UDC 004.94

I. I. BELOGLAZOV [1], *Associate Professor of Department for Automation of Production Process Flows, Candidate of Engineering Sciences, beloglazov@spmi.ru*
P. A. PETROV [1], *Dean of Mineral Processing Faculty, Candidate of Engineering Sciences*
V. Yu. BAZHIN [1], *Head of Department for Automation of Production Process Flows, Doctor of Engineering Sciences, Associate Professor*

[1] *Saint-Petersburg Mining University, Saint-Petersburg, Russia*

THE CONCEPT OF DIGITAL TWINS FOR TECH OPERATOR TRAINING SIMULATOR DESIGN FOR MINING AND PROCESSING INDUSTRY

According to the top-priority trends and challenges in the mineral sector, and as per the mining science strategy, it is highly critical to arrange enhanced control, prediction and safety of production objects and their functioning for the preservation of automation sustainability. Improved control of databases, regulatory bonds, management, logistics and principles of sustainable development in mining makes it possible to reduce technological deviations and accidents at large mining and processing plants.

Most procedural violations and accidents in surface and underground mines occur because of the unskilled actions of process flow operators. Damage in this case can be considerable, especially as compared with the expenses connected with qualitative training and persistent development of personnel engaged with supervisory control and data acquisition for the efficient operation of SCADA-systems within the automation framework of mining and processing plants.

Definition of digital systems and their interrelation with multilevel automated control can be incorrect. The review of new principles can awaken interest in the conceptual assessment of digitalization processes using such notions as: numerical models, simulator, and artificial intelligence. Often applied formulations and principles of a digital model are substituted without justification of functional connections. On the other hand, a digital system today can be assumed as robotic lines and other numerical models and smart technologies, for instance, machining stations with numerical program control. It is necessary to define the practical significance of conceptual modifications and digital transformation regarding objects of the mineral sector, using Big Data; to understand how a digital twin can influence a changeable process situation; to provide prompt prediction; to eliminate an accident; and to preserve the physical balance in the whole production system. Such intelligent and flexible productions particularly need computer-based simulators and digital twins based on technologies of Industry 4.0–extended and virtual reality on the basis of digital twins. Digital twins allow maximal simulation of real-life activity of process flow operators. The skills acquired by personnel after such simulation training enable operators to master the optimized procedure for functioning in emergency situations in mineral mining and processing. This paper exemplifies the remote training and control of process flows, which is of concern in the current international situation.

Keywords: *mining and processing industry, digital twin, simulator, transformation, intelligent system, SCADA-system, production safety, training, extended reality, dynamic modeling.*
DOI: *10.17580/em.2020.02.12*

Introduction

Intelligent systems and smart technologies have become a reality in the mineral mining sector today, which requires reconsidering the engineering and mathematical modeling approaches to the development of new products and to the design of high-performance production lines, especially within a multifunction process system of the mining and processing plant [1–7].

The common and most effective method of operating personnel training is currently the computer-based simulation, which is an effective tool of preparing machine operators to function in routine, emergency and abnormal manufacturing situations [8, 9]. In all developed countries, the use of dedicated simulators is legislative for dangerous production objects (in mining and processing, in metallurgy, chemical industry, etc.). The Fourth Industrial Revolution requires a higher standard of knowledge to implement progressively complex processes on the next level of equipment–automation–human-being interaction. The new principle of operation of technological objects should become a day-to-day tool for any engineer in the case of any product during its whole life, in order that the opportunities offered by Industry 4.0 are used to the full extent [10, 11].

Modeling is not a rare technology addressed exclusively in the case of creation of complex commercial products any more. Presently, modeling is an integral process in any novel R&D project and is called digital transformation in industry. Until recently, the application of modeling methods was limited to a single parameter: one discipline, one part, one project solution. Currently, many design options or technologies are studied at the level of solving of interdisciplinary problems in the mining industry. It is important that modeling is applied both at the stage of R&D and during the whole life of a product—starting from the identification of market demands and design of a prototype and finishing with satisfaction of the demand and recycling of the product. In other words, engineering modeling and digital twinning acquires wider applications owing to their positive effect on innovation, income growth, and concessionally for a final user.

