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METHODOLOGY OF CREATION AND DEVELOPMENT OF INFORMATION SYSTEMS FOR TECHNOLOGICAL SAFETY OF MINING FACILITIES

Purpose. To develop methodological approaches to the process of informatization of technological security (TS) and to propose a project of step-by-step development of the architecture of information system (IS) of TS, which will contribute to effective integration of digital and mining technologies. To develop a mathematical model for finding the number of sensors required for probabilistic assessment of the concentration gradients of hazardous gases.

Methodology. General and special methods of knowledge are used: structural analysis – to establish the structure and tasks of IS of TS; logical generalization – for formation of methodological system of directions of TS information measures; system analysis – to establish synergistic effect of complex implementation of the indicated directions; scientific abstraction – for development of a project for IS architecture derivation; mathematical formalization – for development of mathematical model for estimating gradients of concentration gases and the number of sensors.

Findings. A project for the phased development of IS architecture of mining facilities based on the implementation of diffusion principle is developed, which will allow solving a complex of issues: integrated monitoring of danger of gas environment of underground structure for detection of gas traps and permanent determination of concentration gradients of hazardous gases, implementation of intelligent safety loops using analytical resources of technological mining process. A methodological system of directions for diffusion implementation of TS information measures is formed. The use of the method of system analysis made it possible to point out the synergistic effect of the complex implementation of the directions of implementation of TS information measures.

Originality. A project for the phased development of the information system architecture of the technological safety of mining enterprises has been developed. A mathematical model has been developed to estimate the concentration gradients of hazardous gases and the number of sensors to ensure the appropriate level of probability of finding a sensor in each cell of the underground mine.

Practical value. The methodological approach makes it possible to form an IS that implements a comprehensive approach to ensuring the appropriate level of technological safety of mining facilities.

Keywords: *methodological approach, information system, technological safety, mining facility, mathematical model*

Introduction. The deep digitization of the mining industry is forming "Computer Integrated Mining" as a prerequisite for "Mining 4.0". The fundamental difference of Computer Integrated Mining from traditional mining technologies is that it allows one to change the extraction of minerals radically and to ensure not only advanced optimization of production processes with their in-depth automation, but also to use new information connections of employees, equipment, and IT technologies. Computer Integrated Mining also makes it possible to strengthen human intelligence with artificial intelligence, to transform the processing of large volumes of data into a new quality. As examples of its effectiveness, the introduction of the digitalization strategy in the People's Republic of China – "Made in China 2025" and Japan's "Society 5.0" [1] can be cited. This led to the provision of these countries' own needs in certain types of minerals and even opportunities to realize their export supplies.

With a high level of global competition, deep digitalization of the mining industry is inevitable, but for Ukraine, it is an extremely difficult process. The equipment of Ukrainian mines is worn out, working capital, especially in the conditions of war, is not enough for the most necessary things. Nevertheless, digital innovation will have to be implemented even under such harsh conditions. Otherwise, there is a threat not only to lose competitive positions on the global market, but also suffer significant losses due to accidents, the number of which is increasing at the mining enterprises of the industry.

The mining industry of Ukraine is characterized by a high level of danger due to explosions of mine gas (~89 % of coal mines are "gassy"), coal dust and agglomerate (60 %), downfalls (~45.2 % of mines are characterized by gas-dynamic phenomena), etc. [2]. In terms of the national coefficient of fatal injuries per one million tons of mined coal, Ukraine has one of the worst indicators – 2.14, second only to the People's Republic of China (3.94). For comparison, this indicator for the USA is 0.01, for Poland – 0.25. Negative social, economic, ecological, even political consequences of accidents will force manufacturers to introduce informational measures for the technological safety of mining facilities.

This, even with the lack of financial resources of mining enterprises for digital innovations, increases the need to forecast and plan the development of information systems in order to avoid costs for their further reconstruction, when for each modification of a separate element, the information system must be completely updated. This is not a productive use of company resources. In addition, the complex implementation of information systems makes it possible to synergistically realize the advantages of the Mining 4.0 paradigm, to bring production efficiency not only to the level of guaranteed income, but also to ensure the modernization of production without external investments. Therefore, it is relevant to study the methodology of information systems of mining facilities, first of all, to avoid losses due to accidents.

Literature review. In recent studies by domestic and foreign scientists, a lot of attention has been devoted to the problems of informatization of the mining industry and the introduction of information systems of mining facilities, in particular technological safety systems.

