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V. H. Blizniukov, Dr. Sc. (Tech.), Prof,
S. O. Lutsenko, Cand. Sc. (Tech.), Assoc. Prof.

State Higher Education Establishement "Kryvyi Rih National University", Kryvyi Rih, Ukraine, e-mail: LutsenkoSergeiA@ukr.net

IMPROVEMENT OF TECHNICAL CRITERIA FOR COMPARATIVE EVALUATION OF MINING OPERATION OPTIONS OF IRON ORE OPEN PITS

В. Г. Блізнюков, д-р техн. наук, проф.,
С. О. Луценко, канд. техн. наук, доц.

Державний вищий навчальний заклад „Криворізький національний університет", м. Кривий Ріг, Україна, e-mail: LutsenkoSergeiA@ukr.net

УДОСКОНАЛЕННЯ ТЕХНОЛОГІЧНИХ КРИТЕРІЇВ ПОРІВНЯЛЬНОЇ ОЦІНКИ ВАРІАНТІВ ГІРНИЧИХ РОБІТ ЗАЛІЗОРУДНИХ КАР'ЄРІВ

Purpose. To improve technological criteria for comparative evaluation of mine operation options which would allow doing a complex evaluation of mining operations mode and mine productivity for ore extraction based not on the changeable time and economic figures which are hard to predict but based on technical variables (ore mining productivity, waste volume, mineral content). They are stable and depend only on geological structure of rock.

Methodology. The basis of technological criteria for mining operation mode and mine productivity for ore extraction complex evaluation includes the following idea: it is required to do comparative evaluation of mine operation options based on annually extracted volumes of ore and waste considering technological variables of a mineral which, contrary to time-controlled economic variables, are determined by nature and remain unchangeable. This idea is realized by developing an analytical model of mining operations and ore mining productivity complex evaluation parameter.

Findings. The technological criterion for mining operation mode and productivity complex evaluation has been improved; this is the difference between annual volumes of rock extracted from mine and concentrate volume produced over the same period: maximum absolute value of this index will ensure the biggest economic effect from deposit development.

Originality. The proposed technological criterion allows evaluating the mining operation mode and ore mining productivity in an integrated manner considering their interrelation. At that, the criterion, contrary to economic criteria, includes not just price and production cost values but their correlation – it gives an opportunity to get accurate comparative evaluation of mine operation options over the long period.

Practical value. The proposed technological criteria of mining operation options may be used by designing engineers at the design stage in order to define the best open pit operation mode and ore mining productivity considering their interrelation. By the example of Annovsk mine, SEVGOK PJSC the possibility to do the comparative evaluation of mining operation mode and productivity based on the proposed technological criteria was proved.

Keywords: *mine, mining operation mode, mine productivity, evaluation criteria*

Introduction. Mining operation mode and ore mining productivity are the main parameters for open-cast mining: they define type and quantity of mining equipment, buildings and premises construction volume, headcount. Therefore, the correct solution of current target has a significant value for mining & beneficiation plants of Ukraine.

At present there are significant price and demand fluctuations for ferrous metal ore products observed in local and foreign markets. This fact impacts significantly the operation of mining plants in general as well as separate mines operating. Thus, mineral demand increase results in increasing production volume while demand decrease means decreasing mineral extraction volumes. At that, ore mining productivity variation causes waste extraction volumes variation [1]. It is related to the fact that to increase ore mining productivity, it is often required to develop additional open pit field areas with higher stripping ratio. Therefore, stripping operations are increased disproportionally to productivity growth, i.e. stripping ratio is getting higher. At the same time stripping ratio can be so high that it can cause decrease in possible economic effect from ore mining productivity. Finally, it will be required to solve the following issue: whether it is more profitable to operate with lower productivity and stripping ratio or with higher productivity and higher current stripping ratio. At that, neither minimum values of stripping ratio nor mine productivity value, taken separately, can be a sign of deposit development efficiency.

Unsolved aspects of the problem. The total profit from deposit operation over the specified time period is used as a criterion for mining operations and ore mining productivity evaluation. However, as experience of mines operation shows when evaluating a plant operation over the long time period, the operational expenses as well as product cost are significantly variated (Table). The change of these variables depends on many factors which are hard to predict. The Table shows that the production cost and the price of operation has changed on average by 380 and 350 % accordingly over 9 years. Therefore, economic evaluation of even the same mining operation option based on target year values and operation completion values will be incompatible. Hence, it is almost impossible to get the accurate comparative evaluation of quarry operation options by economic criteria over the long time period. At that, expenses per 1 UAH of product have an insignificant value – from 2 to 30 %. Then while developing the criteria for comparative evaluation of quarry operations with economic value of operation being the basis, it is reasonable to consider the correlation of price and production cost values rather than price and cost values themselves – it will help to increase the accuracy of calculation results.

