Digitalization and Forecasting of the Iron Ore Business

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Abstract: Ukraine's iron ore mining industry is among the most powerful ones in the world, which account for 90% of the volume of iron ore products. All iron ore mining enterprises of Ukraine are private. Current conditions of their operation and prospects for its development bring up the problem of the most accurate forecasting of economic results of mining by implementation of its key process – ore stoping. This determines profitability of the business, its competitiveness and possibility of reasonable planning. To solve this problem, the authors developed a methodology, a system of technical and economic indicators and a computer program to provide multifactor economic analysis of competitive solutions on stoping and selection of optimal one according to the forecast economic results of its application. Use of ore value indicators, the value of ore reserves and the degree of use of the value as a result of stoping makes the basis of this methodology and the system of indicators. Further development of this work implies creation of systems for modeling the entire process of underground iron ore mining the key element of which is stoping with forecasting profitability of the business based on analysis of iron ore market conditions.

1 INTRODUCTION

Currently, Ukraine is in the group of 7 countries with the most developed iron ore mining industry out of 52 countries carrying out activities. Business structures that operate in this area in Ukraine are among the largest. Iron ore enterprises of these structures account for about 9% of the country's GDP. In Ukraine, there are 8 large private iron ore enterprises which produce up to 87.0 Mt of commercial iron ore products (concentrate, pellets, sinter ore, blast furnace and raw ore). About 60% of this volume is consumed by national private metallurgical enterprises, 40% is sold in foreign markets (Kindzerskyi, 2013). Business in the field of iron ore mining is one of the most profitable and forms a powerful source of the country's budget revenues in national and foreign currencies.

Application of the underground method of mining iron ore deposits is one of important and promising directions in production performance and development. This is due to the fact that the specific technology of this mining method provides the possibility of economically effective iron ore extraction at great depths (over 1000 m). At such depths, the open pit method of mining, which is currently the main one, is economically inefficient.

In Ukraine, application of the underground mining method accounts for 15-20% of the volume of commercial iron ore products. In the near future, their volumes will grow as the main reserves of iron ore extend to great depths. Iron ores are already proved to occur at the depth of 2750 m, and the forecast depths are 5.0-7.0 km.

Along with this, it should be noted that in order to achieve the highest economic efficiency of mining these reserves at great depths, mining enterprises

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need to solve a number of complex problems. The most relevant among them is the need for accurate forecasting of technical and economic results of iron ore development according to mining engineering and economic conditions of its implementation. (Kaplenko, 2003) (Kaplenko, 2013). These conditions are very difficult in terms of ore occurrence characteristics, the situation in the markets of iron ore products and the markets of production resources.

The need for such forecasting is determined by the needs for reasonable forecasting of business profitability, its competitiveness, and justified planning of business processes (Kosenko, 2017) (Popov, 2016).

One of the most important tasks in the field of such forecasting is determination of technical and economic results of implementing one of the key processes of underground mining, namely *Stoping*. This is one of the most large-scale, technologically complex, costly and extremely dangerous processes. The implementation of this very process provides the mining enterprise with an ore resource with characteristics necessary for production of commercial iron ore products. The volume of financial costs for its implementation reaches 40-60% of the cost of extracted ore mass, with an increase in the mining depth of development, they increase as well. At the same time, in stoping, significant technological losses of ore occur, up to 9-15% of the reserve, and increased dilution of the extracted ore mass with waste rocks makes up to 10-20% of its volume. All this negatively affects the economic results of mining.

This problem can be solved by applying such technological, technical, parametrical solutions for implementation of stoping which are optimal, i.e. ensure achievement of the highest profitability of mining in specific conditions of its implementation.

This problem can be solved only on the basis of digitalization of the business in the field of iron ore mining, i.e. development and use of application-oriented software means modeling of production and, in particular, the process of ore stoping and optimization of its design solutions based on forecasting the results of mining ore reserves. The degree of compliance of these solutions with the target function of optimality directly determines the profitability of mining, performance of a mining enterprise, (a business structure can include several enterprises of this kind), and this is the basis for formation of economic results and business efficiency.

To successfully solve this problem, it is necessary to have, first of all, the method of economic and mathematical modeling of the stoping process, considering a wide range of mining and economic conditions for stoping. In addition, it is necessary to have a system of indicators that allow correct assessment of its economic results (Veduta, 2017).