Thus, in the article by Wang, et al. [3], the technologies of intellectual mining, the advantages and peculiarities of the introduction of an intellectual mine are researched, in particular, with regard to ensuring its autonomous functioning, and the need to form a "closed loop of security management". The specified peculiarities of the implementation of the intellectual mine were clarified and supplemented in the presented study. Wang, et al. [3] also stated that "intelligent coal mines are complex systems that cannot be expressed, analyzed and investigated using a single mathematical model". This is fair and therefore the formation of intelligent mines requires significant efforts in all aspects of digitalization of mining facilities.

The article by Barnewold, et al. [4] is dedicated to researching the trends of digitization of the mining industry. It is stated that, although the need for the introduction of digital technologies for the mining industry has been identified today, "there is no universally accepted assessment of the current trends in digitization (i.e., the general direction in which the mining sector is adopting digital technologies) and the implementation of digital technologies in the mining sector". This conclusion, according to the authors of the presented study, is questionable. Also in the article Barnewold, et al. [4] pointed out a characteristic feature of the process of digitization of the mining sector even for developed countries – the diffusion nature of the introduction of IT technologies. This is considered in the presented article.

In the article by Onifade, et al. [5], various aspects of intelligent mining that improve mining operations are indicated. But the question of integration of IT technologies in the mining industry remained outside the attention of Onifade, et al. [5].

In the article by Slashchov, et al. [6], the construction of digital models is used to assess the safety of production activities. Unfortunately, Slashchov, et al. [6] did not reveal the issue of complex application of information systems for technological safety of mining enterprises.

In a study by Liu, et al. [7] based on the experience of the risk management information systems of coal mines of Yima Coal Industry Group (PRC), a method of hazard identification "by basic state" is proposed – the so-called "Root-State Hazard Identification" (RSHI). Also in the article by Liu, et al. [7] it is stated that mining operations require a comprehensive threat identification system. This is considered in the presented article.

In the article by Singh, et al. [8], the trends in the implementation of information technology are investigated to increase the safety and productivity of mining based on the IoT approach. Various aspects of this approach are detailed in the works by other scientists. In particular, Tang, et al. [9] developed a system for detecting mining hazards using a platform approach.

Wu, et al. [10] developed a "dynamic information platform for an underground coal mine based on IoT technology" because such a platform allows not only increasing the efficiency of mineral extraction, but also reducing the number of accidents. A dynamic approach to the formation of technological safety information systems was also used in this study.

In the article by Chen, et al. [11] the use of wireless sensor networks (WSN) was studied for detection and early warning of the danger of accumulation of harmful and explosive gases in mines. This idea of using wireless sensor networks for hazard warning is used in the presented research.

Preventing the risks of accidents also required the introduction of analytical intelligent systems.

Thus, in the article by Jo, et al. [12], a monitoring system based on cluster analysis and spatio-temporal statistical analysis is proposed. Such an approach will require the development of a special mathematical apparatus for the formation of an intelligent system for evaluating data from sensors that change their location in real time, without which, in the opinion of Jo, et al. [12], a relevant statistical evaluation is not possible. The relevance of applying statistical analysis to the assessment of sensor data that changes location in real time is questionable.

In the article by Wang, et al. [13], a modeling method based on network theory is proposed. In a study by Niu, et al. [14], a risk assessment based on HFACS-GE and Bayesian networks was carried out, which also raises questions about methods for assessing probable hazards.

In the article by Liu, et al. [15] a structural analysis model for evaluating and ranking factors of technological hazards in the mining industry is proposed. The article by Liu, et al. [15] also indicated the need for an integrated system of prevention and control of dangerous factors. This is considered in the presented article.

A review of research on information methods for forming the technological safety of mining facilities showed that only fragmentary monitoring of underground workings is often proposed, rather than a comprehensive integration of various technological approaches to various dangers of the dynamic underground environment.

A mathematical model for spatial statistical analysis of sensor data also needs to be developed.

Purpose. To develop methodological approaches to the process of informatization of technological security (TB) and to propose a project of phased development of the architecture of the information system (IS) of TB, which will contribute to the effective integration of digital and mining technologies.

To develop a mathematical model for finding the number of sensors required for probabilistic assessment of the concentration gradients of hazardous gases.

