Comprehensive Methodology for Geometrization of Mineral Deposits

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Abstract

The article proposes a comprehensive methodology for geometrization of a mineral deposit. Based on existing concepts of geometrization, a set of methods for building a geometric model of a mineral deposit is developed. In the course of geometrization of mineral deposits, the authors of the research widely use geo-information systems. Geological exploration and survey data are used as the basis for geometrization. The most widely used estimation methods are considered when developing the methodology for estimating mineral reserves. The modified method of parallel vertical sections proves to be the most effective way to estimate the reserves of deposits of complex geometric shapes. The authors develop the methodology for determining optimal location of sections in relation to the mineral deposit under estimation. Both geostatistical estimation methods implemented in geo-information systems and a multidimensional heuristic estimation method developed by the authors of the research are used for geometrization purposes. This set of mining geometric methods enables actual and predictive geometrization of a mineral deposit and estimation of its reserves. The geometrization methodology developed by the authors makes it possible to rationally plan mining operations and increase mining enterprise efficiency.

Keywords: *comprehensive methodology for geometrization, geo-information system, geostatistical estimation methods, multidimensional heuristic estimation method, parallel vertical sections*

1. Introduction

Modern industrial production requires extraction of a large amount of mineral resources [1]. The current tendency of growing needs for raw materials in production leads to the need to increase the volume of mining. Quantitative and qualitative characteristics of minerals must meet modern requirements determined by complexity of production processes. Improving efficiency of mining operations involves solving a number of problems related to mining processes in different conditions of mineral deposit development. This requires a clear understanding of the mining enterprise and the rock massif. Geometrization of mineral deposits makes it possible to assess geological and technological characteristics of mineral deposits developed by mining enterprises [2-6].

Sustainable mining is an essential condition for providing the national economy with the necessary resources [7]. Development of mining depends on investments based on estimations of mineral reserves. Various methods of estimating mineral reserves are grounded on a comprehensive mining and geometric estimation of a mineral deposit [8]. Selecting the optimal, i.e. the most appropriate in different mining and geological conditions, method for estimating mineral reserves is the most important task of geometrization of a mineral deposit [9]. Comprehensive estimation and modelling of mining production can contribute to the efficient design and planning of performance of a mining enterprise or a system of mining enterprises [10].

A digital model of a deposit built on the basis of survey measurements and geological exploration data enables a comprehensive mining and geometric estimation of a mineral deposit [11–14]. Such a model can provide a qualitative ground for performing mining geometric calculations, creating mining and graphic documentation [15], building topographic surfaces and calculating volumes of minerals. The mining and geometric model of a mineral deposit based on its comprehensive geometrization is shown in Fig. 1.

Improvement of the technology for mining minerals is based on application of information on the geometric structure of a mineral deposit [16–17]. Efficient design of a mining enterprise is possible due to geometrically substantiated parameters of mining operations. Efficient extraction of minerals is a priority of mining production [18–21]. For example, in [22, 23], authors show that the results of scientific studies based on the geometrization data help solve not only the problems of the ore formation theory but also the practical tasks concerning improvement of methods for predicting the prospective areas within the deposit.

Mineral processing is an integral part of mining production. The technology for enrichment of minerals depends on their physical and chemical properties, water content, impacts of the nature of mineral occurrence in the rock mass on properties of the raw materials supplied to mining and processing enterprises. Geometrization-based information

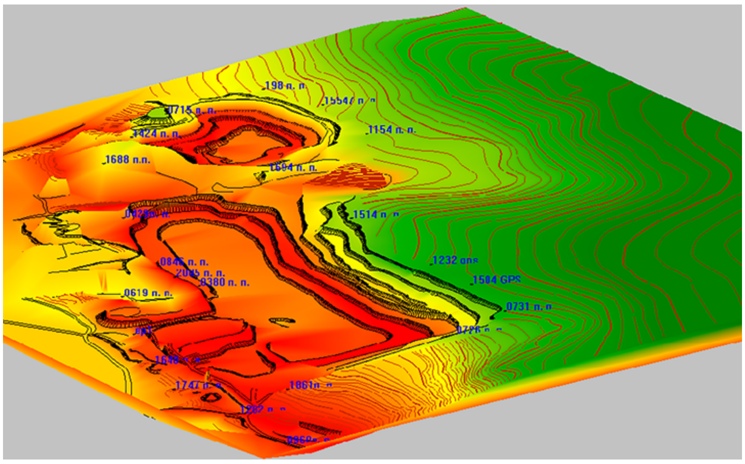

Fig. 1. Mining and geometric model of the deposit in the open pit of Slavyanskyi chalk-lime plant
Rys. 1. Model górniczy i geometryczny złoża odkrywkowego Zakładu Wapna Kredowego Slavyanskyi

provides the foundation for mineral deposit estimation and subsequent development of the mineral enrichment technology [24].

