UDC 519.876.5:504.064.36

S. A. DERYABIN [1]*, head of the ACS department laboratory, deryabin.sa@misis.ru*
E. V. MISINEVA [1]*, assistant of the ACS department*
A. T. AGABUBAEV [1]*, head teacher of the ACS department*
U. A. RZAZADE [1]*, head teacher of the ACS department*

[1]*National University of Science and Technology–NUST MISIS, Moscow, Russia*

MODELS OF ENVIRONMENTAL SAFETY MONITORING IN THE MANAGEMENT OF PRODUCTION PROCESSES IN QUARRIES

Currently, the data obtained during the operation of mining enterprises are not sufficiently used to assess the pollution of the natural environment. In this regard, the purpose of this work is to improve the environmental safety of the functioning of mining enterprises by developing structural and functional schemes for the modernization of technological work management processes and integrating tools for assessing the dynamics of environmental conditions based on hybrid simulation methods and Industry 4.0 technologies. Within the framework of the work done, a structural and functional model of modernization of the technological process control scheme of open-type mining enterprises for dynamic assessment of the environmental condition of polluted territories was proposed, and a software implementation of the application was also implemented, which allows integrating the obtained results into the current information environment of mining enterprises.

Keywords: *hybrid simulation, environmental modeling, multi-agent approach, environmental safety, mining, digital transformation, Industry 4.0*
DOI: *10.17580/em.2022.02.19*

Introduction

At the moment, the mining industry plays a significant role in ensuring the vital activity and economic development of the country, however, the production activities of enterprises obviously affect the state of the biosphere [1–3] due to the energy consumption and high degree of waste of technological processes. At the same time, the development and implementation of various solutions aimed at implementing the digital transformation of mining enterprises within the framework of the Industry 4.0 concept can significantly increase the volume and scale of production processes [4], which, in turn, also increases the burden on the ecological state of the environment [5]. Elimination of the harmful impact on the environment today remains a key strategic task within the framework of sustainable economic development of the Russian Federation.

The relevance of studying problems and finding solutions in the field of rational nature management is confirmed by a large number of scientific papers [6–8]. Particular attention is paid to the development of new methods for rapid assessment of the state of the environment using remote sensing and the introduction of eco-resource-saving technologies [9, 10]. In particular, attention is paid to the issues of forecasting the state of the environment using machine learning and predictive analytics methods, which, in some cases, allow to determine with acceptable accuracy the general trends in the environmental situation in certain geographical zones [11–15].

However, from the perspective of mining enterprises, the proposed approaches to the study of the dynamics of the state of the environment cannot be called perfect, due to the complexity of interpretation of the results obtained and, in particular, due to the lack of formalized approaches and tools for their integration into the structural and functional schemes of operational management of technological processes and planning of mining operations. In this regard, the purpose of this work is to improve the environmental safety of the functioning of mining enterprises through the development of structural and functional schemes for the modernization of technological work management processes and the integration of tools for assessing the dynamics of the state of the environment based on hybrid simulation methods.

Structural and functional modeling of technological process control modernization schemes

Earlier in [16], we proposed a variant of assessing the dynamics of the ecological state of a mining region using a hybrid simulation model based on an agent-oriented approach with elements of system dynamics and discrete event modeling. The model was based on the interaction of polluting agents (open-pit mining enterprises) and environmental agents (individual geostructural units of the region) in the Moore space, on the basis of which an integrated assessment of the ecological state of the region was calculated. The state of the polluting agents was determined in the form of a quantitative assessment of the emissions of harmful substances into the atmosphere during the modal time, and the state of the environmental agents was determined by the parameters of dust transfer from the polluting agents. Thus, the mining region was presented as a geoinformation multi-agent system reproducing the dynamics of the ecological state in accordance with the intensity of the enterprises' activities.