Methods. When performing the presented scientific research, general and special methods of cognition were applied. Content analysis was used to identify the key problems of technological safety of mining facilities. Quantitative and qualitative comparison methods made it possible to identify the need to solve two multifaceted tasks for information systems of technological safety of mining facilities, protecting the health and life of miners: warning against salvo emissions of dangerous gases and warning about the gradient accumulation of dangerous gases in the atmosphere of mining workings. The methods of structural analysis made it possible to establish the structure and tasks of information systems for the technological safety of mining facilities: the need for phased acquisition and coordination of information flows for operational control, environmental sensing; transmission, processing, storage of information; presentation of data; provision of real-time signals about danger and to automated technological systems and life support systems; decision support; forecasting and planning of production activities.

The method of logical generalization was applied to form a methodological system of directions for the implementation of informational measures for the technological safety of mining facilities. The use of the method of system analysis made it possible to indicate the synergistic effect of the complex implementation of directions for the realization of technological safety information measures. The method of induction and deduction made it possible to establish requirements for information systems of technological safety of mining facilities.

The method of scientific abstraction was used to develop and substantiate the project of phased development of the architecture of the information system of technological safety of mining facilities.

The method of mathematical formalization is used to develop a mathematical model for estimating concentration gradients when a hazardous gas fills an entry, detecting the proximity of its concentration to a threshold value, which will allow neutralizing the danger in advance. Fractal mathematics was used for this. The developed model allows one not only to operate with probabilistic values due to the impossibility of using a stochastic distribution function, but also, using the method of mathematical analysis, to estimate the number of necessary stationary sensors and non-stationary individual sensors of miners to ensure the appropriate level of probability of finding a sensor in each chamber of an underground mine.

Results. The methodology of information systems for the technological safety of mining facilities should be based on the peculiarities of planning and operational control of production activities, the need for providing and analyzing information in a spatial form, and the tasks of integrating local subsystems into a single enterprise information system.

Until today, the process of automation of mining operations was focused on the implementation of tasks of control and management of mine equipment [16].

This process features not only many years of sustainability, but also the experience of emergency situations related to the equipment, and, accordingly, the experience of their elimination. The specifics of the specified process are largely determined by the scale of mining, the location of ore bodies, the spatial structure of entries, that is, the conditions of specific mines. That is why, for example, due to changes in the conditions of rock formations and the characteristics of individual mine sites, there are currently no unified technologies for automating mining loading in mines.

This has led to the fact that in this article, the tasks of controlling the parameters of the technological equipment are selected into a separate block, which must be detailed during the development of the information system architecture of a specific mine with the condition of its integration into the general decision-making preparation system of the mining enterprise. An integrated decision-making training system for control and management should work in real time to create both safe working conditions and the implementation of the tasks of planning production resources and increasing production efficiency.

Studies indicate that "coal deposits of Ukraine are characterized by complex mining and geological conditions: low thickness of layers, significant gas content, tendency of coal to self-ignite" [17].

This determines the main dangers of coal mines in Ukraine, which are associated with the fact that mining is carried out mainly in thin layers under weak lateral rocks, complicated by significant tectonic shifts. In such geological conditions, anticlinal and domed structures bordering rocks with low gas permeability form gas traps. This increases the probability of salvo emissions of explosive gases into the atmosphere and, accordingly, requires permanent monitoring of the mining environment.

Even in such difficult mining and geological conditions, it is possible to achieve a significant effect with the use of intelligent technologies, as indicated by the experience of mines in Huanglin, Shanbei, Shandong (PRC), where the cost-effectiveness of intellectual extraction of coal from thin geological layers (less than 1.3 m) has been proven [3].

Salvo emissions of dangerous gases into the atmosphere of underground workings require spectrometric sounding of rocks and subsequent intelligent data analysis to determine the spatial distribution of ore bodies and identify gas traps. The next step of analytical data processing should be operational planning of mining operations to avoid the danger of salvo emissions of dangerous gases into the atmosphere of the mine.

It should also be taken into account that dynamic changes in ventilation conditions can create uneven concentrations of explosive gases in the atmosphere of underground workings.

The danger of the gradual accumulation of gases in the atmosphere of coal mines is exacerbated by the fact that coal is a good sorbent, for example, of methane. For instance, a ton of anthracite can adsorb up to 40 cubic meters of methane. Adsorption and, accordingly, desorption properties of coal can vary in a wide range depending on the temperature, pressure and other physical parameters of the air in the entry [18].