Various scopes of mining require monitoring mineral resources based on an integrated estimation of the mineral deposit. Exploitation of mineral deposits inevitably results in rock massif disturbances [25]. This leads to unstable geomechanical conditions of rocks and mine workings. Mining and geometric methods of estimation provide control of the rock massif condition, without which stable performance of the mining enterprise is impossible [26–28].

Concentration of stresses around mine workings may lead to losses of their integrity [29, 30]. Geometric methods for estimating geophysical processes are an integral part of mine safety [31]. The impact of mining operations on the surrounding rocks and the surface of the mining enterprise should be carefully estimated. Based on such estimations, activities are carried out to ensure stability of rocks [32–36].

The impact of mining on nature is an important issue. Different types of impacts have different consequences. Mineral mining and processing should be conducted in a way that minimizes their impact on nature and a mining enterprise. Estimating and modelling the environmental impact of a mining enterprise is the most important task that arises during the mining process. The amount of pollutants in the air is the most important indicator of the condition of the environment. This issue is particularly relevant in open pit mining, especially when it comes to minerals containing toxic useful components. Assessment of such pollution and reduction of its impact on the environment should be performed with a high degree of responsibility [37].

At mineral deposits with high geological variability, there is a problem of estimating the spatial occurrence of minerals. This reduces efficiency of mineral resources estimation based on the results of geological exploration. Geostatistical and heuristic methods of estimating geological characteristics of the deposit enable reducing the impact of variability on the mineral reserves estimation and determining geological characteristics of the deposit with higher accuracy [38–43].

Methods of heuristic self-organization are the most interesting methods of mining and geometric estimation of mineral deposits. They are characterized by various efficiency and based on different mathematical methods. They are the most flexible and adaptable as well. In combination with geostatistical methods for estimating mineral deposits, heuristic methods are very efficient for estimating deposits with high geological variability. Development and application of these methods is very promising for estimating and modelling mineral deposits [44–46].

Thus, the presented research aims to create a geometrization methodology allowing a comprehensive mining and geometric estimation of the mineral deposit, and ensuring efficient performance of the mining enterprise.

2. Methods

The majority of researches on geometrization of mineral deposits are based on P.K. Sobolevsky's concept on geometrization of shapes, properties, conditions of rock occurrence and subsoil processes [47].

This concept of geometrization underlies graphical and analytical methods of building a mining and geometric model of the deposit, estimating deposits of various geometric shapes as well as mineral reserves, that are developed and proposed by the authors. In addition, the authors of the present research have created a comprehensive methodology for mineral deposit geometrization.

A major disadvantage of the idea of geometrization based on the concept of the geochemical field and the topographic surface is that in the current system only one deposit characteristic is depicted. Simultaneous imaging of multiple characteristics is difficult and does not create a comprehensive model of the deposit if these characteristics are built as isolines. This disadvantage is addressed by applying mathematical operations with topographic functions according to certain rules that take into account genetic characteristics of the set of deposit characteristics. This formal set of characteristics provides a description of variability of the geological structure of the deposit parts or the entire deposit.

Under the general approach, variability arises when transiting, first, from considering individual characteristics to considering their totality; second, from studying the nature of spatial variability of individual characteristics to considering their combined impact on the overall variability factor, taking into account relationships between the characteristics.

Rys. 6. Potencjalne miejsca lokowania kawern Magazynowych w utworach soli kamiennych w Polsce [6]
Fig. 6. Potential locations for locating storage caverns in rock salt formations in Poland [6]

Any characteristic of the deposit P can be determined in a system of spatial-temporal coordinates P=f(x, y, z, t). In this case, location of a characteristic in the x coordinate system is commonly referred to as geochemical, geological, spatial, random. If in the coordinate system a multidimensional vector of various characteristics of the deposit P=f(P1, P2, ..., Pn) is determined, location of such a system of characteristics is called a vector field. However, such a name cannot be recognized as convenient. A system of spatially located deposit characteristics is called a spatial-factor field.

Each characteristic of this field can be formally described individually and exist as a spatial-factor field of an individual characteristic. The complete set of various characteristics of the deposit is specified by a system of spatial-factor fields of individual characteristics, which is described by a function of the type:

$$\begin{aligned} P_1 &= F\left[f_1(x,p);\phi_1(x,p)\right]; \\ P_2 &= F\left[f_2(x,p);\phi_2(x,p)\right]; \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ P_n &= F\left[f_n(x,p);\phi_n(x,p)\right], \end{aligned} \tag{1}$$

where f(x, p) is the regular component of the spatial-factor field; $\Phi_1 1(x, p)$ is the random component of the spatial-factor field or variance of the model.

