

OPTIMIZING THE USE OF RESOURCES OF TECHNOGENIC DEPOSITS TAKING INTO ACCOUNT UNCERTAINTIES

The article discusses the problem of resource deterioration and the exhaustion of natural resources as well as the involvement in economic circulation of waste production, resources of technogenic deposits in order to maintain natural capital and support "green" economic growth. This necessitates the development of the mechanism for the environmental management optimization. This mechanism aims at using technogenic deposits in the economy to decrease of both the nature intensity of production and the cost of production. Furthermore, the environmental management optimization should reduce the negative impact of production on the environment. The authors propose to construct a model of economic relevance for the use of waste based on the theory of sustainable development and the theory of substitution of primary natural resources. Under substitutes, we consider useful products, resources from technogenic deposits, resulting from past economic activities. The article considers the problem of accumulation of municipal solid waste and industrial wastes in the regions of Russia in terms of forming and operating the ever-growing technogenic deposits. The authors propose a set of models for the optimum exploitation of technogenic deposits taking into account various factors of the external and internal environment as well as the time factor. The proposed models allow to substantiate and choose the best technologies for the processing of accumulated waste in terms of the reduction of pollution and "green" revenues from the exploitation of technogenic deposits. To account the probabilistic assessments of the geological structure of the technogenic deposits, we propose to use a combination of Monte-Carlo method and of developed optimization models. The authors describe the calculation results and the prospects for the development of a comprehensive model using regional technogenic deposits. The results of the research allow forming an optimal set of projects for waste processing and rehabilitation of disturbed territories at the regional level. The proposed economic and mathematical tools will be useful for updating the federal target program "Elimination of accumulated environmental damage" for 2015–2026.

Keywords: green economy, depletion of natural resources, technogenic deposits, waste, accumulated environmental damage, performance indicators, field development, optimization model, probabilistic assessment, Monte-Carlo method, probability curve of NPV

Introduction. Problem statement and relevance for regional development

As noted in the report "On the ecological development of the Russian Federation for the benefits of future generations" (2016), to ensure its life activities, humanity has used and produced hundreds of different materials for hundreds of years. At the same time, the volume of total consumption of all basic materials in 2015 approached 90 billion tons, which is 20 times higher than the same figure in 1900. The population of the world during this period increased by 4.6 times, global GDP – 33 times, consumption of all materials – 12 times, fossil fuel sources – 16 times, metal ores – 43 times, raw materials for the production of construction materials – 59 times. The analysis of extra-long term (over 115 years) and contemporary trends of the last 40 years suggests that in the XX and XXI centuries, the consumption of basic materials markedly accelerated.¹

To a large extent, the forecasts of Club of Roma confirm that the consumption of materials is growing exponentially [1], and has increased by 12 times over 115 years. The consumption of mineral (fossil) materials grew significantly faster than the consumption of biomass, which resulted in a fundamental shift in the structure of the materials used from the dominance of biomass to the dominance of fossil materials.

At the same time, the extraction and processing of natural resources lead to the majority of the negative impact on the environment: air and water pollution, greenhouse gas emissions and waste production. The high material intensity of the global economy is the reason for the depletion and

¹ Doklad "Ob ekologicheskom razvitiy Rossiyskoy Federatsii v interesakh budushchikh pololeniy" [The report "On the Environmental Development of the Russian Federation in the Interests of future Generations"]. (2016). Moscow: The State Council of the Russian Federation, 312. (In Russ.)

exhaustion of a number of natural resources. But that, first of all, fossil fuels, ore and mineral resources are meant. In these conditions, effective reuse of materials and the involvement of waste in economic turnover can significantly reduce the risks of both their resource base depletion and the negative impact on the environment.