The explosive concentration of methane also depends on the content of oxygen and ozone in the air of the mine, and their content can also change due to the technological conditions of production and ventilation. This, accordingly, increases the need for permanent control and detection of individual local zones where, as a result of technological conditions, methane concentration can acquire dangerous values and technologies for assessing concentration gradients in the atmosphere of underground workings. This control increases the volume of data about the danger. This problem can be solved by forming chains (stages) of processing, prioritization and selection of information.

This indicates the need to solve two multifaceted tasks for the information systems of technological safety of mining facilities, protecting the health and life of miners: prevention of salvo emissions of hazardous gases and warning of the gradual accumulation of hazardous gases in the atmosphere of mining operations.

In general, the above-mentioned circumstances require informational coordination of operational planning of production activities and protection of health and life of miners.

This also determines the following requirements for information systems for the technological safety of mining facilities: phasing of acquisition and coordination of information flows for operational control and sensing of the environment; transmission, processing, storage of information; presentation of data; provision of real-time signals about danger including those to automated technological systems and life support systems; decision support; forecasting and planning of production activities. Implementation of the specified tasks will allow one to effectively automate dispatching activities, control of production processes and coordinate tactical and strategic management tasks.

This leads to the need to use a highly adaptable and flexible architecture of information systems of mining facilities. The lack of working capital of mining enterprises for the design and implementation of intelligent systems determines the use of stages, the diffusion nature of their implementation. Therefore, it is proposed to apply the modular principle to their architecture with the provision of continuous improvement.

The application of the modular principle to the architecture of information systems of mining facilities is also due to the impossibility of creating a unified project for the development of the information system architecture. This, in particular, is caused by the complex and diverse conditions of mineral deposits in Ukraine, the significant level of differences in mining equipment, engineering solutions, etc. The effectiveness of the implementation of the information system architecture will also depend on specific mining methods and parameters.

To neutralize the threat of an explosion of mine gas, coal or agglomeration dust, an explosion warning module should be provided in the architecture of the information system. The structure of this module is proposed to be implemented in stages. In addition to the task of monitoring the mine environment, there should be constant monitoring of the reliability of the environmental safety information subsystem.

The first level of the specified explosion warning module (Figure) is mobile individual sensors of miners (individual sensors of miners – ISM) and stationary entry sensors (stationary sensors – SS) with built-in verification and calibration modules.

The use of DeviceNet and FoundationFieldbus technologies should help in this.

The need to use a combined network of sensors consists in the need for both permanent control of the gas environment in underground workings, even in the absence of miners there (for example, to protect against the explosion of a gas mixture), and enhanced, detailed by the location of the miners, control of the specified environment, determination of gradients of concentration changes and carrying out an averaged assessment of the distribution of hazardous gas components in the air in the presence of workers in underground workings.

The need to introduce individual miners' sensors also lies in the fact that the factors of technological danger of mining facilities are significantly increased by the human factor, first of all due to the fatigue of those working underground. The fatigue factor is significantly increased by mine conditions – temperature, humidity, dustiness, lack of oxygen, etc.

Individual sensors of miners can reduce this risk by measuring not only the parameters of the gas environment but also the physiological indicators of a person. Then, the relevant and operational determination of the state of fatigue of miners will reduce the accident rate of mining enterprises. To monitor and detect fatigue, it will be necessary to equip individual sensors of miners with appropriate physiological recorders and introduce modern machine learning methods for processing and analyzing data from recorders of human physiological indicators.

The information system of technological safety of mining facilities, presented in the figure, should implement the following methodological system of development directions:

- formation and use of new information connections of employees, mining equipment and IT tools;
- implementation of the diffusion principle when introducing the technological safety of information system of enterprises in the mining industry;
- acquisition of a new level of efficiency of the information system due to its complexity;
- ensuring the principle of modularity of the information system with the possibility of continuous improvement;
- effective integration of digital and mining technologies;
- high adaptability and flexibility of the architecture of information systems for the technological safety of mining facilities;
- an echeloned approach to the implementation of modules for preventing salvo emissions of dangerous gases and warnings about the gradual accumulation of dangerous gases in the atmosphere of mining operations;
- ensuring the possibility of tracking the location of each miner;
- integrated monitoring of both geological structures that can form gas traps and air in the entries;
- implementation of an intelligent security loop using analytical resources;
- implementation of a systematic approach to the formation of the appropriate level of technological safety of mining facilities.