The implemented model, in general, provided an opportunity for operational forecasting of the ecological state of the region for making decisions on enterprise management, but could not be fully integrated into the current process control scheme. This is due to a number of factors, namely:

- low predictive accuracy of the simulation model due to the complexity of formalizing the interrelationships of the transmission of harmful substances in such a macro-environment as a region, in which it is necessary to take into account a large number of parameters, many of which are stochastic in nature (wind speed and direction, atmospheric temperature, precipitation);
- lack of understanding of the specific impact assessment of a single enterprise and the possibility of individual adjustment of its key modeled parameters to find the best strategies for managing technological work and production planning;
- the need to change the schemes themselves for the implementation of technological work management by taking into account the inclusion of an assessment of the state of the environment in the form of an integral parameter regulating the intensity of production operations.

In this regard, we analyzed the generalized structure of the process management implementation scheme at open pit mining enterprises [17], according to the results of which a conceptual model for managing key technological works was proposed, taking into account the prediction of environmental changes in the DEAL 1.0 (Digital Enterprise

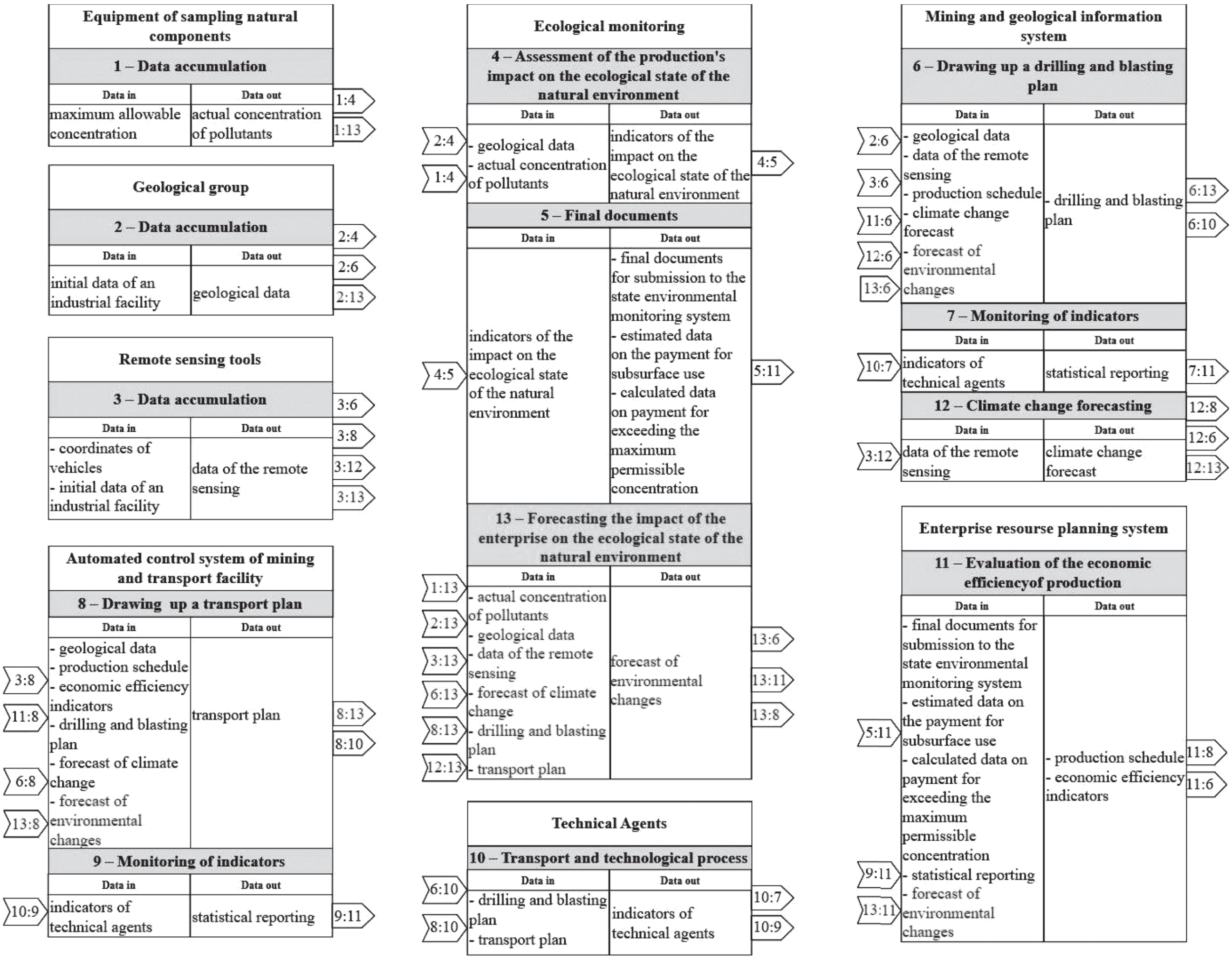

Fig. 1. Conceptual model of modernization of the generalized structure of the technological process control scheme in a quarry

Architecture Language) notation [18]. The formed conceptual model is based on the requirements for the integration of solutions from the field of Industry 4.0 for the digital transformation of enterprises [19], such as:

- representation of all technological processes and operations in the form of independent functional tasks implemented in the form of software and hardware microservices in order to build an autonomous production system;
- formalization of the interaction of such microservices as the process of information exchange on the principle of publishers and subscribers of data, carried out using service (infrastructure) software components – integration buses, message brokers, mappers, etc.

The proposed conceptual model (**Fig. 1**) assumes the formation of a functional microservice (tasks) for predicting the impact of an enterprise on the ecological state of the natural environment (Block 13), which uses:

- data on the actual concentration of pollutants produced by sampling means (Block 1);
- data on the mineral deposit obtained by the exploration group (Block 2);
- data received from remote sensing (Block 3);
- climate change data predicted on the basis of remote sensing data (Block 12);
- data on the planning of drilling and blasting operations (Block 6);
- data on the planning of transport and loading operations (Block 8).