At present, there is no generally recognized modeling methodology and system of indicators available. Developments that exist in this area are based only on determined values of the integrated indicator of efficiency – profit from implementation of the result of the Extracted ore mass stoping. However, they do not solve the important economic problem that arises in this process, namely, determining how fully the economic potential (i.e. an ore reserve with its engineering and economic characteristics) is used as a result of mining, and this directly concerns profitability of mining.

According to the above mentioned, the work is aimed at developing a mathematical model, a set of indicators and a computer system for modeling the process of iron ore stoping to predict its results at the level of the economic activity of the mining enterprise support. The theoretical basis for their development is described below.

2 RELATED WORK

The process of ore stoping is carried out at the main production objects of underground mining enterprises - Mining blocks. Stoping includes implementation of a number of so-called Technological processes of stoping. Specific solutions on the technology of performing each of them, means of labour mechanization, parameters of their implementation determine technical-economic efficiency of stoping (Ray, 2016).

In previous years, the urgent need to increase this efficiency in difficult underground conditions required development of a whole range of technological and technical solutions to extract ore, aimed to improve stoping and eliminate its shortcomings. These solutions are summarized in a special document Typical passports of underground mining systems. Currently, 50 variants of such systems have been developed in Ukraine. In general, over 2,500 patterns have been developed for various conditions of ore in the world.

The passports of mining systems present:

- designs of mining blocks based on different variants of mining systems;
- expected technical and economic results of mining their reserves (productivity of a stope, labour efficiency, specific length of technological

workings, expected technological losses of ore, technological dilution, cost of extracted ore mass).

- criteria for selecting variants of mining systems (mining depth, ore body thickness and dip, physical and mechanical properties of ore and country rocks);

From these passports, based on comparison of the criteria for mining systems selection and actual conditions at mining sites of the deposit, variants of systems for specific blocks are selected. It should be noted that in practice these conditions are unique and are not repeated at other mining sites.

On the basis of the selected mining systems, mining blocks are designed.

However, designing implies certain complexity consisting in the fact that the right choice of the mining system does not guarantee its highest economic results. This situation is due to the fact that in typical passports there are only fundamental solutions for block designs and the technology of stoping treatment for certain simplified forms of ore bodies, elements of their occurrence. Yet, in practice, real characteristics of ore bodies have significant deviations from average values, and this leads to specific economic results of mining which will naturally differ from the values indicated in the passports of the systems. Therefore, in order to obtain the highest economic efficiency of stoping, the selected variant of the mining system still needs to be parametrically adapted to conditions of a particular block, and there may be several competitive variants of systems.

At the mining enterprise, there can be from 4 to 20 mining blocks at the same time and it is necessary to design more and more new blocks as already exhausted blocks are decommissioned. Designing of the kind is a constant and continuous process. These projects are prepared according to a special instruction, in which unfortunately there is no method of detailed economic analysis of decisions made during designing (Barry, 2006).

Parametrical adaptation of mining systems is performed through selecting geometrical parameters of structural elements of the block without violating the principle design of the system chosen for it. In addition, when adapting, the parameters of the stoping technology are calculated, the general scheme of which is regulated by the passport. Naturally, the obtained technical and economic results of ore extraction and its profitability depend on the level of constructive, technological and parametrical adaptability of the entire production and technological complex of a mining unit to specific geological and mining conditions of its design and mining of its reserve.

Such adaptation represents a complex, time-consuming and responsible process in which many options of different solutions are considered. Its implementation requires highly qualified designers with practical experience in technological design and mining economics. At the same time, each of their solutions should be not only due to mining factors, but also economically justified and optimized according to the criteria for obtaining the highest economic efficiency. That is why it is necessary to have an economic and mathematical model of an appropriate nature and a system of estimated economic indicators.

The authors have developed a relevant model and system of indicators. This model is developed on the basis of formalization of three important characteristics of the subject of labour: the *Value* represented by the ore reserve; the *Value of the ore reserve*; the *Degree of the value use* when mining. For this purpose, business structures acquire the right to mine the reserve. This approach to evaluate the efficiency of stoping is applied for the first time.

Specificity of application of the above characteristics consists in the following. The purpose of stoping is to obtain the industrial reserve of ore from the monolithic ore massif, the required volume of ore mass which, in its physical condition (crushed material with a given granulometric composition), quality (metal content) and economic characteristics (cost), allows economically efficient processing it into commercial iron ore products that meet the requirements of the consumer (a metallurgical enterprise). At the same time, the closer to these requirements the characteristics of the mined ore mass are, the more cost-effectively ore mass is processed. Up to 40% of ore mined at mining enterprises, even without detailed optimization of mining immediately after extraction, meets these requirements. But that is not sufficient. To achieve the highest degree of such conformity, it is necessary to choose the most optimal technological, technical and parametrical solutions for implementing each technological process, which make up the structure of stoping. However, this is currently not performed, and designers are guided only by common solutions without their detailed economic analysis.