In this situation, the problem of natural resources depletion, waste accumulation, air, water and soil pollution and the connected problems of biodiversity loss and climate change, which have arisen largely due to the extraction and combustion of fossil fuels, are among the seven major contemporary global environmental problems. In the economy of the Russian Federation, about 5 billion tons of production and consumption waste are generated annually, which is twice as high as in the countries of the European Union. The heaps of ore-dressing plants annually grow by 700 million tons. The total volume of accumulated waste accounts for approximately 80 billion tons of waste, including more than 2 billion tons of ash from thermal power plants, thermal power stations, state district power stations, slags of ferrous and non-ferrous metallurgy [2]. In Russia, the amount of accumulated waste was 31.5 billion tons (as of the end of 2015). Only in the Urals, the total amount of accumulated waste reaches 10 billion tons, of which about 98 % are non-hazardous mineral wastes of the mining industry (overburden and passing breeds, enrichment tails). In the Murmansk region, annually over 150 million tons of waste are stored, the total amount of which has reached 8 billion tons so far. Explored copper reserves account for 67 million tons, zinc reserves – 42 million tons (its annual production accounts for 0.8 and 0.4 million tons respectively), meanwhile, in particular, industrial waste contains more than 8 million tons of copper, 9 million tons of zinc and other useful components [3]. At the same time, extraction of minerals on the basis of traditional fields is becoming more and more expensive. For example, the Talnakh copper-nickel field located in the north of the Krasnoyarsk Krai is more than 600 m in depth. Currently, even mines deeper than 1 km are not rare.

The accumulated industrial waste is spread unevenly across the Russian Federation and corresponds to the established scheme of productive forces location. Sverdlovsk region accounts for up to 30 % of waste. The largest amounts of waste are concentrated in the Urals Federal District, the Kursk Magnetic Anomaly area, the Tula and Ryazan Regions [4].

At the State Council's working session on the issue of environmental development of the Russian Federation for the benefit of future generations held on December 27, 2016, it was noted that in a number of directions the burden on nature has reached its critical levels. According to the results of the all-Russian public opinion poll conducted by VTsIOM in December 2016, almost 45 % of respondents consider waste as the main threat to the environment. Therefore, the necessity of transition to "green", environmentally sustainable development as a national strategic priority is established.²

The issue of processing and neutralizing production and consumption waste is also among prior ones. The total amount of such waste is now over 30 billion tons. Landfills occupy almost 48 thousand hectares. In Russia, more than 90 % of all generated municipal solid waste (MSW) is sent to a waste disposal facility. Nowadays, the level of utilization of MSW is only 8 %. It is expected that by 2025 this figure will be about 40 %. Recently the average amount of utilized MSW per capita has increased and accounts for 393 kg/year, while in other developed countries this figure is 400–700 kg/year. Such wastes include environmentally hazardous products (batteries, fluorescent lamps, automobile tires, polyethylene packaging and dishes, etc.). The majority of these wastes are sent to landfills in Russia, and only 7 % are sent to waste recycling plants, and about 2.5 % – to waste incineration plants.

The EU Waste Framework Directive sets 50 % of municipal solid waste utilization as a target to be reached by 2020 compared to 30 % in 2016 [5]. UNEP has set the task of ensuring that the collection and utilization of such wastes are fully covered [6]. Many middle-income countries, among which Russia is, have already solved this problem. In Germany, Austria, Belgium and Switzerland already more than half of the waste is recycled. The share of landfilled waste in the EU has decreased to 33 %, and in countries such as Austria, Denmark, Norway, the Netherlands, Belgium, Sweden and Germany municipal waste is almost never sent to landfills. On average, 1 ton of extracted natural raw materials causes 2 tons of waste (rock dumps, construction debris, etc.). The volume of waste use and neutralization in Russia amounted to 2.7 billion tones or 53 % in 2015, which is slightly higher than the same figure for the EU

² Zasedanie gosudarstvennoogo soveta po voprosu ob ekologicheskom razvitii Rossiyskoy Federatsii v interesakh budushchikh pokoleniy 27.12.2016 [The meeting of the State Council on the environmental development of the Russian Federation in the interests of future generations 27.12.2016]. Prezident Rossii [President of Russia]. Retrieved from: <http://www.kremlin.ru/events/president/news/53602> (In Russ.)

countries (52 %). In China, Hong Kong and other countries, this problem is now also considered very relevant [7]. In these conditions, an important task is the development of scientific tools and economic and mathematical models for optimizing the use of resources of technogenic fields and wastes taking into account uncertainties.

