

Theoretical approaches to creation of robotic coal mines based on the synthesis of simulation technologies

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Abstract. Methodological approaches to theoretical substantiation of the structure and parameters of robotic coal mines are outlined. The results of mathematical and numerical modeling revealed the features of manifestation of geomechanical and gas dynamic processes in the conditions of robotic mines. Technological solutions for the design and manufacture of technical means for robotic mine are adopted using the method of economic and mathematical modeling and in accordance with the current regulatory documents. For a comparative performance evaluation of technological schemes of traditional and robotic mines, methods of cognitive modeling and matrix search for subsystem elements in the synthesis of a complex geotechnological system are applied. It is substantiated that the process of technical re-equipment of a traditional mine with a phased transition to a robotic mine will reduce unit costs by almost 1.5 times with a significant social effect due to a reduction in the number of personnel engaged in hazardous work.

1. Introduction

At present, the competition of oil, natural gas, coal as natural energy sources leads to a reduction in coal production in many countries. In the developed countries of Europe (France, Belgium, Spain, Great Britain, etc.) coal mining is practically stopped. The tendency for reduction in consumption of coal as an environmentally hazardous energy source will lead to a drop in production at coal mining enterprises. First of all, the volume of production in coal mines, which are dangerous production facilities with the first class of danger, will decrease. However, the use of large coal reserves (for example, in Kuzbass balance reserves to the depth of 600 m is 67.1 billion tonnes [1]), can make the basis of the economy of coal-producing regions now and in the future.

The possibility of mining these coal reserves by traditional technologies is limited by complex mining and geological conditions: depth of development up to 1800 m, high methane content and propensity of coal seams to spontaneous combustion, dynamic forms of rock pressure manifestation. One of the options for extending the period of operation of coal mines is the creation of robotic coal mine, that includes methods and means of underground geotechnology for manless mining and rational use of mineral resources. In accordance with the urgency, the program of research into the underground geotechnology of manless coal mining with underground utilization of waste products in the gob and remote control of technological processes was developed.

Taking into consideration the complexity of the issue and labour inputs, the research program includes several stages. The aim of the research at the first stage is to create scientific foundations of a manless technology for underground mining of coal deposits in complex mining and geological conditions.

The goal of the research can be achieved by solving the following problems (figure 1):



1) Conducting a systematic analysis of fundamental science and production experience achievements in the development of coal deposits for scientific justification of technological scheme of a robotic mine with a manless mining of coal seams.

2) Identification of regularities in manifestation of geomechanical and gas dynamic processes in the remote mining of coal seams by the results of numerical modeling.

3) Justification and optimization of robotic mine parameters by the economic criterion with the maximum coefficient of coal extraction.

4) Justification of technological requirements for the design and manufacture of technical means of a robotic mine.

5) Preparation of a robotic mine draft design for development of coal seams in difficult mining and geological conditions.

2. Methods of research

The solution of the scientific tasks is carried out on the basis of the methodological approaches indicated in figure 1.

To evaluate the state and directions of development of traditional and advanced coal mining technologies, it is proposed to use system analysis by decomposition of the known complex of geotechnologies, characterized by the method of selecting adaptive elements for a wide range of mining and geological conditions, the synthesis of which provides the optimal variants of technological schemes of robotic mines based on the results of cognitive modeling.