2.1 The Structure of Stoping

As mentioned above, stoping involves a number of technological processes that are strictly sequenced and rigidly related. This sequence is given in Fig. 1.

It is the specifics of execution of these processes according to the selected solutions that determines the economic result of stoping in general (Tradin Ecjnomics*)* (Popov, (2020) (Martynov, 2010).

Drilling consists in forming systems of blast holes within the stoping space of the mining block. The holes are located according to a certain pattern and have defined length and diameter parameters. To mine the reserve of one block, 10.0 - 30.0 km of boreholes are drilled. It should be noted that while parametrical adaptation of development systems, the total length of holes can vary significantly in different variants of drilling operations, and this significantly affects the economic results of stoping due to the fact that this process is one of the most costly.

Blasting consists in charging holes with explosives and forming explosive charges of special structures, the blasting circuit switching, initiating detonation of the charges in a certain sequence. Currently, ore is broken by mass blasting when up to 50.0-100.0 t of explosives are detonated in one cycle and up to 200.0-400.0 and sometimes up to 900.0 kt of ore is broken. Depending on mining conditions, costs for blasting reach 40-70% of the total cost of stoping.

Ventilation of the block is removal of explosive gases from the block after detonation of charges in the stoping space. Ventilation is executed, as a rule, due to general depression, sometimes by force applying special ventilation equipment. The need to ventilate the block requires a significant amount of ventilation workings that distribute air flows in the block between different objects. The length of ventilation workings can make up to 40% of the length of all types of mine workings in the block.

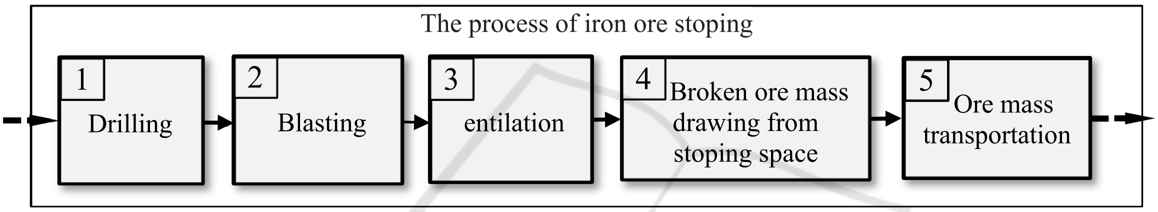

Figure 1: The schematic diagram of stoping.

Broken ore mass drawing consists in removing the broken ore mass from the stoping space. Ore mass drawing can be executed by the gravitational method or applying special vibration equipment. Productivity of the ore mass drawing from the block amounts to 800.0-6000.0 t per working shift.

Ore mass transportation consists in moving the broken ore mass from the stoping space in the block to the place where it can be hauled to the hoisting complex of the mine. To perform this process, a system of technological workings and machines (scrapers, conveyors, vibro-equipment) operates in the block.

Dashed arrows in Fig. 1. show that the process of stoping is an element of a larger production and technological system of an iron ore mining enterprise and executed after implementation of a complex of various processes before and after it. However, in this scheme stoping is a key process. Each of the technological processes of stoping makes its contribution to the formation of its technical and economic results.

2.2 The Main Factors of Forming Economic Characteristics of Stoping

Implementation of all technological processes of stoping requires appropriate financial investments, the specific value of which is determined by the following factors:

- characteristics of the raw material resource, namely ore and its industrial reserve (grade, volume);
- mining conditions of ore reserve occurence (geological, geomechanical, mining-geometric, hydrogeological);
- the nature of technological, technical, parametrical and organizational solutions for implementation of stoping;
- economic conditions in which a mining enterprise operates (prices for resources, volume of costs during construction of the block and mining of itst reserve, volumes of works).

To determine the expected economic results of stoping at the stage of preparation of the project for its implementation, these factors, or rather, their influence on the economic results of stoping, should be mathematically formalized and analyzed when solving economic problems.

2.3 Theoretical Bases of Development of Economic and Mathematical Model of Stoping

According to the above, we will proceed directly to development of the economic and mathematical model which describes formation of economic results of stoping and indicators by which it is possible to assess the economic efficiency of stoping. This model and the indicators are a tool for selecting optimal design solutions for implementing each component of the technological process of stoping in preparing designs of mining blocks.