1. Industrial and municipal wastes as technogenic fields of the XXI century

At the level of the Federal subjects' administrations measures are planned to reduce waste, among which the most common is the introduction of additional taxation later to develop low-waste production and environmentally safe waste management. It should be noted that this way is dead-end, as it leads to an increase of utility bills, discontent among the population and air pollution because of waste incineration. Within an annual mass of municipal solid waste possible secondary raw materials could be waste paper, food waste, polymeric materials, ferrous and non-ferrous metals, glass. At the same time, scrap ferrous and non-ferrous metals must be sorted by magnetic separation, compressed and sent to the foundry for smelting. Reuse of polymer residues requires excessively high expenditures due to a high degree of their contamination and non-compliance with quality requirements. Secondary recycling of polymers is carried out only in the absence of strict requirements to the resulting material, for example, in the production of building materials (fillers). The remains of glass can be used for the production of technical glass applied in construction. Paper waste can be used for paper production. Recycling electronic devices' remains enable receiving gold, silver, palladium, nickel, iron, copper and glass polymers during processing. Wastes from petroleum products can be used to get asphalt, bitumen and oils.

Even more promising are accumulated reserves of mining, thermal power stations and primary ore recycling enterprises [8]. For example, in Canada with the help of new recycling methods up to 40 % of copper is extracted from the waste of copper-mining enterprises. The extraction of copper concentrate from natural raw materials in Bulgaria is three times higher than from technogenic fields [9]. The maximum application of useful components of man-made raw materials formed only in mining will increase the volume of industrial products produced in the Russian Federation by 10 trillion rubles, tax deductions to the budget may amount up to 20 billion rubles per year (in 2010 prices) [10].

2. Theoretical and practical aspects of economic feasibility of technogenic fields use in a region

Nowadays a considerable number of scientific papers are devoted to forecasting the volume of waste being generated in megacities [11–13]. The most important reason for the insignificant interest in the use of technogenic fields is, first of all, high costs of extracting useful products that exceed the costs of extracting traditional minerals. In addition, the unstable percentage of useful products extraction while developing a technogenic deposit should be mentioned. However, a number of factors point to the possibility of overcoming the gap between the costs of extracting useful products on a traditional (natural) field and technogenic deposit:

- reduction of capital costs required for the development of technogenic deposits, as production waste is concentrated in areas with developed industrial and transport infrastructure;
- reduction of costs for underground mining because of the location of technogenic deposits mainly on the earth's surface;
- reduction of operational costs for extraction (mining) as a result of the fragmented state of rock mass in the technogenic field;
- reduction of mining costs in the result of scientific and technical progress– development of new, more efficient and less costly technologies for extraction and processing of mineral raw materials;
- the increase in costs for mining natural deposits due to the depletion of natural deposits.

The model for assessing the economic feasibility of waste use can be formed on the basis of the theory of natural resources substitution by substitute resources which are minerals (products) from a technogenic deposit. As a criterion of optimality maximization of net discounted income should be used [14]. The economic-mathematical model that enables estimation of volumes and time terms of economically profitable extraction of resources from a technogenic deposit, without taking into account the economic assessment of environmental damage reduction, can be written in the following way:

Criterion: maximizing net discounted income from the use of product from a technogenic field

$$\sum_{t=0}^T [U(C_t) - R_t(X_t) - Z_t(Y_t)](1+E)^{-t} \rightarrow \max. \quad (1)$$

Ensuring society's need for the product

$$C_t \leq X_t + Y_t, \quad t = 0, 1, \dots, T. \quad (2)$$

Extreme capacity of the traditional field

$$\sum_{t=0}^T X_t \leq V. \quad (3)$$

Variables non-negativity

$$C_t \geq 0, X_t \geq 0, Y_t \geq 0, \quad t = 0, 1, \dots, T \quad (4)$$

where: $U(C_t)$ – consumers income as a result of the product use in the volume of C_t , rub.; $R_t(X_t)$ – costs of extraction (mining) of the useful product in the volume of X_t on the base of the traditional (natural) field, rub.; $Z_t(Y_t)$ – costs of receiving the useful product from the technogenic field Y_t , rub.; V – annual volume of the useful product extraction (mining) in the natural environment, tons; E – discount rate; t – current time (years).