Besides, when evaluating quarry operation options by economic criteria there is a high probability to miss the best option for mining operation mode and mine productivity for ore extraction at the designing stage. It is related to the fact that economic variables are estimated by economic departments of either Design Companies or Mining Plants. Significant volumes of estimate and financial calculations are limited by the number of considered options. As a result, there are only two or three options of mining operation, proposed by mining divisions, evaluated. At that mining specialists take these

Table

Economic variables of concentrate production and sales at Mining Plants of Ukraine

Business Unit	Year	Production cost, UAH/t	Price, UAH/t	Expenses per 1 UAH of product, UAH/UAH
SEVGOK	2005	102.9	261.7	0.39
	2010	216.7	430.5	0.50
	2013	450.0	947.1	0.48
Poltavskyi GOK	2005	108.0	186.0	0.58
	2010	263.0	329.5	0.80
	2013	464.0	658.4	0.70
TSGOK	2005	141.6	265.0	0.53
	2010	294.2	477.0	0.62
	2013	589.1	954.0	0.62
UGOK	2005	107.7	154.6	0.70
	2010	350.3	513.6	0.68
	2013	510.0	750.0	0.68
InGOK	2005	113.6	145.3	0.78
	2010	364.3	488.6	0.75
	2013	729.3	979.3	0.74

options for economic evaluation using technological criteria separately taken for mining operation mode and productivity without considering their interrelations (stripping ratio, rock ratio, ore mining productivity). Therefore, the natural intention is to design the higher ore extraction productivity along with lower waste volumes. As a result, only rational option of mining operation is selected, i.e. the best option out of ones offered by design engineers, but the optimal option can be just missed at the stage of designing.

In its turn, the main technological variables of a mineral which define economic variables of deposit development (concentrate output, Fe content, deposit capacity and shape, its location), are defined by nature and remain unchangeable. Therefore, for the complex evaluation of mining operation mode and ore mining productivity it is the best to use the technological criteria [2]. In this case along with the specified technology for ore extraction and its processing at the specified plant and other equal conditions, mining operation efficiency will be determined by ore and waste volumes and their variations in time. However, in some cases the offered parameter may have negative values, which is contrary to logics: variation between volumes cannot be negative.

Analysis of the recent research and publications. Issues related to mining operation mode and productivity have always been the center of attention of leading scientists specializing in the field of open-cast mining. The most significant contribution to solving these issues was done by founders of mine designing theory: Rzhevskiy V.V., Arsentiev A.I., Novozhilov M.G., Melnikov N.V., Khokhriakov V.S., Astafiev Yu.P., Yumatov B.P. and their present-day followers Shapar A.G., Chetveryk M.S., Kovalchuk V.A., Blizniukova V.G., Drizhenko A.Yu., Gumenyk I.L., Panchenko V.V. and others. Until recently there have been developed two methodology groups for ore mining productivity determination: by mining-technical and economic factors. To determine possible options for mining operation modes and selection of the best one, the methods of open-pit field geometric analysis are used [3]. At that, the mining operation mode and mining productivity have always been evaluated without considering their interrelation. It was considered that the best option of mining operation mode is to ensure the minimum value of current stripping ratio through all life periods and the highest mine productivity, selected with regard to abovementioned restrictions.

Objectives of the article. The objective of the current work is to improve the technological criteria for quarry operation options which can be used by designing engineers at the stage of engineering and at the same time it would allow carrying out the complex evaluation of mining operation mode and productivity.

Presentation of the main research and results. The economic base of technological criteria for evaluation involves generally accepted variables of economic evaluation, namely mine profit from deposit development. This profit will be equal, UAH/year

$$P = A_k \cdot z_k - A_p \cdot a - A_p \cdot n \cdot b,$$

where $a = a_o + a_n$ is extraction production cost (a_o) and processing (a_n) of one ton of ore into concentrate without costs for stripping operations, UAH/t; z_k is concentrate price, UAH/t; A_k stands for produced concentrate volume, t; A_p is ore extraction productivity, t; b stands for stripping operation costs, UAH/t; T is evaluation period, years.