Ore is the subject of stoping. This resource has an economic characteristic of the *Gross Value* G_1 (Subject of labor, 2001) (The concept of value, 2005). By definition, G_1 represents the market value of a useful component (in this case *Iron*) which is contained in 1.0 t of the industrial ore reserve. The value of this indicator is determined at the stage of geological and economic evaluation of the ore reserve by the formula

$$G_1 = 0{,}01 \frac{P}{N} \sum_{n=1}^{N} C_m \quad (1)$$

Where

- P is the metal price, UAH/t;
- C_m is concentration of metal in ore at geological sampling sites, %;
- N is the number of sampling sites on the deposit, pcs.

In the process of mining by stages of its implementation, the industrial reserve of ore moves from the state of a monolithic rock massif to the state of extracted ore mass and changes one of its most important characteristics, namely the content of metal C_m.

As a result, the extracted ore mass also acquires a certain value which is determined by the *Extracted Value* indicator G_2. This indicator determines the cost of metal which is contained in 1.0 of the mined ore resource at concentration of metal in it C_{mr} and is calculated by the formula

$$G_2 = 0{,}01 P C_{mr} \quad (2)$$

The G_2 value is in a certain dependence on the G_1 indicator, but this dependence is not functional, although it is not accidental. Their relationship depends on many factors of a natural and man-made nature.

In G_2, the initial part is G_1,, because formation of G_2 begins with G_1,. Their relationship can be described as follows

$$G_1 \in X \rightarrow G_2 \quad (3)$$

This expression suggests that the parameter G_1 is an element of the set of parameters X that form value of the parameter G_2, as the final characteristic of the development by changing the value of the object of labor.

The G_1 and G_2, indicators are important for assessing changes in the economic nature of ore after its extraction depending on the value the G_2 parameter differs from the G_2 value, taking into account in what way the G_2 value is formed and what factors influence the parameters of this formation. In practice, their values can be relative to each other as $G_2 < G_1$; $G_2 = G_1$; $G_2 > G_1$ and each of these options has its own economic meaning that depends on specific mining conditions.

It should be noted that G_1 and G_2 characterize only the ore itself and the ore mass extracted from the subsoil as raw materials, but they do not consider the fact that in addition to the difference in value there is a difference in volume of these materials. These volumes characterize the scale of mining and between them there is already a clearer dependence $Q_2 = f(Q_1)$ (Mossakovskyi, 2004).

To describe it, one can use the following indicators: the total value of the industrial ore reserve $G_{ir} = Q_1 G_1$ that is the one that characterizes its economic potential; the total value of the iron ore product $G_p = Q_2 G_2$. In this case, G_p is a general economic characteristic of the entire volume of ore extracted.

To what extent a mining enterprise will be able to use the potential of G_p in mining depends on the following factors:

1. Factors that are determined by objective conditions and do not depend on the mining enterprise, namely: geographical conditions of deposit location (distance, nature of the area, climate); geological conditions (composition of rocks, morphology of subsoil, hydrogeological conditions); geochemical characteristics (chemical composition of ore, content of useful components and harmful impurities); mining conditions (subsoil geomechanics, seismics, physical properties of rocks); administrative and social conditions (development of the mining area, population that will be influenced by production activities of the enterprise). The same group includes factors of economic nature according to the economic policy of

the state regarding the use of subsoil and business activities of mining enterprises (subsoil fees, taxes, mandatory payments).

These factors determine the amount of funds that should be invested in production to settle technical, environmental, social issues that will arise before the mining enterprise under the specified conditions because each of them imposes certain restrictions on mining the ore reserve.

2. Factors that depend on the enterprise, i.e. how it solves the following tasks:

- correct assessment of the potential of the enterprise: its technical, technological, labour, financial resources;
- rational planning and organization of the production process (stoping and all preparation processes for it);
- selection and adaptation to specific conditions of the stoping technology;
- selection and efficient use of labour mechanization and equipment;
- motivation of workers to productive and high-quality work;
- provision of production with necessary resources including the relevant transportation mode and their efficient use;
- organization of control over implementation of the production process at all its stages;
- organization of an appropriate level of analysis and evaluation of economic efficiency of production which should provide the most accurate results.

It is quite difficult to do all this, but without this it is almost impossible to obtain necessary production results using the economic potential of the ore reserve to the full extent and get such profitability of the business, the value of which will be the maximum possible in these conditions. In order to properly assess this completeness, we formalize the process of mining the ore reserve of the mining block and obtaining a commercial iron ore product where the key role is played by stoping.