The moment of economically expedient use of a substitute resource is defined by the crossing of curves of costs on a substitute resource and on natural resource extraction (fig. 1).

Taking into account economic assessment of environmental damage in the above-mentioned model the criterion of optimality will be changed:

$$\sum_{t=0}^T [U(C_t) - R_t(X_t) - Z_t(Y_t) + W(Y_t)](1+E)^{-t} \rightarrow \max, \quad (5)$$

where: $W(Y_t)$ – economic assessment of prevented environmental damage due to the reduction of waste volume, rub.

Thus, operation of a technogenic field becomes favourable in that case when costs per 1 unit (1 t) of the received produce from the technogenic field are below costs per 1 unit (1 t) of produce received from the traditional field after its deduction by economic assessment of prevented environmental damage due to the reduction of waste volume. The solution to this issue will enable determining the onset of the moment of economically profitable exploitation of a technogenic deposit.

Total loss the society gets because of grounds and landfills operation as well as the refuse to recycle waste accumulated in landfills lead to losses for a society which include additional expenses of enterprises-pollutants on the placement of waste on grounds, environmental damage and dotations from budgets of different levels. The traditional approach to environmental management is focused on the partial decrease of environmental damage due to increase in expenses of enterprises-pollutants for placement of waste and due to dotations from the state. However, it also leads to increase in the price

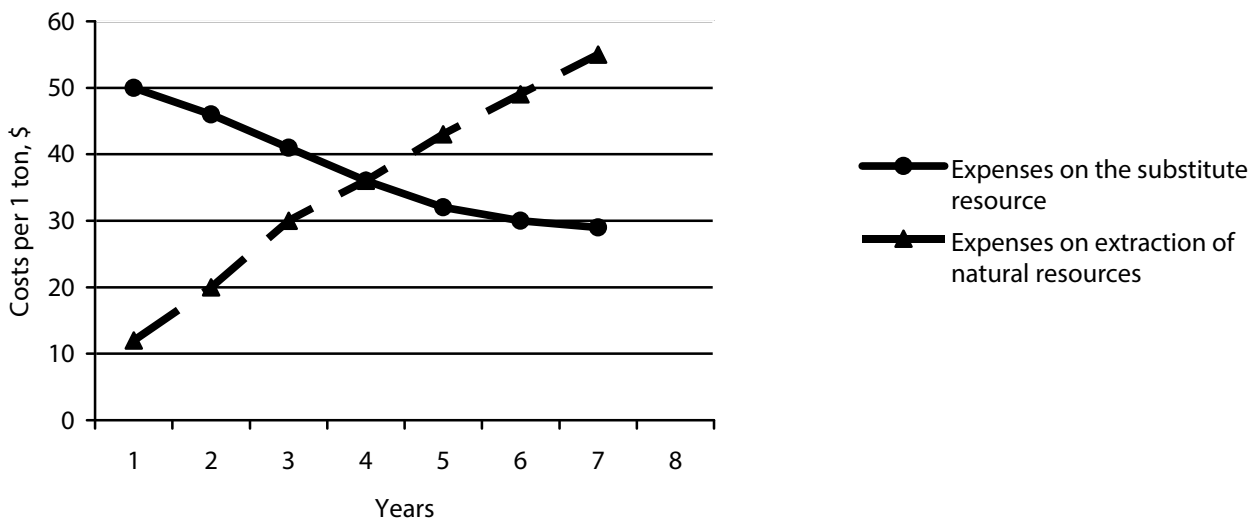


Fig. 1. Results of calculations on the basis of the model for assessment of economic feasibility of technogenic field development start

of products—as compensation for the increase in its production costs. But if the closed cycle of waste use is applied, the environmental damage will be liquidated, enterprises will get additional profit from waste use, and that will enable refuse from state dotations and reduction of products prices.