The analysis of properties of individual fields and their systems is based on mining and geometric analysis of the deposit and topographic functions.

The variability model is expressed as a topographic function of the following type:

$$V = f(x, y, z). \tag{2}$$

This topographic function is scalar. If it is differentiated, it is transformed into a vector-topographic surface described by the expression:

$$q_v = \frac{\Delta P}{\Delta l} \tag{3}$$

where ΔP is the section of the isolines; Δl is the distance between adjacent profiles in the direction of the gradient.

To differentiate the variability at geological exploration network points located on the plan, values of the main gradients are calculated and the isogradients, which are derivatives of the given surface, are built on them. Isogradient surfaces are built on the basis of difference of the obtained characteristics in a given interval and allow finding any values within this interval and performing predictive modelling of deposit characteristics, as well as solving problems related to predicting and modelling spatial location of mineral reserves.

If necessary, coefficients of variability of the characteristics are calculated and accuracy of building the plans is assessed. If the accuracy of the model meets the requirements, the plans of the isolines are sufficiently informative.

The relationship between the network parameters and the error of determining the useful layer thickness is further established by comparing the amount of reserves obtained from the geological exploration data and that calculated from the exploitation data.

This error is determined as the mean square deviation of the surfaces of isothicknesses, built according to experimental parameters of the geological exploration networks, from the true surface, built according to the exploitation data, by the formula:

$$m = \pm\sqrt{\frac{\Sigma\Delta^2}{n}} \tag{4}$$

where $\Sigma\Delta^2$ is the total of squares of value deviations from the true surface; n is the number of points where deviations are determined.

Predictive modelling of mineral reserves is based on building vector-gradient fields of the useful layer thicknesses of mineral reserves. This process enables establishing regularities of spatial distribution of mineral resources, as well as managing reserves during exploration and exploitation of mineral deposits [48, 49].

These starting points for field differentiation and field gradient determination, known in the general rigorous mathematical field theory, enable new approaches to creating a geometric understanding of the deposit structure variability and solving problems of geological exploration and mining.

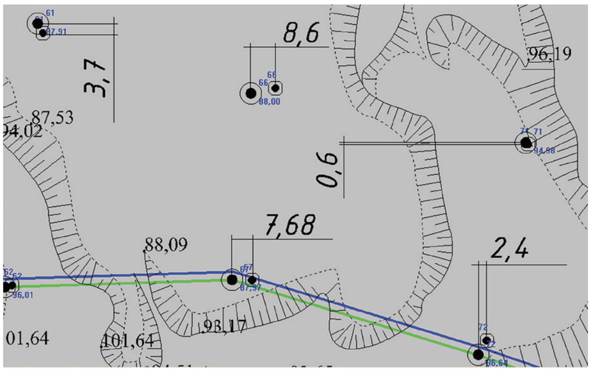

Fig. 2. Deviation of the position of boreholes plotted on the plan based on data of surveys and processed images

Rys. 2. Odchylenie położenia otworów wiertniczych, naniesione na planie na podstawie danych pomiarowych i przetworzonych zdjęć

The geostatistical analysis of the deposit provides an opportunity to assess the relationship between parameters of the exploration network and variability, to clarify distribution of the qualitative characteristics of the deposit, and improve accuracy of deposit reserves estimation. The geostatistical method of kriging is implemented in detail in geo-information systems used for geometrization of mineral deposits [50–52].

Within the framework of the comprehensive methodology for mineral deposit geometrization, the authors of the present research develop a method of mining and geometric modelling based on multidimensional heuristic self-organization of the function of deposit characteristics location [53]. The function looks like:

$$\begin{aligned} f_i = {} & [c_i^p (a_{11}^p x_1^p + b_{11}^p x_1^p)^p \times (a_{12}^p x_2^p + b_{12}^p x_2^p)^p \cdot \ldots \\ & \cdot (a_{1n}^p x_2^p + b_{1n}^p x_2^p)^p \times (a_{21}^p x_1^p + b_{21}^p x_1^p)^p \cdot \\ & \cdot (a_{22}^p x_2^p + b_{22}^p x_2^p)^p \times \ldots (a_{mn}^p x_n^p + b_{mn}^p x_n^p)^p], \end{aligned} \quad (5)$$