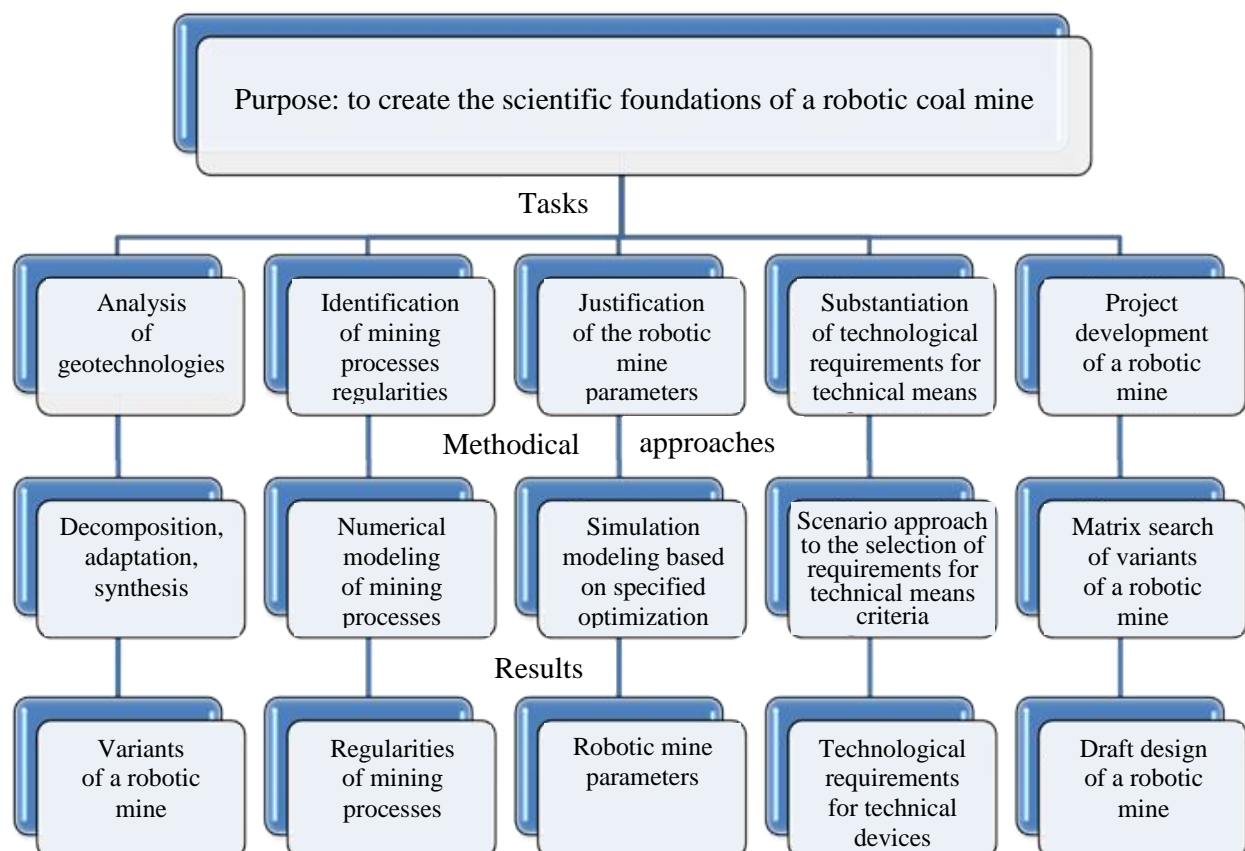


Figure 1. System structure of development of theoretical foundations for design of robotic coal mines.

Identification of regularities in the manifestation of geomechanical and gas-dynamic processes and justification of robotic mine parameters are planned to be carried out by mathematical and numerical

simulation methods using the developed set of problem-oriented programs that differ from analogs by taking account of rocks transition from elastic to elastoplastic, limiting and transverse states in their nonlinear deformation.

When justifying the robotic mine parameters, it is planned to use new approaches that are distinguished by the application of methods for geomechanical processes simulation to establish the dependencies of main technical and economic indicators of a mine on geological and technological parameters of the mining system.

3. Results and discussion

Creation of scientific foundations of a robotic mine, where the development of coal seams is carried out in complex mining and geological conditions, is planned to be performed on the basis of a scenario approach characterized by a variety of variants of robotic mine technological schemes adapting to complex geological and mining conditions, by choose of an optimal option according to integral criterion including minimum production costs and a risk of a dangerous production situation not higher than acceptable.

Justification of technological requirements for the design and manufacture of technical means of a robotic mine is supposed to be carried out using the method of economic and mathematical modeling, which is distinguished by the development of bounding algorithm of parameters of robotic mine technological system in accordance with the requirements of existing regulatory documents.