Based on the results of processing the received data, the microservice calculates an estimate of the predicted environmental changes in the environment, transmitted in turn in the form of an integral parameter:

- into the contour of the automated control system of the mining and transport facility for the microservice of building an operational transport plan (Block 6);
- to the microservice for constructing a drilling and blasting plan for the contour of the mining and geological information system (Block 8);
- into the contour of the enterprise resource planning system for assessing the economic performance of production activities (Block 11).

In accordance with the developed structural and functional scheme of the organization of management of technological processes of open-pit mining, the following tasks were further set within the framework of this study:

1. Modification of the mathematical apparatus of the hybrid simulation model, taking into account the peculiarities of transport and technological processes during the development of the field by the open method.

2. Modification of the structure of solving the simulation problem, in which the central element is not the region as a whole, but a separate mining enterprise and adjacent territories with a regulated scale of coverage of the geographical area.

3. Software implementation of the model in the form of an independent module with a unified micro-service architecture, which assumes the possibility of integration into a generalized structural and functional process control scheme operating at enterprises.

Modification of the mathematical apparatus and structure of the hybrid simulation problem

In accordance with the objectives of this study, work was carried out to modify the mathematical apparatus and structure of solving the problem of simulation of the ecological state of the geospatial technological environment.

It is proposed to calculate the amount of pollutants entering the atmospheric air for a month during blasting operations, taking into account the characteristics of the explosives used and the cleaning equipment used, as well as the quality and quantity of the explosive rock, as follows:

$$M^E_i = M^E_{1i} + M^E_{2i}, \quad (1)$$

where M^E_{1i} – the amount of the *i*-th pollutant emitted with a dust and gas cloud during the production of an explosion, tons per month; M^E_{2i} – the amount of the *i*-th pollutant gradually released into the atmosphere from the exploded rock mass, tons per month.

$$M^E_{1i} = \Sigma^m_{j=1} q_{ij} A_j (1 - \eta), \quad (2)$$

where *m* – the number of brands of explosives (E) used during the month; q_{ij} – specific release of the *i*-th contaminant at the *j*-th explosive, tons per tons; A_j – quantity of detonated *j*-th explosive, tons per month; η – a dimensionless coefficient that takes into account the effectiveness of gas suppression devices used in an explosion.

$$M^E_{2i} = \Sigma^m_{j=1} q'_{ij} A_j, \quad (3)$$

where q'_{ij} – specific release of the *i*-th contaminant from the exploded rock mass, tons per tons.