$$\begin{aligned} F_i(x_1, x_2, \ldots, x_n) = {} & d_i^p [f_1(x_1, x_2, \ldots, x_n) + \\ & + f_2(x_1, x_2, \ldots, x_n) + \ldots + f_n(x_1, x_2, \ldots, x_n)]^p + e^p, \end{aligned} \quad (6)$$

$$\begin{aligned} P(x_1, x_2, \ldots, x_n) = {} & g^p [F_1(x_1, x_2, \ldots, x_n) + \\ & + F_2(x_1, x_2, \ldots, x_n) + \ldots + F_n(x_1, x_2, \ldots, x_n)]^p + h^p, \end{aligned} \quad (7)$$

where x are the function arguments determined from reliable geological exploration data; a, b, c, e, g, h are the numerical coefficients obtained during modelling; p is the power calculated by (7).

In (5) – (7), the process of repetitive calculation cycles results in complicating the mathematical model of the deposit. The search for the functional relationship between the deposit characteristics takes place in worked-out areas of the deposit. While calculating, the factors are determined that impact distribution of the modelled characteristic most of all. Thus, the optimal type of functional relationship between geological characteristics is determined. The calculation cycles are performed according to the criterion of the modelling accuracy increase. The set of algorithms included in the described modelling method make this mathematical model very flexible, which allows it to be used in complex mining and geological conditions at deposits with high variability of geological characteristics. This makes it possible to describe very complex mathematical relationships between geological characteristics, distinguish the regular component of a multidimensional geochemical field, and estimate the error of modelling.

Large errors occur when processing maps and plans that can be used as a basis for modelling. These are made when building plans, or result from incorrect recognition of information on maps and plans due to their poor physical condition, or are related to inaccurate connection to the coordinate grids of the original image, etc.

To study these errors, two models are built for each open pit. One of them uses vectorized information from scanned plans, and the other is built on survey data. Then, the two models are compared for identity. Deviation of the values makes about 7% (Fig. 2).

Thus, accuracy of the volume calculations based on the data obtained by processing the scanned plans is much lower than that of the calculations based on the survey and geological exploration data. Survey and geological exploration data is a priority for geometrizaton of mineral deposits.

The comprehensive methodology for geometrization of mineral deposits created by the authors widely employs such geo-information systems as Micromine, K-mine, Surfer, and Autocad. These systems have detailed methods for estimation and geometrization of mineral deposits including geostatistical ones which are of particular interest given the complex geometry of mineral deposits. This methodology has been used for geometrization of Ukrainian mineral deposits of various shapes and complexity.

Mining enterprises most commonly use the following methods to calculate solid mineral reserves: vertical and horizontal sections, arithmetic mean, geological blocks, production blocks, polygons, triangles, isolines, isohypse, average dip, equal dip areas, etc.

The parallel section method is the most common for estimating reserves of ore deposits, as these deposits are characterized by highly variable morphology and very uneven distribution of the useful component. The section method divides the mineral body into a number of blocks located between parallel lines of the exploration network.

Depending on the geological exploration network, the method of vertical or horizontal sections can be used. For example, if the deposit is explored with vertical or inclined borehole profiles, the vertical section method provides the most complete direct use of all geological data obtained during exploration drilling.

To apply the horizontal section method in this case, it is necessary to average the geological data obtained from these boreholes and project them as individual points on the hor-

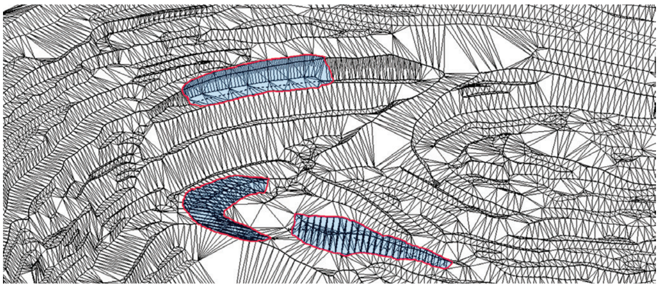

Fig. 3. A fragment of the triangulation surface of the digital model of the Pivdennyi GZK open pit. Experimental mine blocks are highlighted in color
Rys. 3. Fragment powierzchni triangulacyjnej cyfrowego modelu odkrywki Pivdennyi GZK. Eksperymentalne bloki kopalniane są wyróżnione kolorem

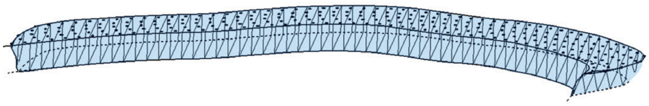

Fig. 4. Mine block with sections for calculating volumes
Rys. 4. Blok kopalniany z sekcjami do obliczania objętości