The thesis that it is necessary to use new information connections of employees, equipment and IT technologies is to implement the principle of inherence of the "intellectual mine" as a single system.

The thesis that the formation of the information system should be organized according to the diffusion principle means the possibility of its phased, modular introduction, which will allow more rational distribution of the expenditure of financial resources on the specified system.

Implementation of the principle of modularity of the information system allows solving a group of disparate issues: ensuring survivability and reliability; providing the possibility of complete reconstruction of the module with the appearance of technological innovations or the need to replace the software code of the module, etc., without the need for a radical reconstruction of the entire architecture of the information system, which will provide the possibility of significant cost savings and time for replacing components of the information system.

The introduction of each subsequent module of the information system increases its effectiveness according to the principle of emergency. Efficiency will progress in a non-linear manner with the implementation of an integrated approach. This, in particular, can be illustrated by controlling a wider range of risk factors. As a result, the effectiveness of the analysis and forecasting of hazards increases, offering options for solutions to dangerous situations, opportunities for optimizing technological processes and developing technological ways of neutralizing hazards are opening up, such as, in particular, optimal design of the location of gas extraction wells on the territory of the enterprise.

The thesis that a comprehensive approach to the formation of the appropriate level of technological safety of mining facilities should be implemented consists of multi-level control, multi-level management (dispatch, operational, strate-

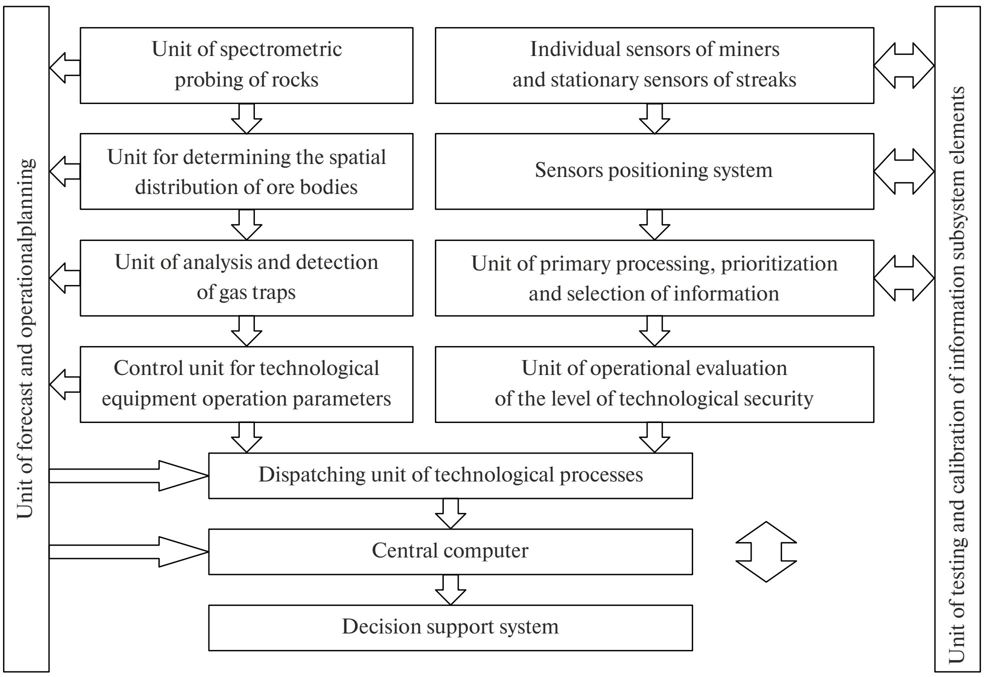

Fig. The project of phased modular development of the architecture of the information system of technological safety of mining facilities gic), and the possibility of providing individual information to each miner for independent assessment of the level of danger.

Implementation of the intelligent safety loop using analytical resources should be provided by models that apply the methods of the theory of complex adaptive systems and multiagent analysis.

The use of the system analysis method makes it possible to point to the synergistic effect of the complex implementation of the above-mentioned areas of applying technological security information measures.

A system of wireless sensors is offered as the first level of echeloning modules for the warning of salvo emissions of hazardous gases and warning of the gradual accumulation of hazardous gases in the atmosphere of mining operations. Sensors can be tested with a variable sampling rate depending on the requirements for monitoring the environment. The infrastructure of wireless mobile devices must support high data throughput while reducing errors. This determines the deterministic transfer of information.