The relationship between G_{ir} and G_p can be formalized by the following function

$$G_p = K_\varphi G_{ir} = Q_2 G_2 = K_\varphi Q_1 G_1 \qquad (4)$$

The coefficient K_φ in this formula characterizes the degree of change of the product QtpGvil relative to the value of the product Q_s(salary)G_g(gross), that is obtained as a result of development. In the case of different solutions for development will be different value $Q_{tp}G_{rv}$. You can calculate the value of K_φ as follows:

$$K_\varphi = \frac{Q_2 G_2}{Q_1 G_1} \qquad (5)$$

Note that this formula for calculating Kφ shows only the final result of ore mining by completeness of the value use, but it does not reflect the fact that this result is not instantaneous, but is the result of a long time of a number of processes (geological exploration, geological economic evaluation of the stock, design of development, opening of the stock, drainage of the extraction site, preparation of the stock, its cutting, implementation of a set of technological processes of purification of ore, rolling of extracted ore mass, its rise to the earth's surface, processing ore mass at the crushing and sorting plant products). The implementation of each of these processes requires the investment of certain financial resources. The magnitude of these investments depends on geological, mining, geomechanical, hydrogeological conditions at each extraction site and the nature of the decisions on which these processes will be performed. Therefore, the distribution of these investments in different processes in different extractive countries and their total amount will be different. And, most importantly, will be different and economic characteristics of the process of ore extraction and its economic results.

An important aspect is that the financial costs of all development processes and the distribution of these costs form certain financial constraints on the implementation of the removal extraction and its components of technological processes. This means that when designing the development of the production unit stock in specific conditions, not all options of technological, technical and parametric solutions can be used, even when they are technically acceptable, but the financial costs of their implementation in these conditions will exceed acceptable limits.

These limitations must be predicted as accurately as possible during project preparation - because they are the basis for choosing the best design solutions for different development conditions.

Industrial ore reserves Q_1 with gross value G_1, forms a certain common value $G_{ir} = Q_1 G_1$. Ideally, this stock could be sold at a price equal to the value of this value. However, in the development of each completed process over the stock, from the above, and the money invested in it reduces its value for the mining company, because its sale at the market price of the metal will no longer be so profitable for each work performed. If the total value of a certain process is equal to the amount of money invested in development, the profitability of such development will be equal to R = 0 and formally perform all other processes will be economically unprofitable.

However, if at a certain level of the process sequence to optimize solutions for each of them, it is possible to optimize the entire production process, including not only reducing the financial costs of each process, but also their optimal distribution between different processes. Such optimization can be performed only with the use of economic and mathematical modeling of the entire development process, in which the basis is the modeling of the cleaning extraction.

The basis for such optimization is this approach. Based on the expression (5), the calculation of K_φ by stages of development can be done as follows

$$K_\varphi = \frac{Q_2 G_2}{Q_1 G_1} - \frac{\sum_{i=1}^{N} S_i}{Q_1 G_1} = \frac{Q_2 G_2 - \sum_{i=1}^{N} S_i}{Q_1 G_1} \qquad (6)$$

In this formula the expression $\Sigma S_i / Q_1 G_1$ determines the specific value of financial investments in processes in the sequence of their implementation 1, 2, 3,…, i. This is the relationship between the values Q_2G_2 i Q_1G_1 taking into account the financial costs of receipt Q_2 з Q_1 can be formalized as follows

$$Q_2 G_2 = Q_1 G_1 - Q_3 G_1 + Q_4 G_4 - \sum_{i=1}^{N} S_i, \qquad (7)$$

Where

- Q_3 volume of ore of industrial stock, which is lost during treatment, thousand tons;
- Q_4 the volume of rock that clogs the ore during removal, thousand tons;
- G_4 value contained in the ore mass in the form of ore material that meets the requirements for the iron ore product, UAH.

At each stage of development the value K_φ will change as the values change Q_{2i}, G_{2i}, S_i.

Indicator K_φ, in the given form we will name the Indicator of efficiency of use of economic potential of an industrial stock of ore. This indicator determines the degree of use of the economic potential of the stock, which is formed by the value of the ore G_1 i the volume of its stock Q_1, $G_{ir} = Q_1 G_1$ upon receipt of an iron ore product, on any cstages of the production process.