New approaches in the development of a robotic mine draft design consist in the use of dynamic programming, matrix searching of scenarios and the method of constructing options for coal mining with remote control over machines and units, taking into account the variability of mining and geological conditions.

Implementation of these methodological approaches has been carried out by the authors for the last 7 years [2 - 6]. The novelty of the results of scientific research obtained during development of the main principles of robotic mine is protected by patents for invention and inventor's certificates. The efficiency of results is confirmed by the cost-effective operation of mines in the south of Kuzbass, where separate technological solutions have been implemented.

More than 10 patents for inventions have been received that include methods of extracting coal from chambers with methane production (patent No. 2415266) and hydraulic mining of steep seams by boreholes with methane production (patent No. 2473806). The originality of technological solutions in these patents consists in combining the processes of coal mining in a face and extraction of methane from the gas reservoir in the gob. The efficiency of coal extraction is achieved by applying a hydraulic method of coal destruction and hydrotransport without presence of people in the face, while simultaneous methane extraction is carried out by evacuation through pipes to the soil surface. The use of a hydraulic mining method reduces the possibility of endogenous fire in the gob due to the phlegmatization of methane and coal dust in a humid atmosphere.

The original solution of the method coal mining from interseam strata during development of thick seams is proposed in patent No. 2416721, which is distinguished by the use of a slicing method with coal extraction by a drilling complex and supporting the roof rocks by a hydroficated support with a re-entry of the drilling complex onto the lower seam under the cantilevered part of the support.

Promising for the robotic coal mining technology is the method proposed in patent No. 2381364 consisting in the developing steep seams by a sublevel hydraulic winning with the release of coal from the upper-level chambers. Originality of technological solutions lies in preliminary drilling of wells and coal fracturing with its subsequent muck draw into the face of the lower layer and fencing of this zone by the coal pillars.

The theoretical foundations of robotic coal mines design were developed based on the results of R&D projects: "Development of measures aimed at preventing soil heave in the mine workings of the branch *Mine Yerunakovskaya-VIII* of *Yuzhkuzbassugol JSC*", "Recommendations for strengthening the support of the transport slope of seam 45 and adjacent workings taking into account the forecast of the state of the host rocks in the vicinity of these excavations for accident-free conduct and maintenance

of capital mine workings along seam 45 in the conditions of the branch *Mine Yerunakovskaya-VIII of Yuzhkuzbassugol JSC*. The originality of technological solutions developed and implemented in the conditions of this mine consists in justifying the parameters of multi-entry preparation and conducting mining of superimposed seams 45 and 48 by fully-mechanized longwalls. A positive effect was achieved due to group preparation of seams with the thickness of interseam rocks up to 10 m.

Recommendations developed on the basis of full-scale research results of R&D project “Justification of recommendations for the safe completion of reserves mining on site 6-1-11 in the conditions of *Mine Alardinskaya LLC*” are distinguished by original solutions concerning the reduction of number of unloading wells in the process of prevention of gas-dynamic phenomena in seam 6.

Two- and three-dimensional mathematical models of the stress-strain state of a gas-bearing geomass were developed for numerical modeling of the processes of non-linear rock deformation, modification of the finite element method was performed, allowing the transition of rocks from elastic to elastoplastic, limit and beyond the limit states to be taken into account.

Complexes of authorial programs, characterized by the possibility of 3D modeling of geomechanical processes in the massif during underground mining of coal seams (Certificate No. 17997), modeling of dynamic block rock caving with successive accumulation of damage (Certificate No. 326723), determination of the parameters of the bulk geomechanical state of a layered rock massif when mining a series of shallow or inclined coal seams (Certificate No. 6605) ensure the prediction of geomechanical parameters of workings in the conditions of a robotic mine.

The developed software packages are registered in the Joint Fund of Electronic Resources “Science and Education”, they received certificates confirming the novelty and priority of developments.

The originality of authors’ developments designs was repeatedly awarded at international specialized exhibitions, including “Software and hardware complex for monitoring and prediction of parameters of interacting gas-dynamic and geomechanical processes during underground mining of coal deposits” which was awarded in 2015 Diplomas and Gold medals at the International Specialized Exhibition “Coal of Russia and Mining”, and the International Fair “Expo-Siberia”.