The amount of dust released into the atmosphere during explosions is taken into account:

$$M^E_n = 0.16 q_n V_{rm} (1 - \eta) 10^{-3}, \quad (4)$$

where 0.16 – dimensionless correction factor used to account for the gravitational settling of solid particles within the section; q_n – specific dust emission, kg/m^3; V_{rm} – volume of the exploded rock mass, m^3/month.

Thus, the total increase in pollution during blasting operations per unit of model time was determined as follows:

$$M^E_{general} = M^E_i + M^E_n = M^E_{1i} + M^E_{2i} + M^E_n, \quad (5)$$

The unit of equipment operating during the development of the field is also characterized by emissions of pollutants and dust generated during the combustion of fuel, and excavators and dump trucks are an integral part of loading and unloading operations. The calculation took into account the volume and dust release of the overloaded and transported materials, the humidity of the material, the speed of wind gusts and the effectiveness of dust suppression means. In this regard, it is proposed to calculate the amount of dust emitted into the atmosphere during the operation of excavators per unit of modal time as:

$$M_{ex} = \sum_{j=1}^{n} q^{ex}_j V_j K_1 K_2 (1 - \eta) 10^{-6}, \quad (6)$$

where n – the number of brands of excavators operating during the month; q^{ex}_j – specific dust extraction with the material shipped by the excavator of the *j*-th brand, kg/m^3; V_j – the volume of material handled by excavators of the *j*-th brand, m^3; K_1 – dimensionless coefficient that takes into account the moisture content of the material; K_2 – dimensionless coefficient that takes into account wind speed; η – a dimensionless coefficient that takes into account the effectiveness of dust suppression means.

The amount of dust emitted into the atmosphere per month during the operation of dump trucks is proposed to be calculated as:

$$M_{dt} = \sum_{j=1}^{k} q^{dt}_j P_j K_1 K_2 10^{-6}, \quad (6)$$

where k – the number of dump truck brands that worked during the month; q^{dt}_j – specific dust release from the material transported by dump trucks of the *j*-th grade, tons; P_j – the amount of material transported by dump trucks of the *j*-th brand, tons.

The total increase in pollution during loading and unloading operations per unit of model time will be calculated as:

$$M_{ttp} = M_{ex} + M_{dt}. \quad (8)$$

In accordance with the above parameters, the overall estimate of the increase in pollution per unit of model time produced by the mining enterprise will be determined as follows:

$$dM_{n^*}/dt = M^E_{general} + M_{ttp} = M^E_{1i} + M^E_{2i} + M^E_n + M_{ex} + M_{dt}. \quad (9)$$

The increase in pollution for each agent that is part of a mining enterprise is presented in the following form:

$$dM_{i^*}/dt = (\Sigma^{n^*}_1 M^E_{general} + M_{ttp})/i^* = (\Sigma^{n^*}_1 M^E_{1i} + M^E_{2i} + M^E_n + M_{ex} + M_{dt})/i^*. \quad (10)$$

The remoteness of each non-pollutant agent from the pollutant agents is determined using a weighted sum of coordinate differences:

$$l = (\Sigma^{i^*}_1 \sqrt{M^E_{general}{}^2 + M_{ttp}{}^2})/i^*. \quad (11)$$

The assessment of the environmental condition of each agent has the following form:

$$e_i(t) = e_i(t - 1) + (1 - dt/dM_{i^*})/l, \quad (12)$$

where:

$$e_i(t) = \begin{cases} <1 \text{ – the agent is contaminated} \\ =1 \text{ – the agent is subject to contamination,} \\ <1 \text{ – the agent is not contaminated} \end{cases} \quad (13)$$

Thus, the overall environmental assessment of the state of the territories occupied by the mining enterprise and the territories adjacent to it is the sum of the ecological state of each section of territories divided by their number:

$$E = \Sigma^i_1 e_i/i. \quad (14)$$

Experimental modeling and results

The primary software implementation and experimental runs of the modified model to assess its operability were carried out in the AnyLogic simulation environment (**Fig. 2**), according to the results of which its functional viability was determined. The experimental data necessary for the operation of the model were set in the form of a random distribution of parameters using a triangular membership function [16].