3. Model for the optimum choice of the best technology for waste use

In case of a technogenic field development, there is an issue if production of useful products which can be received from the dumps formed during past periods is complete. At the same time to extract the same product, various technologies of production can be used. Choosing the technology of solid waste utilization, it is recommended to focus on cutting waste recycling costs per unit and capital investments in waste recycling and to minimize environmental damage. Taking into account the mentioned factors must provide profit increase from the sale of a produce unit. Then the optimization model for choosing the best technology of multiproduct extraction from a technogenic field takes a form:

Maximizing "green" profit from operation of a technogenic field

$$\sum_{i=1}^n P_{ij} V_{ij} - \sum_{i=1}^n Z_{ij} V_{ij} - Y_j \sum_{i=1}^n V_{ij} \rightarrow \max. \quad (6)$$

Restriction on volume of investment in a technogenic field development

$$\sum_{j=1}^m \sum_{i=1}^n D_j * V_{ij} \leq B. \quad (7)$$

The limited opportunities of a natural field operation

$$\sum_{j=1}^m V_{ij} = V_i. \quad (8)$$

Possibilities of receiving a product from a technogenic field taking into account the applied technology

$$V_{ij} = \begin{cases} = 0, & \text{when } A_{ij} = 0, \\ \geq 0, & \text{when } A_{ij} = 1. \end{cases} \quad (9)$$

where: i —type of a product, $i = 1, \dots, n$; j —technology of product extraction, $j = 1, \dots, m$; V_{ij} —the volume of product of type i extracted by technology j , tons; V_i —the maximal forecasted volume of possible extraction of product i on a natural field, tons; Z_{ij} —costs of extraction of a unit of product i with the use of technology j , rub./ton; Y_j —environmental damage caused by extraction of a unit of product with technology j , rub./ton; P_{ij} —price per unit of extracted useful product i with technology j , rub.; D_j —capital expenditure on production of a power unit for waste recycling with technology j , rub.; B —volume of investment, rub.; A_{ij} —matrix showing the possibility of recycling of waste of type i with technology j .

This model enables determining the volumes of receiving useful products from a technogenic field, as more efficient ones compared to the corresponding products from a traditional (natural) field, at the simultaneous choice of the best extraction technologies taking into account decrease in environmental damage. In these conditions profit from the operation of a technogenic field could be called as "green" profit.

This model has a number of shortcomings, including lack of information on dynamics of useful products extracted from a technogenic field and on risk factors.

4. Optimal use of a technogenic field taking into account dynamics of its development

To take into account dynamics of a technogenic field development, it is recommended to use the common model of raw mineral resources mining dynamics, which is based on anticipated extracted reserves of the useful product [15]. It is expedient to present mining dynamics by the change of a share of extracted useful product in an overall volume of stocks:

$$f_i(t) = \begin{cases} s \frac{t}{t_1} & | t = 1, 2, \dots, t_1, \\ s & | t = t_1 + 1, t_1 + 2, \dots, t_1 + t_2, \\ s \exp\{-\beta[t - (t_1 + t_2)]\} & | t = t_2 + 1, t_2 + 2, \dots, t_2 + t_3, \end{cases} \quad (10)$$

where: s —relative amount (a share in extracted reserves) of annual extraction during the period of maximal extraction; β —extraction (mining) decrease parameter which variations are usually in an interval $0,1-0,2$; t_1 —mining increase period duration; t_2 —duration of the period of maximal extraction (mining); t_3 —duration of the period of extraction (mining) reduction until its completion.

The use of the dependences reflecting dynamics of extraction (production) of produce from a technogenic field will enable determining the annual volume of extraction (production) X_{it} for every year t , based on the maximal value X_i^{\max} , by a formula

$$X_{it} = X_i^{\max} f_i(t). \quad (11)$$

Then the optimization model with the use of the criterion of maximizing the net discounted income or net present value (*NPV*) applied for a technogenic field should enable search of optimal values X_i^{\max} within the restrictions on investment in the technogenic field development B and the limited volume of the extracted useful resource \bar{Q}_i . For this purpose it is possible to use the following variation of the model:

Criterion: maximizing net discounted income

$$\sum_{i=1}^n \sum_{t=1}^T [(P_i - S_i - I_{it} + \Delta Y_i) X_i^{\max} f_i(t)] (1+r)^{1-t} \rightarrow \max. \quad (12)$$