For sensor positioning, the Ekahau Positioning Engine (EPE) system is proposed, which allows using a wireless sensor network (WSN) according to the IEEE 802.11 standard. EPE in real time positions the location of the sensor, identifies the device and the status of Wi-Fi tags. Positioning is implemented by the algorithm of comparing signals from several stationary Wi-Fi points [19]. The usefulness of the Ekahau Positioning system also lies in the fact that it allows tracking not only sensors, but also all devices that have Wi-Fi adapters. This allows one, if necessary, to modernize the warning system, introduce its testing, calibration, and use it to find cracks in the rock through which harmful gases penetrate into the working area.

It is proposed to implement orthogonal frequency division to avoid WSN signal transmission problems underground. In this network, nodes are divided depending on their function. Thus, stationary air quality measurement sensors of the mine face and individual miners' sensors, which should measure not only the parameters of the gas environment, but also the physiological indicators of the person, are the basic monitoring nodes, and the router nodes (RN) are integrating devices for the cluster from the SS and ISM groups.

The primary measurement data from the router nodes are transmitted to the units of primary processing, prioritization and selection of sensor information, from which the data are sent to the cloud and to the central computer. An option that will lead to an increase in the cost of the system, but will allow increasing its efficiency, is proposed – to equip individual sensors of miners with units for primary processing and visualization of information. This will allow miners to make decisions in the absence of communication with the central computer, that is, with the dispatcher and operators of the information system, which increases the chances of survival in emergency situations.

From this point of view, in the future, it is worth diversifying the general task of the "intellectual mine" to use autonomous information subsystems instead of a single center, that is, to put only control functions on the central computer, the function of ensuring management in crisis situations, general planning, forecasting and information support of business execution processes.

It should also be taken into account that the traditional architecture of the information system for an "intelligent mine" must ensure faultless integration of data at the level of the mine face and the mine as a whole, which is a difficult task for extremely large volumes of primary information. This also determines the need for intermediate units to ensure effective processing, prioritization and selection of primary information to ensure proper data quality at the input to the central computer. Procedures that allow reducing information flows are proposed. For example, comparing previous data from the sensor while its location remains unchanged, fixing the gas environment unchanged, in this case, eliminates the need to send all received data to the central computer.

Databases should also combine relational and object-oriented approaches.

Spectrometric sounding of rocks can be performed periodically or permanently. This will make it possible to prevent the opening of voids in the massif of rock and to plan the work of miners. It should be considered that this will significantly increase the flow of data. The difficulty is that mines must provide three-dimensional spatial information. This will also allow representing the ore body, the location of the mine and the equipment in it.

For planning and operational control of production activities, including for the purpose of harmonizing the use of equipment productivity and fulfilling the tasks of technological safety of mining facilities, the information system must provide reliable feedback of dispatchers with equipment operators. This requires the use of intellectual analysis methods.

Implementation of the process of acquiring information, its initial processing and presentation, consistency of information flows should take place with the perspective of expanding the tasks of information systems of mining facilities with the tasks of management and optimization of technological processes. Therefore, it is necessary to provide for interaction between individual modules of the information system, implementation of system design both "from top to bottom" and "from bottom to top", coordination of protocols and data formats, etc.

Since production activity at mining sites is a mixed process that combines both periodic tasks (loading, dumping of ore, etc.) and continuous technological tasks, it is necessary to provide for the tasks of operational management of resource allocation, reduction of the total cost of a unit of production, and, for this, the cost of technical maintenance and support of equipment, the formation of the best production cycles for equipment and workers, the configuration of the mine, planning the development of target states of production units in the enterprise as a whole, etc.

Software coding in an object-oriented paradigm will require a spiral approach. In the future, subsystems must collaborate in the planning, deployment, performance and health monitoring, and management of a fleet of remote sensors, machines, and technology systems. Practical users and software developers should work on common interface requirements for exchanging information between programs.

The mining industry needs such agreed industry-wide standards to integrate the full range of planning and operational control systems for the future integration of industry information resources and the implementation of an integrated industry decision support and decision-making system.

The use of a network of sensors makes it possible to warn workers in advance that the concentration of dangerous gases is approaching limit values. And upon a signal from only one danger sensor, personnel must be evacuated. At the same time, for safety control and planning of underground works, it is necessary to evaluate the concentration gradients in their complex dynamics and the process of changing the averaged concentrations for all sensors in the isolated underground environment.