In turn, the iron ore product at each stage of development is characterized by total value $G_p = Q_2 G_2$, which differs from the value G_{ir} due to certain losses of ore and its clogging with empty floors and financial costs ΣS to carry out development. This changes the value of the stock to values G_p as the sequence of development work.

In this formula, the values of the parameters are known G_1, G_2 they are determined by the content and price of the metal in the ore of the industrial stock and in the iron ore product. The value is known ΣS, it is determined by economic and mathematical modeling of the development process, or according to practice. The value is also known Q_1, it is provided by the geological service of the enterprise.

Only the value remains uncertain Q_2. At the stage of project development for the development of the production unit stock, it can be determined by the nature of design decisions for development and based on the value of the indicator Q_1, by such expression

$$Q_2 = \frac{(100 - k_1)}{(100 - k_2)} Q_1 = K_v Q_1 \qquad (8)$$

Where

- k_1 the coefficient of industrial stock ore during its extraction, %;
- k_2 the coefficient of clogging of the extracted ore mass during mining, %;
- K_v the coefficient of visible extraction of ore during mining, USD

Indicator k_1 represents the ratio of the volume of ore Q_3, which was lost during the development of a certain amount of ore Q_1, $k_1 = 100Q_3/Q_1$, %. Indicator k_2 - the ratio of the volume of waste rock Q_4, which is contained in the extracted ore mass Q_2, which got into it in the process of stock development Q_1, $k_2 = 100Q_4/Q_2$.

Thus, from function (8) formula (6) can be written as follows.

Taking into account these aspects of the approach to the economic evaluation of the efficiency of the removal process that are used in this work in the final version, this formula is as follows

$$K_\varphi = \frac{1}{G_1} \left(\frac{(100 - k_1) G_2}{(100 - k_2)} - \frac{\sum_{i=1}^{N} S_i}{Q_1} \right) K_1 K_2 K_3 \qquad (9)$$

K_1, K_2, K_3 coefficients that take into account different types of taxes K_1, payments K_2, repayment of receivables, etc. from each unit of profit received from the sale of a unit of iron ore product.

From the expression for determining Kφ it is seen that in the case of equalization of values

$$\frac{(100-k_1)G_{вил}}{(100-k_2)} = \frac{\sum_{i=1}^{N} S_i}{Q_1} \qquad (10)$$

the value of this indicator will be equal to 0, where the ratio $\sum S/Q_1$ determines the specific financial costs of development to a certain stage, and the ratio

$$\frac{(100-k_1)G_2}{(100-k_2)}, \qquad (11)$$

determines the magnitude of the change in value G_1 taking into account its reduction as a result of technological losses k_1 and ore clogging k_2.

Thus from this expression it is possible to predict at what sizes of parameters k_1 k_2, Q_1, S_i, G_2 development will reach the limit of profitability, when the income from the sale of products only compensates for the costs of development without making a profit.

Therefore, in order to prevent unprofitable development, it is necessary to determine the limit of the value of ΣS, which cannot be exceeded when making design decisions. This limit (limΣS) can be determined on the basis of the value indicator

$$\lim \sum_{i=1}^{N} S_i < \frac{(100-k_1)Q_2G_2}{100-k_2} \qquad (12)$$

Let us consider how this limitation applies to the second mining. The amount of financial costs that forms the value ΣS includes the second mining costs and is as follows:

$$\sum_{i=1}^{N} З_i = S_1+S_2+S_3+S_4+S_5+S_6+S_7+S_8+S_9+ \\ +S_{10}+S_{11}++S_{12}+S_{13}+S_{14}, \qquad (13)$$

Where

- S_1 is the amount of financial costs for geological prospecting works, UAH;
- S_2 is for the construction of a surface system, UAH;
- S_3 is for the stock preparation, UAH;
- S_4 is for the stock division, UAH;
- S_5 is for the drilling and blasting works, UAH;
- S_6 is for the ventilation of the mining space, UAH;
- S_7 is for the restoration of dislocated objects, UAH;
- S_8 is for the performance of works on the drawing of ore mass, UAH;
- S_9 is for the delivery of ore mass, UAH;
- S_{10} is for the ore mass hauling, UAH;
- S_{11} is for the hoisting of ore mass on the earth's surface, UAH;
- S_{12} is the costs for processing of ore mass at the grinding-sorting factory or the enrichment, UAH;
- S_{13} is the financial costs for capital mining operations (it is calculated as % of the total amount of weight-to-volume ratio), UAH;
- S_{14} is the costs, which were not taken into account at the performance of actual mining (defined as% of the total amount of weight-to-volume ratio), UAH;
- S_{15} is the amount of unaccounted financial costs (defined as % of the total amount of weight-to-volume ratio), UAH.