Restriction on a limit of extraction of useful product

$$\sum_{t=1}^T X_i^{\max} f_i(t) \leq \bar{Q}_i, \quad i = 1, 2, \dots, n. \quad (13)$$

Restriction on costs of field development

$$\sum_{i=1}^n I_i X_i^{\max} \leq B, \quad (14)$$

where: P_i —price for useful product i ($i = 1, 2, \dots, n$), rub.; S_i —cost of production of useful product i ($i = 1, 2, \dots, n$) from a technogenic field, rub.; I_{it} —unit capital expenditure on construction of an enterprise for production of useful product i ($i = 1, 2, \dots, n$) on base of a technogenic field in year t , rub./ton; Z_i —cost of production of useful product of i ($i = 1, 2, \dots, n$) with use of traditional raw materials, rub.; ΔY_i —the annual volume of prevented damage at mining useful product i from a technogenic field (a dump, a waste ground, etc), rub./ton.

Since the value \bar{Q}_i is not known reliably, in addition, costs on field development also depend on its mining and geological features, and forecasted values $f_i(t)$ received with use of model (10) cannot be found authentically neither, it is necessary to correct model (12–14) taking into account uncertainty of the parameters stated above. These parameters are presented in models (15–17) taking into account an uncertainty factor ω .

Criterion: maximizing net discounted income

$$\sum_{i=1}^n \sum_{t=1}^T [(P_i - S_i - I_i + \Delta Y_i) X_i^{\max} f_i(t)] (1+r)^{1-t} \rightarrow \max. \quad (15)$$

Restriction on a limit of extraction of useful product

$$\sum_{t=1}^T X_i^{\max} f_i(t, \omega) \leq \bar{Q}_i(\omega), \quad i = 1, 2, \dots, n. \quad (16)$$

Restriction on costs of field development

$$\sum_{i=1}^n I_i(\omega) X_i^{\max} \leq B. \quad (17)$$

To carry out the calculations a computing procedure integrating the method of statistical experiments and the optimization model given above was developed. The parameters of the model (15–17) which depend on random factors are set by minimum and maximal limits and an intermediate (expected) value, which means that generally $c = (c^{left}; c^{exp}; c^{right})$. Then it is possible to use the triangular distribution law [16].

$$c(\omega) = \begin{cases} c^{left} + \sqrt{\omega(c^{exp} - c^{left})(c^{right} - c^{left})}, & \text{when } \omega \leq \frac{c^{exp} - c^{left}}{c^{right} - c^{left}}, \\ c^{right} - \sqrt{(1-\omega)(c^{right} - c^{exp})(c^{right} - c^{left})}, & \text{when } \omega > \frac{c^{exp} - c^{left}}{c^{right} - c^{left}}, \end{cases} \quad (18)$$

where: $\omega \in (0, 1)$ – random number received by use of random number generator.

According to the method of statistical experiments, it is necessary to carry out a large number of calculations for parameters of the model (15–17), for example, $N = 1000$. It will enable the creation of various numerical values of the model for each one of the received options and carrying out optimizing calculations for them. It will provide a possibility to assess probable NPV from the operation of a technogenic field and to find the interval of optimal values of extraction of useful products from a technogenic field for each of the clusters used to form the probability curve.

Such approach makes it possible to ensure the realization of resource saving principle of and to create conditions for the interaction of interested parties in ecologically focused projects [17]. In addition, economic conditions for rehabilitation of damaged lands in a mining zone and for the elimination of accumulated environmental damage could be created [18].

5. Case assessment of probable NPV from operation of a technogenic field with use of tools suggested above

The object of this case is the technogenic field formed as a result of operating heat power plant. As a result of geological research useful products which can be extracted from this field were defined: cementitious materials for the cement industry, aglopomite (artificial porous filler for lightweight concrete), components for production of slag blocks, slag and slag pumice, raw materials for the production of alumina and synthetic zeolites [19]. It was recommended to extract three types of products at the field: x_1 – cementitious materials for the cement industry; x_2 – components for the production of slag blocks; x_3 – raw materials for the production of synthetic zeolites. The solution to the task was carried out using the model (10–18), which made it possible to determine the probabilistic estimation of the economic feasibility of the technogenic deposit development.