The problem of estimating concentration gradients and even their averaged values is that the complex dynamics of convection air flows in closed spaces of mining operations can create locations with concentrations of hazardous gases above the average statistical value for the underground environment. For this, it is proposed to use the mathematics of fractals [20]. This is possible because, as it is known, multifractals are a singular measure, a third way of describing a random variable in contrast to a stochastic distribution function using "probability density" for continuous parameter values and "distribution series" for discrete parameter sets [21, 22].

As it is known from the theory of fractals, a multifractal is interpreted not as a set, but as a measure, since the Hausdorff-Bezykovich dimension (D) for a fractal is not equal to its topological dimension (D_t) [20, 23]. At the same time, the condition for using the theory of fractals is the inequality $D > D_t$. The above allows applying this peculiarity to assess the risks of changes in dangerous gas concentrations over time in individual areas of the entry, and for this purpose the so-called mathematical model of "stochastic" (irregular) multifractal will be used.

For this, the network of sensors is considered as a fractal structure of dimension N with n localized sensors that occupy a limited area θ (an entry) in the Euclidean space of dimension $D_t = 3$.

Next, the region θ is divided into cubic chambers of volume v and side l.

In the next step, the Hausdorf–Bezykovich topological dimension [20] is calculated and its value relative to the topological dimension is estimated

$$D = \frac{ln ln N(v)}{ln ln l} > D_t.$$

Next, it is necessary to assess the sufficiency of the available number of sensors in the isolated underground environment for the application of averaging. This is particularly necessary since a combination of static and dynamic location of sensors is proposed. That is, the number of sensors in the isolated underground environment can be a variable value. For this the following approach is used. If there are $i = 1, 2, 3, ..., N_g$ sensors in chambers numbered $n_i \geq 1$, they are considered "populated". The population of chambers is evaluated according to the method given in [20].

In this case, in the given mathematical expressions, it is necessary to take into account the level of non-compactness (looseness) of the fractal, since in the general case $N(l) \gg N_g$ and to recalculate the indicated mathematical expressions for $N(l) \equiv N_g$.

Then the probability of finding the sensor in chamber (i) is

$$p = \frac{n_i}{N(v)}.$$

The total risk can be determined by considering the generalized statistical sum

$$Z(q,v) = \sum_{i=1}^{N_g(v)} p_i^q,$$

where the degree q is identified with the scaling exponent (mass index) $\tau(q)$ which is related to the spectrum of generalized Regny dimensions (D_q)

$$D_q = \tau(q)(q-1)^{-1}.$$

For a non-multifractal random variable, the singular measure defined on the interval 0-t can be calculated as

$$\mu^* = \frac{\{\mu([0,t+\Delta t] - \mu([0,t])\}}{\Delta t}.$$

Such a model allows one not only to operate with probabilistic values due to the impossibility of using a stochastic distribution function, but also to estimate the number of necessary stationary sensors and non-stationary individual sensors of miners to ensure the appropriate level of probability of finding a sensor in each chamber of an underground mine. This will provide an opportunity to assess the dynamics of filling the entry with dangerous gas, to assess the proximity of its concentration to the threshold value, which will allow neutralizing the danger in advance.

Conclusions. It is indicated that the methodology of information systems of technological safety of mining facilities should be based on the peculiarities of planning and operational control of production activities, the need for providing and analyzing information in a spatial form, and the tasks of integrating local subsystems into a single information system of the enterprise.

The following key problems of technological safety of mining facilities are singled out: prevention of salvo emissions of hazardous gases and warning of gradual accumulation of hazardous gases in the atmosphere of mining workings. In addition to the flow of information about the condition, operation and accidents of mining equipment, the above said also determined the need to form data flows of spectrometric sounding of rocks and from sensors of the gas environment of underground workings: mobile individual sensors of miners and stationary entry sensors with built-in verification and calibration modules. It is indicated that it would also be expedient to equip the miners' mobile individual sensors with recorders of human physiological indicators. Then, the relevant and operational determination of the state of fatigue of miners will reduce the accident rate of mining enterprises. It is indicated that monitoring and detection of fatigue will also require modern machine learning methods for processing and analyzing data from recorders of human physiological indicators.