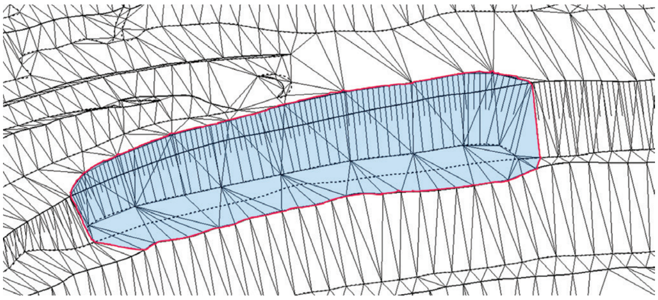

Fig. 5. Fragment of the triangulation surface of the pit after mine block extraction
Rys. 5. Fragment powierzchni triangulacyjnej wyrobiska po wydobyciu bloku kopalnianego

izontal section plane, which complicates the calculation of mineral reserves and inevitably reduces its reliability. On the contrary, if there are a number of mine working levels with underground horizontal boreholes, it is more expedient to use horizontal sections for calculating mineral reserves.

A huge advantage of the parallel section method is that it enables clear demonstration of geological features of the deposit, namely, the morphology of mineral bodies, the distribution of certain ore types and grades, the nature of mineralization changes along the dip, strike and thickness of the deposit. This method makes it possible to calculate reserves in the case of extremely complex deposit contours and availability of ore or non-ore layers.

In the general case of using the method of parallel sections, the volume of the block is calculated by the formula:

$$V = l_1\left(\frac{S_1 + S_2}{2}\right) + l_2\left(\frac{S_2 + S_3}{2}\right) + \ldots + l_n\left(\frac{S_n + S_{n+1}}{2}\right) \tag{8}$$

where S is the area of the section; l is the distance between the sections at the right angle to the dip; n is the number of sections.

When using the section method, the area of the ore body is determined for each section. Section areas are mostly determined by automated methods based on known plan-height coordinates of the digital section model. Depending on the shape and relative sizes of the areas in adjacent sections, volumes of blocks are calculated using the formulas of the pyramid, truncated pyramid, cone, wedge, etc. The average content of useful components in the sections is determined as the weighted average of the ore intervals of individual workings. If the geological sampling network of a mineral deposit is uneven, it is advisable to determine the content of the mineral component as a weighted average of the block areas using geostatistical estimation methods such as kriging.

The above data should be used for determining block parameters. Blocks are usually singled out between two exploration profiles, but in the case of a dense network of exploration workings, sometimes it is possible to include several sections in a block.

If the dip of mineral bodies is long, blocks formed by two sections are excessively large and it is advisable to divide them into several independent blocks, especially when there are significant vertical changes in the nature of the mineral distribution.

Most mineral deposits are limited by complex surfaces. It is impossible to accurately reproduce and identify them based on exploration data. Therefore, the principle of transforming complex bodies into simpler ones, within which reserves are estimated, underlies all geological exploration-based methods of reserve estimation.

The vertical section method is used to calculate volumes of complex block figures consisting of objects of different types that can be located in several different layers or pit benches and have a complex section profile.

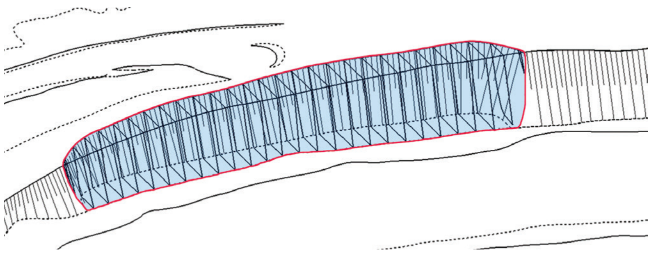

Fig. 6. Fragment of the triangulation surface of a mine block divided by parallel section planes
Rys. 6. Fragment powierzchni triangulacyjnej bloku kopalnianego, podzielonego równoległymi płaszczyznami przekroju