In this formula, the parameters $S_6+S_7+S_8+S_9+S_{10}$ are determined by the financial costs for the process of second mining of ore $З_{ios}$, and the other ones – by the general mine costs $З_{gm}$ Thus, the formula (9) will appear as:

$$K_\varphi = \frac{1}{G_1}\left(\frac{(100-k_1)G_{вил}}{(100-k_2)} - \frac{S_{gm}+S_{ios}}{Q_1}\right). \qquad (14)$$

Based on the equation (12), the maximum allowable value $З_{ios}$ can be calculated as follows

$$З_{ios} < \frac{(100-k_1)Q_1G_1}{100-k_2} - З_{gm} \qquad (15)$$

The obtained ratio allows to determine what should be the values of all basic technological features of the process of second mining Q_p, k_1, k_2 and especially S_{ios}, which is the part of a series of items of financial costs for development, in order to ensure the economic feasibility of its making in each mining unit in economic conditions of operation of a particular mining enterprise.

As mentioned above, the limit of the financial costs for the performance of each of the development processes is affected not only by the maximum allowable value of the prime cost of iron ore products, but also by the fact of correlation of the values of financial costs for all development processes. This determines the opportunities and limitations of investing in each process. These ratios must be determined in the project of second mining, for cost-effective decisions on projects, for these development conditions, for example, when the financial losses, outsized due to objective reasons, on one process can be compensated by certain technological, parametric solutions of performance of another process, so that the total costs of its implementation do not exceed the maximum value $\lim\sum S$, and their technical results were acceptable for the enterprise.

This situation requires the detailed organization of work throughout the production cycle, taking into account the relationships and dependencies between individual processes and works.

All this applies to the technological processes of second mining, which have a lot of options for technology, mechanization means, parameterization and all of them provide different economic results in the specific conditions.

To implement this approach, it is proposed to use a number of indexes that reflect the efficiency of the economic potential of the ore stock in the implementation of each technological process of second mining, which are the target optimization functions of these processes:

$$K_{\varphi d} = 100\frac{S_d}{Q_1 \cdot G_1} \to \min \qquad (16)$$

$$K_{\varphi b} = 100\frac{S_b}{Q_1 \cdot G_1} \to \min$$

$$K_{\varphi v} = 100\frac{S_v}{Q_1 \cdot G_1} \to \min$$

$$K_{\varphi br} = 100\frac{S_{br}}{Q_1 \cdot G_1} \to \min$$

$$K_{\varphi ot} = 100\frac{S_{ot}}{Q_1 \cdot G_1} \to \min$$

Where

- $K_{\varphi d}$ is for the drilling works, %;
- $K_{\varphi b}$ is for the blasting works, %;
- $K_{\varphi v}$ is for the ventilation, %;
- $K_{\varphi br}$ is for the works on ore mass drawing, %;
- $K_{\varphi ot}$ is for the works on delivery of ore mass, %;

The amount of financial costs for implementation, respectively

- S_d is for the drilling works, UAH;
- S_b is for the blasting works, UAH,
- S_v is for the ventilation, UAH,
- S_{br} is the work on the drawing of ore mass from the mining space, UAH,
- S_{ot} is the work on delivery of ore mass, UAH;

The comparison of the values of these indexes on their respective groups makes it possible to determine how effectively each of the components of the second mining process was implemented, as well as provides an opportunity to identify the problems in the distribution of financial costs for their performance.

It should be noted that these indicators in the complex characterize the efficiency of a single process of ore stoping. In this case, the values of the parameters S_d, S_b, S_{br}, S_{ot} substantially different from each other. Their integral contribution to the use of the value of industrial ore reserves and evaluation of the efficiency of its use can be carried out applying the following formula

$$K_{\varphi} = 100\frac{S_d + S_b + S_v + S_{br} + S_{ot}}{Q_{пз} \cdot G_{вал}}\frac{Q_{зп}}{Q_{пз}} \to \min \qquad (17)$$

This expression is the target function of the stoping process optimization on the entire range of works that must be performed during its implementation. Such optimization is performed through economic and mathematical modeling of the stoping when considering different options for the technological and technical competitive solutions for the implementation of the components of the stoping processes according to the variational approach to its design.

The technique described above formed the basis for computer program, that was developed by the authors, for modeling of the stoping process, determining its optimal parameters and evaluating its economic efficiency.