The block of prevention and neutralization of the danger of salvo emissions of dangerous gases into the atmosphere of underground workings requires not only spectrometric sounding of rocks, but also intelligent data analysis to determine the spatial distribution of ore bodies and to detect gas traps. The next step of analytical processing of spectrometric rock sounding data should be operational planning of mining operations to avoid the danger of salvo emissions of harmful gases into the mine atmosphere.

The need to control the gradual accumulation of gases in the atmosphere of coal mines is due to the fact that coal is a good sorbent of harmful gases, for example, methane. The task of assessing the gradual accumulation of gases is complicated by the peculiarities of the laying of underground workings and the uneven dynamics of air flows in them.

This led to the need to assess concentration gradients to prevent dangerous gases reaching threshold values in underground locations. It was also established that standard methods of statistical analysis are not suitable for estimating the average values of concentrations of dangerous gases. Therefore, a mathematical model based on the theory of fractals was developed. The specified mathematical model allows one not only to estimate the concentration gradients when filling the shaft with dangerous gas, to detect the proximity of the concentration to the threshold value and to neutralize the danger in advance, but also to estimate the number of necessary stationary sensors and non-stationary individual sensors of miners to ensure the appropriate level of probability of finding a sensor in each chamber of the underground mine.

A methodological system of directions for the implementation of informational measures for the technological safety of mining facilities was also formed. The use of the method of system analysis made it possible to indicate the synergistic effect of the complex implementation of directions for the realization of technological safety of information measures.

As a result of the establishment of requirements for information systems of technological safety of mining facilities, a project for the diffusion development of the architecture of the information system of technological safety of mining facilities was developed for the implementation of the principle of diffusion of information technology in the mining process of mining enterprises.

The practical significance of the proposed methodological approach is that it allows gradually forming an information system that will provide: early warning of danger; tracking the location of each miner; integrated monitoring of both geological structures that can form gas traps, and air control in the mine faces; implementation of an intelligent security loop using analytical resources; ensuring dispatching, forecasting and operational planning of the technological process of mineral extraction.

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Методологія створення й розвитку інформаційних систем технологічної безпеки гірничих об'єктів

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Мета. Розробити методологічні підходи до процесу інформатизації технологічної безпеки (ТБ) і запропонувати проєкт поетапного розвитку архітектури інформаційної системи (ІС) ТБ, що сприятиме ефективній інтеграції цифрових і гірничих технологій. Розробити математичну модель для знаходження кількості датчиків, необхідних для вірогідністної оцінки градієнтів концентрації небезпечних газів.

Методика. Використані загальні та спеціальні методи пізнання: структурного аналізу – для встановлення структури й задач ІС ТБ; логічного узагальнення – для формування методологічної системи напрямів інформаційних заходів ТБ; системного аналізу – для встановлення синергетичного ефекту комплексного впровадження вказаних напрямів; наукового абстрагування – для розроблення проєкту поетапного розвитку архітектури ІС ТБ; математичної формалізації – для розроблення математичної моделі оцінки градієнтів концентрації небезпечних газів і кількості датчиків.

Результати. Розроблено проєкт поетапного розвитку архітектури ІС ТБ гірничих об'єктів зі впровадження принципу дифузії, що дозволить вирішити комплекс питань, зокрема, інтегрального моніторингу небезпеки газового середовища підземних структур з виявлення газових пасток і перманентного визначення градієнтів концентрації небезпечних газів, реалізації інтелектуальної петлі безпеки з використанням аналітичних ресурсів технологічного процесу видобутку копалин. Сформована методологічна система напрямів дифузійної реалізації інформаційних заходів ТБ. Використання методу системного аналізу дозволило вказати на синергетичний ефект комплексного впровадження напрямів реалізації інформаційних заходів ТБ.

Наукова новизна. Розроблено проєкт поетапного розвитку архітектури інформаційної системи технологічної безпеки гірничих підприємств. Розроблена математична модель оцінки градієнтів концентрації небезпечних газів і кількості датчиків для забезпечення належного рівня вірогідності знаходження датчика в кожній комірці підземної виробки.

Практична значимість. Методологічний підхід дозволяє сформувати ІС, що реалізує комплексний підхід до забезпечення належного рівня технологічної безпеки гірничих об'єктів.

Ключові слова: *методологічний підхід, інформаційна система, технологічна безпека, гірничий об'єкт, математична модель*

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