Table 1

Results of data processing received by mixed use of statistical tests and optimization model

Number	Limits of NPV, million rubles		Frequencies
1	7759,53	8343,56	10,0
2	8343,56	8927,59	30,8
3	8927,59	9511,62	43,0
4	9511,62	10095,65	14,2
5	10095,65	10679,68	2,0

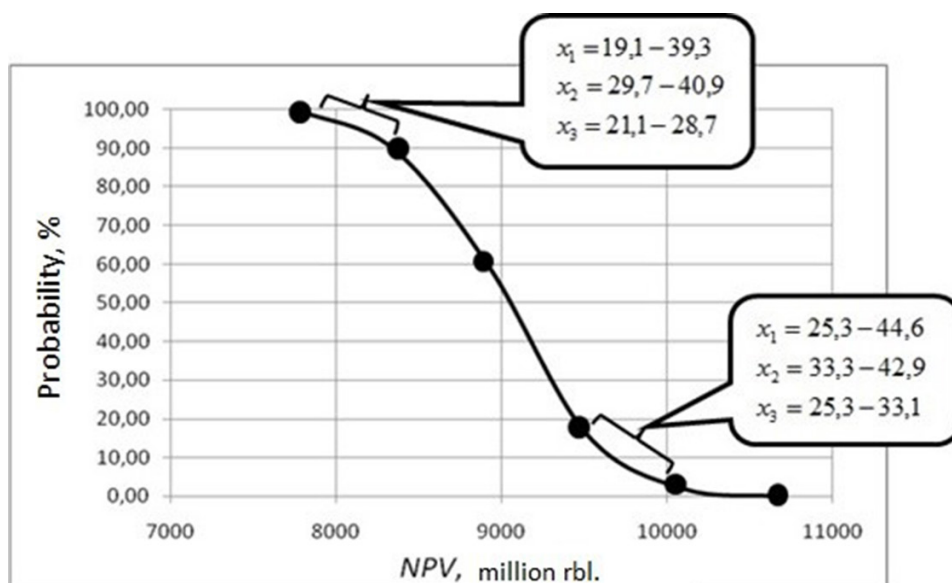


Fig. 2. A probability curve with reflection of production borders of the useful products for two allocated intervals

Table 1 shows the results of the application of the statistical experiments method, which made it possible to determine the optimal NPV for technogenic deposit for each of the calculation options (the number of calculations $N = 1000$).

Based on the data in Table 1, probabilistic estimations of the achievement of the NPV boundary values were determined. With the use of these probabilities, a probabilistic curve for estimating the efficiency of exploitation of the technogenic deposit was constructed (Fig. 2).

In Figure 2, for several selected intervals, the production limits of each of the useful products are given. The results of the calculations show that NPV growth is ensured by a fairly uniform increase in the production of all three types of useful products. The minimum value of NPV, equal to 7759.53 million rubles, turns out to be positive, and the payback period at that was at the level of 3.5 years, which confirms the economic feasibility of field operation.

With a 60 % probability, the NPV will increase to 8927.59 million rubles. with a reduction in the payback period to 3.2 years. The yield of such performance indicators can be achieved under favorable geological conditions of the technogenic deposit in question.

Conclusion

The use of the developed tools makes it possible to apply both budgetary sources of financing and extrabudgetary funds for implementation of such projects, making this sphere of economic activity for processing waste for business attractive [20]. The methodical support developed by the authors allows to find the optimal variant of effective exploitation of the technogenic deposit in conditions of uncertainty, which gives confidence in the refusal to practice the accumulation of solid municipal wastes at the landfills, as well as tools for involving accumulated wastes of mining enterprises in economic circulation. Thus, the possibility of considering solid municipal waste and industrial waste not as waste, but as secondary, technogenic resources or technogenic deposits of useful products, the extraction of which is less costly than the extraction of natural resources. The next stage in the development of this modeling apparatus is the creation of a regional model linking technogenic deposits, sources of production waste and MSW, enterprises that consume useful products. The model will be the final link in the system of valuation, planning and forecasting models that will allow to get rid of landfills that alienate significant land resources and are a source of environmental pollution at the regional level.

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