An example of the results of modeling with this system is given in Table 1, which presents its results for one of the mining units at the “Yuvileyna” mine of the Private Joint Stock Company "Sukha Balka of Kryvyi Rih Iron Ore Basin.

Table 1: Results of economic and mathematical modeling of the stoping process.

The indicators	Marking	Unit of meas	Value
Reserve	Q_1	t	260000,0
The content of metal	C_m	%	62,0
Gross Value	G_1	UAH / t	50000,0
The total value	Q_1G_1	UAH / t	8060000000,0
Results of modelling			
Losses of ore	k_1	%	9,0
Clogging	k_2	%	12,0
Ore mass	Q_2	t	268863,6
The content of metal	Cm	%	58,0
The total value	Q_2G_2	UAH	7797045454,5
Driling	S_6	UAH	87360000,0
Blasting	S_7	UAH	145600000,0
Ventilation	S_8	UAH	2912000,0
Drawing	S_9	UAH	37856000,0
Transportation	S_{10}	UAH	20384000,0
Amount	S_{io}	UAH	294112000,0
The indicators:	Kφd	%	1,08387
	Kφb	%	1,80645
	Kφv	%	0,03613
	Kφbr	%	0,46968
	Kφot	%	0,25290
Total	Kφ	%	3,52998
Cost		UAH/t	1131,2

The above table shows that relative to the total value of the industrial ore reserve Q1G1 in this block, the finantional costs for the stoping is 3.52%. That is, by this amount there will be an extracted value decline relative to the stock value in the implementation of the stoping. At the same time, with the calculated projections of this process, the profitability of the mining itself will be quite high because when the cost of extracted ore mass is 11301.2 UAH / t for the main development process - stoping, the selling price of iron ore in the current market conditions of different consumers ranges from 2259.0 to 6213.0 UAH/t, that is 1.99-5.49 times higher than the production cost according to this process.

In conclusion, we note that the authors are currently working on the wider implementation of this modeling system in the design departments of iron ore mining companies in Ukraine.

The methodology described above is the basis of a computer program developed by the authors for the modeling of the process of second mining, determination of its optimal parameters and assessment of the economic efficiency. Currently, the work is underway to implement it in the project departments of iron ore mining enterprises in Ukraine.

3 CONCLUSION AND FURTHER WORK

As a result of the research on the topic of this publication, the following conclusions can be made:

1. The iron ore mining industry of Ukraine is one of the most powerful in the world, producing 90% of iron ore products. An important direction in its functioning and development is the use of the underground method of development of iron ore deposits. This can be explained by the fact that the specifics of its technology provides the possibility of cost-effective mining of iron ore at great depths (greater than 1000 m), which have the main stock of these ores in the bowels of Ukraine.

2. All iron ore mining enterprises of Ukraine are private and part of large business structures. The conditions in which they currently carry out the underground development and prospects for its development raise the problem of accurate and reliable forecasting of economic results of the development, because it directly determines the profitability of the business, its competitiveness in the iron ore market, and provides reasonable business planning.

3. Such results can be achieved by ensuring the cost-effective implementation of the key process of development, which is the second mining of ore. The financial costs for its implementation reach 60-70% of the prime cost of extracted ore mass.

4. To solve this problem, it is necessary to have a method of modeling and calculating the parameters of the second mining, which would determine the optimal solutions for its performance in specific mining and economic conditions based on accurate forecasting of economic results, which is currently missing. The authors have developed the following methodology and system of technical and economic indexes, which provide the possibility of multifactor economic analysis of competitive solutions for the performance of second mining and selection of the optimal one.

5. The basis of this methodology and system of indexes of second mining efficiency is the use of indexes of the value of ore, the value of its stock and the degree of use of value as a result of this process

on the final result of development.

6. This methodology also provides a method of determining the financial limitations, which function in specific economic conditions of operation of mining enterprises, and which determine the amount of allowable financial costs for the performance of second mining. This limitation is one of the basic factors that provide the optimization of the parameters of the second mining.

7. Based on this methodology, the authors developed a computer program for modeling and determining the optimal parameters of the second mining in the development of iron ore at great depths. The need for this program is due to the great complexity of solving the problem of optimization of mining solutions.

8. Further development of this work will be the creation of systems for modeling the entire process of the underground iron ore production, a key element of which is second mining of ore, as well as the implementation of this system at mining enterprises to prepare projects for mining units and determination of the planning parameters for the process of development of iron ore deposits and the support of business planning.

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