Economic criteria of the best option for mining operation mode and mine productivity will be the maximum profit value over its entire life time. Discounted profit of the evaluation period will be defined by formula, UAH

$$P = (z_k \cdot A_k - a \cdot A_p - b \cdot A_p \cdot n) \cdot \sum_{t=1}^{T} \frac{1}{(1+E)^t} \to \max.$$

Having done transformation, we will get, UAH

$$P = \left(z_k \cdot A_p \cdot \gamma_k - a \cdot A_p - b \cdot A_v \cdot n\right) \cdot T =$$
$$= z_k \cdot A_p \cdot \gamma_k \cdot \left(1 - \frac{a}{z_k \cdot \gamma_k} - \frac{b}{z_k \cdot \gamma_k} \cdot n\right) \cdot T =$$
$$= z_k \cdot A_p \cdot \gamma_k \cdot \left(1 - \frac{a + b \cdot n}{z_k \cdot \gamma_k}\right) \cdot T =$$
$$= z_k \cdot A_p \cdot \gamma_k \cdot \left(1 - \frac{a \cdot \left(1 + \frac{b}{a} \cdot n\right)}{z_k \cdot \gamma_k}\right) \cdot T =$$
$$= z_k \cdot A_p \cdot \gamma_k \cdot \left[1 - \frac{a}{z_k} \cdot \left(\frac{1 + \delta \cdot n}{\gamma_k}\right)\right] \cdot T =$$
$$= z_k \cdot A_k \cdot \left(1 - \frac{a}{z_k} \cdot m\right) \cdot T \to \max,$$

where $m = \frac{1 + \delta \cdot n}{\gamma}$ is rock ratio, t/t.

Rock mass ratio shows what volume of extracted ore is required to produce one ton of concentrate.

Discounted profit of evaluation period will be defined by formula, UAH

$$P_p = z_k \cdot A_k \cdot \left(1 - \frac{a}{z_k} \cdot m\right) \cdot \sum_{t=1}^{T} \frac{1}{\left(1+E\right)^t}$$

or

$$P_p = z_k \cdot A_k \cdot \left(1 - x \cdot m\right) \cdot \sum_{t=1}^{T} K^t \to \max, \quad (1)$$

where $x = \frac{a}{z_k}$ is physical rock volume ratio to concentrate volume at its price (this ratio value is constant: it was calculated based on design parameters and concentrate sale); $K = \frac{1}{1+E}$; E is accepted rate of discount.

The (1) represents economic criteria for complex evaluation of efficiency of mining operation mode and concentrate production productivity. Here mining operation mode specifies rock ratio variable.

When switching to technological criteria, using their properties, economic variables were excluded from the (1). Thereafter

$$P_p \to \max \quad \text{with} \quad M = A_k \cdot \left(1 - x \cdot m\right) \cdot \sum_{t=1}^{T} K^t \to \max$$

or

$$P_p \to \max,$$

with

$$M = A_k - \left(\frac{a}{z_k} \cdot A_p + \frac{b}{z_k} \cdot A_p \cdot n\right) \to \max. \quad (2)$$

The best combination of mining operation mode and mine productivity over the long period is to be evaluated based on discounted variation of rock and concentrate volumes, t

$$P_p \to \max,$$

with

$$M = \sum_{t=1}^{T} \frac{1}{\left(1+E\right)^t} \cdot \left[A_{kt} - \left(\delta_p \cdot A_{pt} + \delta_v \cdot A_{pt} \cdot n_t\right)\right] \to \max, \quad (3)$$

where $\delta_p = \frac{a}{z_k}$ is physical rock volume ratio to concentrate volume at its price; $\delta_v = \frac{b}{z_k}$ is physical waste volume ratio to concentrate volume at its price; A_k, A_p stand for annual volume of concentrate and ore, t; t is year ordinal number, starting from estimation year; T is duration of evaluation period, years.

The index in brackets represents variation between annual concentrate productivity and rock productivity over the i period of Plant operation. The higher this variation is, the higher is the current income (annual) of Plant.

Here physical volumes of ore and waste at the price of concentrate are correlated with physical volumes of concentrate.