In the future, due to the limitations of the possibility of using the AnyLogic environment to form a microservice, the source code of the mathematical apparatus of the model was unloaded and brought to the form of an independent software application. The AnyChart library was used to draw the results of the model. In particular, application programming interfaces were developed using REST API technology, unifying the possibilities of integration interaction of a microservice with operated automated and information systems at enterprises. In the future, it is planned to build the service in Docker-container in order to minimize labor costs for its deployment in the information environment of enterprises, as well as transfer the results to open access through the domestic GitFlic source code repository storage system.

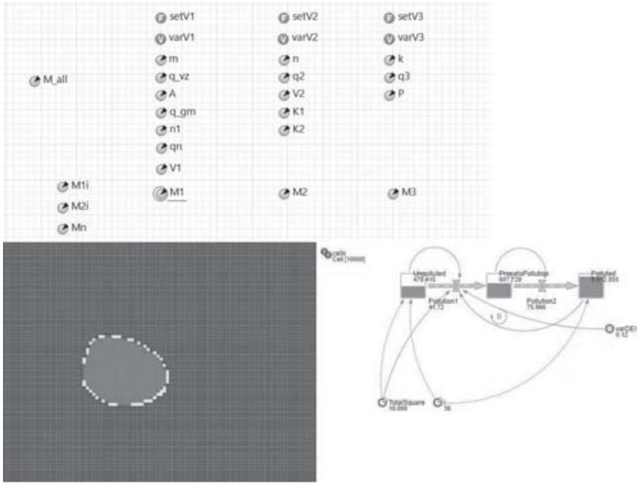

Fig. 2. An example of an experimental run of a hybrid simulation model

Conclusions

Thus, according to the results of the study, the following was achieved:

1. A structural and functional model of modernization of the technological process control scheme of open-pit mining enterprises is proposed, taking into account the dynamic assessment of the impact on the ecological state of the environment, as well as the requirements for the integration of Industry 4.0 technologies within the framework of the digital transformation of industry.

2. Work has been carried out to improve the proposed early approach for the dynamic assessment of the ecological condition of territories exposed to pollution from mining enterprises, including:

• modification of the mathematical apparatus of the hybrid simulation model, which allows to assess the dynamic impact of technological processes on the environment during operational management and planning of mining operations;

• modification of the structure of the solution of the simulation problem, which provides the possibility of integrating the results into the structural and functional schemes of the implementation of technological processes, including the software implementation of the application, which allows integrating the results into the current information environment of mining enterprises.

In the future, it is planned to continue research in this direction, during which the shortcomings of the results obtained at the moment will be taken into account, namely:

• expansion of the mathematical apparatus of the model by including additional factors of the impact of enterprises on the environment, as well as natural phenomena that neutralize or enhance such an impact;

• inclusion of geoinformation tools for the restoration of the surface terrain in the structure of the problem solution;

• conducting experimental modeling with real statistical data on the activities of mining enterprises, during which the parametric relationships of the simulation model will be calibrated or modified in order to improve its predictive ability.