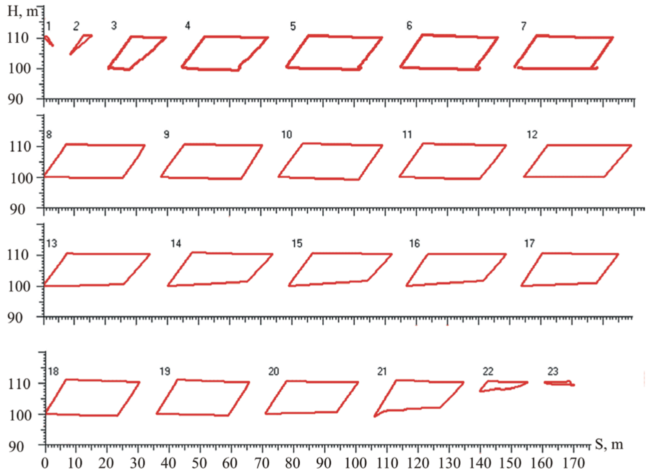

Fig. 7. Formation of sections to determine the volume
Rys. 7. Tworzenie przekrojów w celu określenia objętości

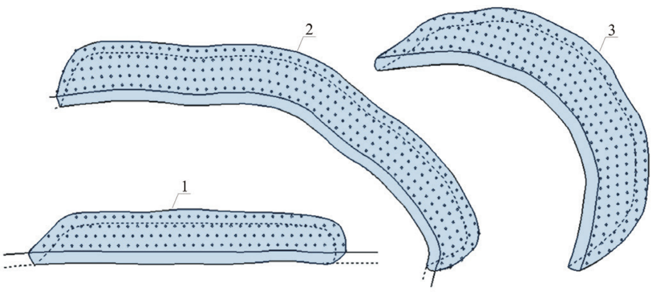

Fig. 8. Form of experimental mine blocks: 1 – straight elongated block; 2 – intermediate variation; 3 – block of a sharply rounded geometric shape
Rys. 8. Forma eksperymentalnych bloków kopalnianych: 1 – blok prosty wydłużony; 2 – zmienność pośrednia; 3 – bryła o ostro zaokrąglonym kształcie geometrycznym

3. Results and their discussion

The methodology for geometrization of mineral deposits developed in the present research has been applied to geometrization and modelling of Ukrainian mineral deposits, e.g. the deposit at Pivdennyi Ore Mining and Processing Plant (GZK).

The specifics of calculating volumes by the method of sections in geo-information systems used in the present research consists in building triangulation surfaces at the initial stage (Fig. 3).

The volume between two triangulation surfaces can be determined within a specified area of the mineral deposit limited by a closed contour exemplified in Fig. 4.

This method employs information on the condition of the pit surface at the beginning and the end of a certain time interval to calculate volumes with possible determination of volumes within a closed contour or multiple contours. For this, there should be indicated pit contours at the beginning and the end of the reporting period in different layers of the model. This information may be presented in the form of contours of workings, bench edges, surfaces, etc., which, in turn, are represented in the form of splines, polylines, surfaces, point elevation marks, etc. Based on these data, the contour of the mineral reserves in the XY plane is determined within which the reserves are estimated. A triangulation surface is built based on the set of objects describing information on the pit boundaries at the beginning and the end of the reporting period. The volume is found based on the difference in surfaces at the beginning and the end of the reporting period. Volumetric difference fragments with a positive mark are considered balance rock mass, and those with a negative mark are considered off-balance rock mass (Fig. 5)

Triangulation surfaces are built based on data from all objects included in each layer category. Triangulation surfaces are built for the new and old boundaries of a pit bench.

Next, the triangulation surfaces are intersected with vertical planes and the contours of intersection figures are deter-

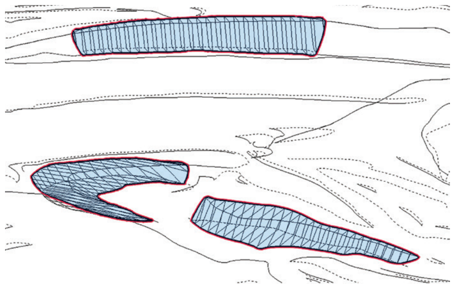

Fig. 9. Mine blocks of various shapes with sections for calculating volumes at the Pivdennyi GZK pit
Rys. 9. Bloki kopalniane o różnych kształtach z przekrojami do obliczania objętości w kopalni Pivdennyi GZK

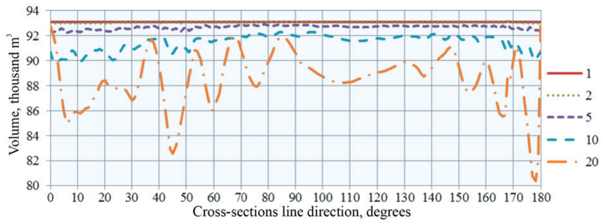

Fig. 10. Dependency of the calculated volume of a mine block of complex geometric shape on the direction of the line of vertical sections at different distances between the sections: 1, 2, 5, 10, 20 – dependencies at distances of 1 m, 2 m, 5 m, 10 m and 20 m, respectively
Rys. 10. Zależność obliczona objętości bloku kopalnianego o skomplikowanym kształcie geometrycznym od kierunku linii przekrojów pionowych, przy różnych odległościach między przekrojami: 1, 2, 5, 10, 20 – zależności w odległościach odpowiednio: 1 m, 2 m, 5 m, 10 m i 20 m

mined. Subsequently, the solution to the problem is reduced to solving the standard problem of calculating volumes by the method of parallel sections (Fig. 6).