For the generalization and development of theoretical foundations of robotic mine design principles, the results of the research in geotechnologies conducted by other scientific schools have been used

In article [14], in addition to traditional technologies, a group of high geotechnologies is distinguished, among which the underground well leaching, underground well drilling, heap underground and ground leaching, etc., can be identified. This group can also include underground technologies using robotic technical means for performing basic technological processes.

Synthesis of a coal mine technological scheme in works [7 - 9] is proposed to be implemented in accordance with the theory of adaptive control. Mining technology is considered as a three-component complex system, including subsystems S_1 – personnel; S_2 – unit as a set of artificial objects; S_3 – environment, as a combination of mining, geological, technological and climatic conditions. Each subsystem is characterized by a set of elements and connections between the elements of one subsystem and neighboring subsystems. Elements and connections of subsystems can be quantitative or qualitative. It is customary to evaluate the complexity of geotechnology as a single system by the number of connections on a quasi-ordered graph. For the mathematical description of such systems with weakly structured objects and situations in recent years a cognitive approach is widely used that is associated with a certain family of formal models and is based on the use of cognitive maps, including the mathematical apparatus of signed and weighted graphs.

When designing the robotic mine technological scheme in comparison with the technological scheme of a traditional mine, the number of such connections is smaller, since personnel in working shifts do not contact with the unit elements and the environment. For a comparative evaluation of the complexity of technological schemes of a traditional and robotic mine, methods of cognitive modeling and matrix search for variants of subsystem elements synthesis into a complex geotechnological system are applied.

To form scenarios for the creation of a robotic coal mine, taking into account the novelty of robotic elements of an enterprise and the risks of their inefficiency, the principle of phased integration of individual or groups of robotic elements into the technological scheme of the mine (TSM) was adopted. The choice of progressive elements of technological schemes of robotic mines was made using domestic and foreign experience of development of coal deposits in difficult conditions [10 - 14].

To select the optimal scenario for the phased conversion of a traditional mine into a robotic mine, a simulation using matrix search for variants of elements of this system was carried out according to a given quantitative optimality criterion [15].

In the matrix (table 1) for each element of the mine technological scheme, two levels of costs are allocated: capital costs for the creation or acquisition of technical devices and construction of facilities and operational ones. Alternative options of costs for each element of the mine technological scheme are formed by experts.

Table 1. Initial data for the evaluation of option effectiveness of the mine technological scheme.

Number and name of the TSM element	Expenses, rub/t (capital / operational)		
	traditional mine (basic version)	automated mine with robotic elements	robotic mine
1. Technological complex on the surface	360/60	360/50	330/50
2. Method and scheme of opening the mine field	150/135	180/110	200/90
3. Method and scheme for preparation of the mine field	75/60	80/50	100/40
4. Method of mine ventilation	60/75	60/60	70/40
5. Mining system	120/600	140/500	200/300
6. Degassing	150/90	150/80	100/60
7. Industrial Safety	240/150	240/100	300/50
8. Environmental Safety	90/150	90/100	120/50

Specialists from mines, design and expert organizations, as well as university professors in the field of *Mining* were involved as experts. Experts evaluated the costs for three options of mine technological scheme: a traditional, automated mine with robotic elements and a robotic mine (Table 1). One of the options is adopted as a basic one, as a rule, it is an operating mine with traditional coal mining technology.

For the formation of alternative options of mine technological scheme and the choice of an optimal variant, a computer program has been developed which, through the matrix search, determines and ranks all options according to the given criterion and chooses the one optimal from them. The results of the program implementation with the accumulation of costs according to the levels of the mine technological scheme are given in table 2.

Table 2. Results of modeling with accumulation of costs for the base and optimal options of mine technological scheme.