However the offered variable does not respond to logic because rock volumes extracted from mine are always bigger than concentrate volumes produced at the plant. Therefore, it is more logical when variable will include variation between rocks and concentrate volumes. For that it is enough to put "–" out of the brackets in (2) or (3).

$$P_p \to \max,$$

with

$$K_k = \left(\frac{a}{z_k} \cdot A_p + \frac{b}{z_k} \cdot A_p \cdot n\right) - A_k \to \min \quad (4)$$

or

$$P_p \to \max,$$

with

$$K_k = \sum_{t=1}^{T} \frac{1}{\left(1+E\right)^t} \cdot \left[\left(\delta_\partial \cdot A_{\partial t} + \delta_v \cdot A_{pt} \cdot n_t\right) - A_{ki}\right] \to \min. \quad (5)$$

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However, since rock mass volume is correlated with concentrate volume at its price and in some cases the value of this variable can be negative, it is required to take the maximum absolute value of variation between rocks and concentrate volumes as a criterion for evaluation. Thereafter

$$P_p \to \max,$$

with

$$K_k = \left| \sum_{t=1}^{T} \frac{1}{(1+E)^t} \left[\left(\delta_p \cdot A_{pt} + \delta_v \cdot A_{pt} \cdot n_t \right) - A_{ki} \right] \right| \to \max. \quad (6)$$

The variable in brackets (4, 5) represents the variation between the volumes of rocks and concentrate. The lower the value of the criterion is, the higher current profit the plant makes. At the same time, the higher the absolute value of current variable is, the higher current profit the plant makes (6), i.e. the physical sense of the criterion has not changed.

By the example of Annovsk open pit "SEVGOK" PJSC we calculate the value of technical parameter "M" and "K_k" along with different mining operation mode options and ore mining productivity, and will show $M = f(A_p)$ relation to $K_k = f(A_p)$ which are represented in Fig. 1.

Initial data for calculating possible options of mining operation mode and Annovsk mine productivity were calendar plans of mining operations.

Fig. 1 shows that the curves which characterize the variables of recommended technological criteria for complex evaluation of mining operations and mine productivity $M = f(A_p)$ and $K_k = |f(A_p)|$ are completely equal. In case when $K_k = f(A_p)$ they are mirror-image of one another. At that, boundary conditions of the compared criteria (M and K_k) are opposite (in first case-criteria M tends to maximum, in the second K_k – to the minimum). Therefore, we can talk about the identity of options evaluation based on criteria M, as well as K_k.

In order to prove the validity of using the developed technological criteria of evaluating considered options let us evaluate the operation of Annovsk mine for over 30 years based on the generally accepted economic variable – "Net Present Value (*NPV*)".

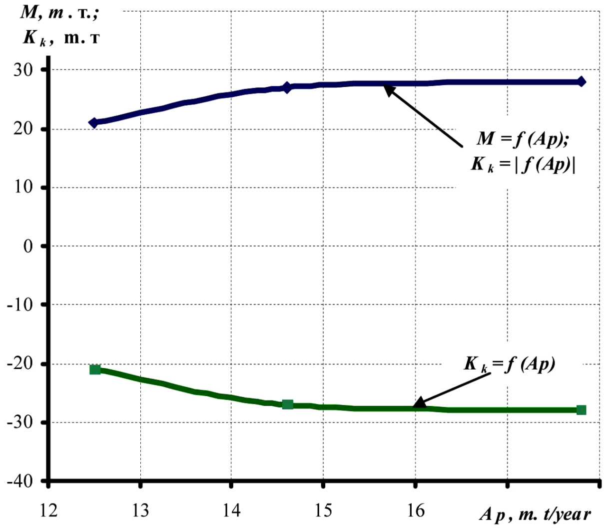

Fig. 1. Graph of variation of evaluation technological variable depending on Annovsk mine productivity variation (A_p)

For clarity we will draw graphs of variations of NPV and recommended technological criteria for complex economic evaluation of mining operations and productivity of Annovsk mine considering all options (Fig. 2).

The graphs show that curves which characterize the variable of NPV and recommended technological criteria for complex economic evaluation of mining operations and mine productivity are placed in parallel – it proves the identity of evaluation of options according to economic and technological criteria.

Conclusions:

1. The technological criterion which allows doing a complex evaluation of mining operation mode and ore mining productivity has been improved. At that, the parameter of complex evaluation of mining operation mode and mine productivity is a variation between annual volume of rock extracted from pit and concentrate produced over the same period. The higher the absolute value of this parameter is, the higher economic effect from deposit development is achieved.

2. The identity of complex evaluation of mining operation mode and productivity based on economic variables and proposed technological variable has been proved. It allows excluding the economic parameter when evaluating the mining operation mode and mine productivity.