This method is based on the parallel vertical section method and involves availability of a digital pit surface at the beginning and the end of the deposit mining. A contour, or a set of contours, that allows singling out the determined amounts of rock mass into categories is also taken into account. Such categories include, for example, accessed commercial mineral reserves, mineral reserves prepared for extraction, technological reserves, mineral reserves on individual mining horizons, balance and off-balance reserves within geological contours, reserves with a certain content of useful component.

At the same time, a reporting documentation package is generated for the calculated figure and all the necessary calculations are performed. The report contains a calculation table with calculations of the area for each section, as well as a graphical representation of each vertical section at a given scale (Fig. 7).

The method of estimating mineral volumes is studied on experimental modelled mine blocks of three main geometric shapes: a straight elongated block, a block of a sharply rounded geometric shape and the intermediate variation. For statistical data, the method of horizontal and vertical sections and that of arithmetic mean are used to calculate the volume of the obtained figures. The geometric shapes of the blocks are shown in Fig. 8.

The methods of horizontal and vertical sections employ sections located radially, parallelly and arbitrarily relative to each other. Each of the methods proves to produce more accurate results with certain shapes of the figures. That is, the method of parallel vertical sections provides a more reliable calculation of volume when applied to estimating a straight elongated block. The radial arrangement of vertical parallels provides higher accuracy in estimating rounded blocks. This is logical, since these methods are developed to determine amounts of rock mass in blocks of the geometric shape corresponding to these methods. To universalize the arrangement of vertical sections, the following procedure is employed: the point of the centre of the surface formed by the closure of the contour within which the volume is determined on the plan is used for arrangement of sections. Through this surface, in the north direction, a block strike line is drawn, perpendicular to which vertical sections are built. The line is then rotated at an angle of one degree, and the procedure is repeated. The obtained volumes are summarized in a table of calculated volumes of the block. As a result of these operations, angular ranges are determined within which the calculated values of volumes remain unchanged. These ranges are combined to provide minimum angular rotation values for calculating volumes and vary at different enterprises due to employment of different mining systems. The values of the rotation angles at which volumes of blocks differ sharply, become reference values for estimation of the block mineral reserves.

The calculation of volumes is carried out for mine blocks of different shapes at the Pivdennyi GZK pit, to clarify the impacts of different shapes of the calculated figures on calculation accuracy. Three shapes of mine blocks are chosen on different horizons: a straight elongated block, a sharply rounded block and the intermediate variation (Fig. 9).

At the same time, it is noted that reduction of distances between the sections leads to reduction of the difference between the obtained maximum and minimum values of the volumes calculated for all the section rotation options. Therefore, at the second stage of the experiment, an attempt is made to minimize the distance between sections. For this purpose, the volume in the given blocks is calculated several times with a gradual fixed reduction of the distance between the sections. The following distances are chosen for the volume calculation: 20 m; 10 m; 5 m; 2 m and 1 m (Fig. 10).

When analyzing the obtained results, it is concluded that with a certain reduction of the distance between sections, nu-

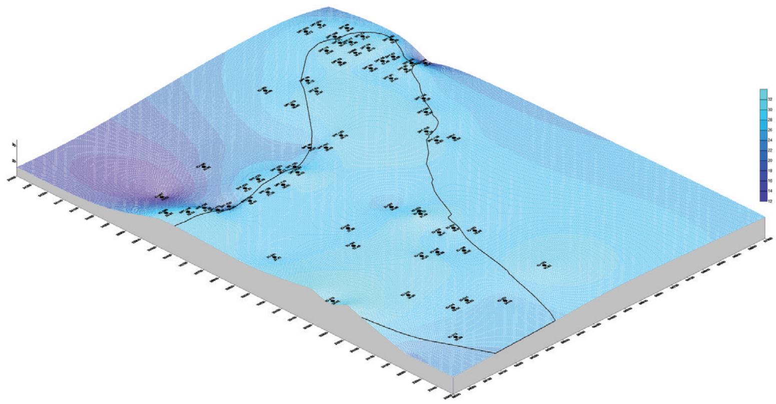

Fig. 11. Mining and geometric model of magnetic iron reserves distribution at the Pivdennyi GZK pit. The gradient shows the change in the percentage of the useful component content