Number and name of the TSM element	TSM options	Costs distribution by TSM elements, rub/t		
		capital	maintenance	total
1. Technological complex on the surface	Basic	360.00	60.00	420.00
	Optimal	331.20	49.80	381.00
2. Method and scheme of opening the mine field	Basic	510.00	195.00	705.00
	Optimal	511.20	160.50	671.70
3. Method and scheme for preparation of the mine field	Basic	585.00	255.00	840.00
	Optimal	591.45	160.50	751.95

4. Method of mine ventilation	Basic	645.00	330.00	975.00
	Optimal	651.45	220.50	871.95
5. Mining system	Basic	765.00	930.00	1695.00
	Optimal	791.85	220.50	1012.35
6. Degassing	Basic	915.00	1020.00	1935.00
	Optimal	941.85	300.60	1242.45
7. Industrial Safety	Basic	1155.00	1170.00	2325.00
	Optimal	1181.85	401.10	1582.95
8. Environmental Safety	Basic	1245.00	1320.00	2565.00
	Optimal	1298.86	450.60	1749.45

The analysis of the obtained results make it possible to state that the main economic effect can be achieved in the structure of the mining system due to the use of manless coal mining with remote control over the excavating unit figure 2).

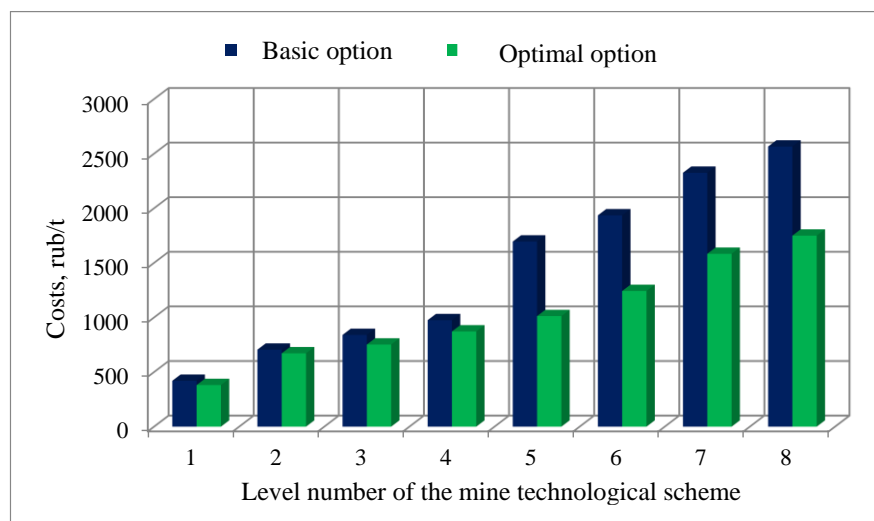


Figure 2. Diagram of costs distribution by the levels of TSM.

In the process of modeling 109 options of combinations of mine elements with traditional technology and automated mine with the elements of robotization were considered. The structure analysis of optimal scenario showed that of the 8 elements only 2 elements of robotic mine are included into the optimal option, and the remaining elements are taken from an automated mine with robotic elements. The reasons for this structure formation of the optimal option are the following: experts do not have information about the parameters of robotic mine and the overestimated capital costs for the acquisition of robotic technical devices that have not been produced serially yet.

4. Conclusions

1. The main theoretical approaches to the creation of robotic coal mines are:

- system analysis of the achievements of fundamental science and production experience in the development of coal deposits for the scientific justification of robotic mine technological scheme of a with a manless mining of coal seams;
- identification of regularities in the manifestation of geomechanical and gasdynamic processes based on the results of numerical modeling in the case of remote mining of coal seams;
- parameters optimization of robotic mine by the economic criterion with the maximal coal mining coefficient;

- justification of technological requirements for design and manufacture of technical means of a robotic mine;
- development of a robotic mine draft design for mining coal seams in difficult mining and geological conditions.

2. The simulation results confirm that the creation of a robotic mine should be carried out in stages according to the scheme: traditional mine → automated mine with robotic elements → robotic mine. Such a process of technical re-equipment of a traditional mine with a phased transition to a robotic mine will reduce unit costs by almost 1.5 times with a significant social effect due to reduction in the number of personnel engaged in hazardous work.

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