3. The possibility and feasibility of replacing the comparison of mining operation options based on income presented to one estimation point by the comparison based on production volumes variation presented to one estimation point were proved analytically. The options ranking is the same but the scope of work required to define the best option for deposit development has decreased.

4. The proposed technological criteria for evaluating mining operation options may be used by designing engineers at the design stage to define the optimal mode of mining operation mode and mine productivity.

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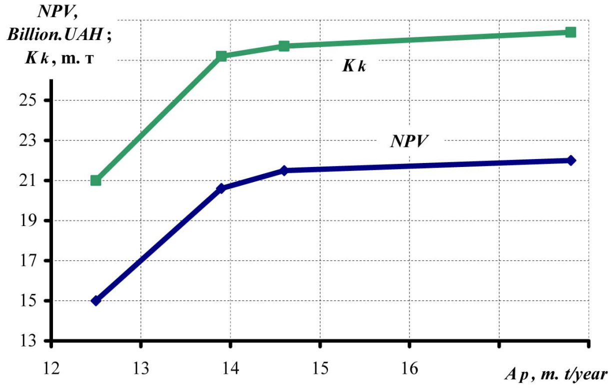

Fig. 2. Graph of variation of NPV and technological criteria depending mine productivity variation (A_p) at Annovsk

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Мета. Удосконалити технологічний критерій порівняльної оцінки варіантів роботи кар'єру, який би дозволив здійснювати комплексну оцінку режиму гірничих робіт і продуктивності кар'єру по руді не за економічними показниками, що змінюються в часі й важко прогнозовані, а за технологічними показниками (продуктивність по руді, об'єм розкриву, вміст корисного компонента), що стабільні та залежать тільки від геологічної будови гірських порід.

Методика. В основу технологічного критерію комплексної оцінки режиму гірничих робіт і продуктивності кар'єру по руді покладена ідея: порівняння варіантів роботи кар'єру необхідно здійснювати за річними об'ємами руди й розкривних порід, що виймаються, з урахуванням технологічних показників корисної копалини, які, на відміну від мінливих у часі економічних показників роботи кар'єру, визначені природою й тисячоліттями залишаються незмінними. Реалізація цієї ідеї здійснювалася за рахунок розробки аналітичної моделі показника комплексної оцінки режиму гірничих робіт і продуктивності кар'єру по руді.

Результати. Удосконалено технологічний критерій комплексної оцінки режиму гірничих робіт і продуктивності кар'єру – різниця між річними об'ємами гірничої маси, що витягується з кар'єру та кількістю концентрату, виробленого за той же період: максимальне абсолютне значення цього показника забезпечить найбільший економічний ефект від розробки родовища.

Наукова новизна. Запропонований технологічний критерій дозволяє комплексно оцінювати режим гірничих робіт і продуктивність кар'єру по руді з урахуванням їх взаємозв'язку та при цьому, на відміну від економічних критеріїв, ураховувати не значення ціни й собівартості товарної продукції, а їх співвідношення, що дає можливість отримати точну порівняльну оцінку варіантів роботи кар'єру за тривалий період часу.

Практична значимість. Запропонований технологічний критерій оцінки варіантів роботи кар'єру, може використовуватися інженерами-проектувальниками вже на стадії проектування для визначення оптимального варіанта режиму гірничих робіт і продуктивності кар'єру по руді з урахуванням їх взаємозв'язку. На прикладі Ганнівського кар'єру ПАТ „ПівнГЗК" доведена можливість порівняльної оцінки режиму гірничих робіт і продуктивності кар'єру за запропонованим технологічним критерієм.

Ключові слова: *кар'єр, режим гірничих робіт, продуктивність кар'єрів, критерій оцінки*

Цель. Усовершенствовать технологический критерий сравнительной оценки вариантов работы карьера, который бы позволил осуществлять комплексную оценку режима горных работ и производительности карьера по руде не по изменяющимся во времени и трудно прогнозируемым экономическим показателям, а по технологическим показателям (производительность по руде, объем вскрыши, содержание полезного компонента), которые стабильны и зависят только от геологического строения горных пород.

Методика. В основу технологического критерия комплексной оценки режима горных работ и производительности карьера по руде положена идея: сравнение вариантов работы карьера необходимо осуществлять по годовым извлекаемым объемам руды и вскрышных пород, с учетом технологических показателей полезного ископаемого, которые, в отличии от изменяющихся во времени экономических показателей работы карьера, определены природой и тысячелетиями остаются неизменными. Реализация этой идеи осуществлялась за счет разработки аналитической модели показателя комплексной оценки режима горных работ и производительности карьера по руде

Результаты. Усовершенствован технологический критерий комплексной оценки режима горных работ и производительности карьера – разница между годовыми объемами горной массы, извлекаемой из карьера и количеством концентрата, производимого за тот же период: максимальное абсолютное значение этого показателя обеспечит наибольший экономический эффект от разработки месторождения.

