. Almagambetov, “Remelting the high-carbon ferrochrome dust in a direct current arc furnace (DCF),” Metalurgija, 59, No. 4, 533–536 (2020).
14. V. I. Zhuchkov, O. V. Zayakin, and A. V. Sychev, “Slags and dusts of ferroalloy production,” Russ. Metall. (Met.), Issue 6, 662–666 (2019).
15. V. I. Zhuchkov and O. V. Zayakin, “Nature-conservation measures in the ferroalloy production,” Rasplav, No. 4, 66–69 (2010).
16. A. Damodaran, Investment Assessment. Tools and Techniques for Evaluating Any Assets [in English], Moscow, Alpima Business Books (2004).
17. V. N. Makarova, “Economic efficiency of slag utilization at ferroalloy production,” in: Tr. Nauch.-Prakt. Conf., “Prospects for the Development of Metallurgy and Mechanical Engineering Using Completed Fundamental Research and R&D: Ferroalloys”, OOO Izl-vo i tipografiya “Alfa Print”, Yekaterinburg (2018), pp. 340–341.
18. A. I. Tatarkin, V. V. Balashenko, V. G. Loginov, and M. N. Ignatieva, “Methodological tools for assessing the investment attractiveness of renewable resources of the Northern and Arctic territories,” Econ. Region., 12, No. 3, 627–637 (2016).
19. L. I. Dvorkin and O. L. Dvorkin, Building Materials from Industrial Waste [in Russian], Phoenix, Rostov-on-Don (2007).
20. K. A. Vyvarets and A. D. Vyvarets, “Conceptual approach to overcoming the “tyranny” of discounting,” Vestn. SUSU, Ser. “Economy and Management,” No. 20 (120), 33–39 (2008).
21. O. A. Romanova and D. V. Sirotin, “Processing of technogenic formations within the framework of the formation of a circular economy,” Izv. UGGU, Issue 4 (60), 183–193 (2020); DOI 10.21440/2307-2091-2020-4-183-193.
22. O. V. Zayakin, R. N. Statnykh, and V. I. Zhuchkov, “Study of the possibility of obtaining non-decomposing slag during lowcarbon ferrochrome production,” Metallurgist, 62 (9–10), 875–881 (2019).
23. O. V. Zayakin and I. N. Kev’, “Promising directions for the stabilization of ferroalloy production slags,” Mater. Sci. Forum, 946, 401–405 (2019).
24. J. G. Flethcer and F. P. Glasser, “Phase relations in system CaO–B2O3–SiO2 .” J. Mater. Sci., 28, No. 10, 2677–2686 (1993).
25. A. Ghose, S. Chopra, and J. F. Young, “Microstructural Characterization of Doped Dicalcium Silicate Polymorphs,” J. Mater. Sci., 18, No. 10, 2905–2914 (1983).
26. A. A. Akberdin, A. S. Kim, A. B. Esenzhulov, and K. Z. Sarekenov, “Implementation of technology of stabilizing basic metallurgical slags from dicalcium silicate disintegration,” in: Tr. Mezhd. Nauch.-Prakt. Konf., Poslyashch. 70-letiyu KGGMK “Krivorozhstal” “Theory and Practice of Cast iron Production” [in Ukrainian], Krivy Rog (2004), pp. 295–297.