Rys. 11. Model górniczy i geometryczny rozkładu zasobów żelaza magnetycznego w kopalni Piwdennyj GZK. Gradient pokazuje zmianę procentowej zawartości składników użytecznych

merical values of the calculated volumes of a block are equal at different orientation of the sections relative to the center of the surface formed by the closed limiting contour. In addition, the calculated values of volumes are equal to those obtained by other methods. It follows that this method can be used as a universal one for any geometric shape of the block with even greater accuracy. Volumes are calculated more accurately due to a greater number of sections that describe the contour of the figure, the volume of which is being calculated, in more detail. Optimal distances between sections are obtained empirically, their use confirms efficiency of the method of parallel vertical sections programmatically implemented in geo-information systems. A feature of the method is the ability to automatically arrange sections at optimal distances due to employment of geo-information systems. This eliminates the need to use other methods of calculating volumes of individual blocks of different geometric shapes.

Comprehensive estimation and geometrization of the deposit at the Pivdennyi GZK pit is performed employing geostatistical methods of estimation implemented in geo-information systems, as well as heuristic methods of estimation developed by the authors of the research. Comprehensive geometrization results in a mining and geometric model of mineral reserves distribution at the Pivdennyi GZK pit (Fig.11).

The resulting mining and geometric model of the deposit makes it possible to effectively plan both short- and long-term mining activities of the mining enterprise. The model describes the actual and predicted distribution of minerals by area and depth of the mineral deposit. The model enables geometrization of mineral deposits of complex geometric shapes with different detailing. The results of geometrization of individual parts of the deposit form the basis for creation of a complex mining and geometric model of a deposit.

4. Conclusions

Thus, the comprehensive methodology for geometrization of mineral deposits developed by the authors provides an opportunity of efficient geometrization of mineral deposits. The set of methods included in the methodology enables estimation and calculation of mineral deposit reserves with an error not exceeding 6–8%, depending on the amount of variability of the deposit characteristics. This results in rational and efficient mining operations.

It is advisable to perform geometrizaton of mineral deposits of various geometric shapes using the modified method of vertical parallel sections by selecting the optimal direction of sections and the optimal distance between them. It is expedient to determine the optimal arrangement of sections applying geo-information systems, which programmatically implement various ways of estimating mineral reserves.

Comprehensive geometrization of a mineral deposit requires extensive use of geostatistical and heuristic methods of estimation, which enable actual and predictive geometrization of a mineral deposit in conditions of high variability of the spatial occurrence of minerals.

Further development of the methodology for geometrization of mineral deposits consists in developing methods based on detailed geometrization of mineral deposits, as well as developing and creating geostatistical and heuristic methods of estimation enabling comprehensive geometrization of mineral deposits of various geometric complexity.

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Kompleksowa metodologia geometryzacji złóż minerałów

W artykule zaproponowano kompleksową metodologię geometryzacji złóż kopaliny. Na podstawie istniejących koncepcji geometryzacji opracowano zestaw metod budowy modelu geometrycznego złoża kopaliny. W procesie geometryzacji złóż kopalin autorzy badań szeroko wykorzystują systemy geoinformacyjne. Podstawą geometryzacji są dane z badań geologicznych. Przy opracowywaniu metodologii szacowania zasobów kopalin uwzględniane są najczęściej stosowane metody. Zmodyfikowana metoda równoległych przekrojów pionowych okazuje się najskuteczniejszą metodą szacowania zasobów złóż o skomplikowanych kształtach geometrycznych. Autorzy opracowują metodykę wyznaczania optymalnej lokalizacji przekrojów szacowanego złoża kopaliny. Do celów geometryzacji wykorzystywane są zarówno metody estymacji geostatystycznej stosowane w systemach geoinformacyjnych, jak i opracowana przez autorów wielowymiarowa metoda estymacji heurystycznej. Ten zestaw górniczych metod geometrycznych umożliwia rzeczywistą i predykcyjną geometrię złoża kopaliny oraz oszacowanie jej zasobów. Opracowana przez autorów metodologia geometryzacji pozwala racjonalnie planować działalność górniczą i zwiększać efektywność przedsiębiorstwa górniczego.

Słowa kluczowe: *kompleksowa metodologia geometrii, system geoinformacyjny, geostatystyczne metody estymacji, wielowymiarowa heurystyczna metoda estymacji, równoległe przekroje pionowe*