Научная новизна. Предложенный технологический критерий позволяет комплексно оценивать режим горных работ и производительность карьера по руде с учетом их взаимосвязи и при этом, в отличие от экономических критериев, учитывать не значения цены и себестоимости товарной продукции, а их соотношение, что дает возможность получить точную сравнительную оценку вариантов работы карьера за длительный период времени.

Практическая значимость. Предложенный технологический критерий оценки вариантов работы

карьера, может использоваться инженерами-проектировщиками уже на стадии проектирования для определения оптимального варианта режима горных работ и производительности карьера по руде с учетом их взаимосвязи. На примере Анновского карьера ПАО „СевГОК“ доказана возможность сравнительной оценки режима горных работ и производительности карьера по предложенному технологическому критерию.

Ключевые слова: *карьер, режим горных работ, производительность карьеров, критерий оценки*

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P. Shcherbakov, Cand. Sc. (Tech.), Assoc. Prof.,
D. Klymenko,
S. Tymchenko, Cand. Sc. (Tech.), Assoc. Prof.

State Higher Educational Institution "National Mining University", Dnipro, Ukraine, e-mail: dinklim@mail.ru

STATISTICAL RESEARCH OF SHOVEL EXCAVATOR PERFORMANCE DURING LOADING OF ROCK MASS OF DIFFERENT CRUSHING QUALITY

П. М. Щербаков, канд. техн. наук, доц.,
Д. В. Клименко,
С. Є. Тимченко, канд. техн. наук, доц.

Державний вищий навчальний заклад „Національний гірничий університет“, м. Дніпро, Україна, e-mail: dinklim@mail.ru

СТАТИСТИЧНІ ДОСЛІДЖЕННЯ ПРОДУКТИВНОСТІ ОДНОКОВШЕВИХ ЕКСКАВАТОРІВ ПРИ НАГРУЖЕННІ ГІРНИЧОЇ МАСИ РІЗНОЇ ЯКОСТІ ДРОБЛЕННЯ

Purpose. Applying technical means to control excavator performance and quality of rock crushing by explosion. Establishing the dependence of time consumption required for rock mass excavation on its particle size distribution and mathematical description of this dependence as a function of two variables.

Methodology. The methodological basis to solve the problem is a comprehensive approach including research by means of IGS-5M devices, applying mathematical statistics methods and analysing the results in the mathematical package.

Findings. The possibility to maintain operational control of the time consumption required for rock mass excavation and direct measurement of its particle size distribution at the same time has been implemented. The concept of cycle rate has been introduced and its dependence on the mean diameter of the piece has been determined. The empirical formula to determine excavator technical performance as a function of two variables that uniquely characterize the quality of rock mass fragmentation has been obtained.

Originality. For the first time in the practice of mining the hardware specifically designed for operational control of excavators and crushing of rocks by explosion has been used (IGS-5M devices is in the invention stage). A two-parameter distribution function of the rock mass particle size distribution was proposed where one parameter is the size of the dominant fraction, the other one is the fraction in the test volume of blasted rock. The formula to determine excavator technical performance as a function of specified parameters has been obtained.

Practical value. Applying specified devices while organizing and carrying out mining operations will allow using technically feasible solutions at the design stage of mass explosions. Using the formula to calculate excavator technical performance in specific conditions will help improve planning technological processes, especially the rational distribution of freight flows. In the long view, the above mentioned formula will be a critical part of the mathematical model while optimizing basic technological processes at the open pits.

Keywords: *open pit, excavator, performance, particle size distribution, rock mass*

Introduction. The priority trend to improve the extraction and processing of rock minerals by opencast mining is establishing and practically applying optimal methods to control the main industrial processes.

It is well-known that production costs required for performing the whole technological process greatly depend on the crushing quality of rocks developed by explosion, which is usually characterized by particle size distribution of obtained rock mass, i. e. by the content of individual cubs (fractions) in its volume. Intensive mineral crushing reduces the costs of loading and transport operations and mechanical crushing, but results in increasing costs of drilling and blasting operations (D&B). Conversely, decreasing D&B costs contributes to coarse