References

1. Bazarova S. B. Impact of mining on the ecosystem of the region and the assessment of the effectiveness of their environmental performance. *Regional economics and management: electronic scientific journal*. 2007. No. 2(10). pp. 60–70.
2. Golik V., Dmytrak Yu., Gabaraev O., Kozhiev K. Minimizing the Impact of Mining on the Environment. *Ecology and Industry of Russia*. Vol. 22, No. 6. 2018. pp. 26–29.
3. Tolvanen A., Eilu P., Juutinen A. et al. Mining in the Arctic environment – A review from ecological, socioeconomic and legal perspectives. *Journal of Environmental Management*. 2019. Vol. 233. pp. 832–844.
4. Sander R., Pan Z., Connell L. D. Laboratory measurement of low permeability unconventional gas reservoir rocks: a review of experimental methods. *Journal of Natural Gas Science and Engineering*. 2017. Vol. 37. pp. 248–279.
5. Khayrutdinov M. M, Kongar-syuryun Ch. B., Tyulyaeva Yu. S., Khayrutdinov A. M. cementless backfill mixtures based on water-soluble manmade waste. *Bulletin of the Tomsk Polytechnic University. Geo assets engineering*. 2020. Vol. 331, No. 11. pp. 30–36.
6. Chernyshova Y. S., Savelyev B. I., Solodov S. V., Pronichkin S. V. Applying distributed ledger technologies in megacities to face anthropogenic burden challenges. *IOP Conference. Series: Earth and Environmental Science*. 2022. Vol. 1069(1). 012028.
7. Rybak J., Adigamov A., Kongar-syuryun C., Khayrutdinov M., Tyulyaeva Y. Renewable-resource technologies in mining and metallurgical enterprises providing environmental safety. *Minerals*. 2021. Vol. 11, No. 10. 1145.
8. Trubetskoy K. N., Galchenko Y. P., Sabyanin G. V. Ecological evaluation of the production-induced change in the lithosphere. *Journal of Mining Science*. 2014. Vol. 50, No. 2. pp. 379–384.
9. Domingues Maria S. Q., Baptista Adelina L. F., Diogo Miguel Tato. Engineering complex systems applied to risk management in the mining industry. *International Journal of Mining Science and Technology*. 2017. Vol. 27, Iss. 4. pp. 611–616.
10. Patil G. P., Balbus J., Biging G. et al. Multiscale advanced raster map analysis system: Definition, design and development. *Environmental and Ecological Statistics*. 2004. Vol. 11. pp. 113–138.
11. Ruchkin V. N., Kolesenkov A. N., Kostrov B. V., Ruchkina E. V. Algorithms of fire seat detection, modelling their dynamics and observation of forest fires via communication technologies. *4th Mediterranean Conference on Embedded Computing (MECO 2015)*. Montenegro : IEEE, 2015. pp. 254–257.
12. Solodov S. V., Mamai I. B., Pronichkin S. V. Framing regional innovation and technology policies for transformative change. *IOP Conference Series: Earth and Environmental Science*. 2022. Vol. 981. 022007.
13. Khokhryakov A. V., Larionova I. V., Moskvina O. A., Tseytlin E. M. A system approach to environmental safety management in mining. *GIAB*. 2020. No. 3-1. pp. 501–517.
14. Korchagina T. V., Stepanov Yu. A., Burmin L. N. Method of environmental impact indicators assessment within coal enterprises footprint. *Ugol*. No. 8(1109). 2018. pp. 119–123.
15. Skorobogatov A. G., Ferezanova M.V., Mandych V. G., Sherbakov A. A. Modeling the transfer of toxic substances in water bodies. *Rossijskij himicheskij zhurnal*. 2007. Vol. 51, No. 2. pp. 74–76.
16. Deryabin S. A., Misineva E. V. Hybrid simulation modeling of ecological state of a mining region using a multi-agent approach. *GIAB*. 2022. No. 4. pp. 169–181.
17. Temkin I. O., Myaskov A. V., Konov I. S., Deryabin S. A. Construction and functioning of digital platform for transportation control in opencast mines. *Gornyi Zhurnal*. 2019. No. 11. pp. 82–86. DOI: 10.17580/gzh.2019.11.15
18. Deryabin S. A., Kondratev E. I., Rzazade Ulvi Azar Ogly, Temkin I. O. Digital mine architecture modeling language: methodological approach to design in industry 4.0. *GIAB*. 2022. No. 2. pp. 97–110.
19. Savelyev B. I., Solodov S. V., Tropin D. V. Formalizing and securing relationships on multi-task metric learning for IoT-based smart cities. *Journal of Physics: Conference Series*. 2021. Vol. 2094. 032062. EM