Vividly used in multistage production, modeling improves its efficiency, economy, and flexibility. Assisted by remote Big data acquisition systems, analytics, and system simulators, engineers generate digital twins of facilities and objects with improved prediction of the remaining lives of structural components and optimized maintenance and repair. The use of simulation modeling with virtual systems and simulators is especially effective when it is impossible to utilize a physical object, or its inspection and operation are limited, especially in the conditions of confined areas of underground mines [12, 13].

Today, the digital twin technology is at its inception stage and is a component of Industry 4.0 including, among other things, smart production, global Internet of Things and Internet of Services networks, and large-scale cloud computing. Modeling becomes a part of the process in which a digital twin is tightly integrated into design and operation procedures alongside with artificial intelligence and machine learning.

Digital simulators

The systems of dynamic modeling and operator simulators are for a long time present on the market. In the last 5 years, such technologies as computer-aided calculation, software and analysis tools have been rapidly developed. Simulators are widely applied in many industries as a result. Simulators serve in the training of pilots, space men, and operators of A-plants. Simulators are operated at floating structures for mining, preparation, storage, and handling of hydrocarbons, at LNG terminals, at gas–liquid conversion plants, oil refineries, etc. The simulation techniques can be fruitfully applied in the mineral mining and processing industry.

In view of the onrush of technology, as well as the employment of high-performance computers and advanced software, toward the satisfaction of the steady rising demand on the part of consumers, it is necessary to develop a new interactive environment for computer-based simulators including detailed modeling of real-time process flows included in production. The use of such an approach and special-purpose virtualization software can help solve such urgent problems as modeling and production of possible process flow scenarios. Such systems of safe learning, using contextual information and digital models of full immersion provides operators with real professional competences in the solution of off-nominal situations and in the prevention of adverse process flow conditions caused by industrial or anthropogenic factors [14–17].

The main problem in mine personnel training is the impossible intervention of the learner into a flow process. From the experience gained in personnel training and refresher courses, it can be stated that the learning process is either unbound with a real-life process flow and the skills are inapplicable at the workplace, or the learning process is passive and a trainee can only watch how a master or an instructor acts. By expert estimates, the latter method is extremely ineffective, takes much time, and, the worst of it, neglects off-normal and emergency situations typical of the mining and chemical industries [18, 19].

After proforma training, unexperienced operators can either break a process flow without high consequences, at best, or, at the worst, can cause a serious accident, with injuries and deaths at operating mines or chemical plants [20]. Therefore, it is required to use dedicated learning technologies and means capable to comprehensively simulate an operator’s workplace process flow or a user’s interface.

Such digital models in combination with technical facilities (simulators) represent a unified personnel training system, both in routine mode and in emergency situations, without hazard to process flows (**Fig. 1**). The information simulator requirements consist in simulation of process equipment, modeling of physicochemical processes, accurate implementation of control at operator’s stations, training in various modes regarding real or model time, and planning of training scenarios.

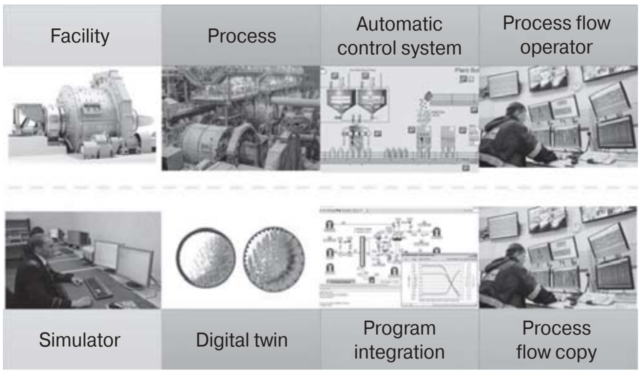

Figure 1. Example of the simulation system combined with process flow

Efficiency of computer-based simulators is in many ways governed by the knowledge and skills of specialists in the field of technology and process flow control, by personnel qualification, as well as by the implementation, operation and maintenance of simulators [21].

Digital twins for mining and processing plants

Digital twins in mineral mining and processing are for the first turn intended for experimentation not with a process flow or equipment but with a more convenient representation – a digital model. Furthermore, the problem connected with the training of process engineers and operators at the mining and processing plant is solved concurrently through the use of the digital model as a simulator. Computer-based simulation systems (CSS) are meant for personnel training and qualification validation in computer-aided manufacturing.

One of the top-priority targets of digital systems for mines is the analysis of dynamic parameters within a process flowchart. By way of illustration, we can discuss the process stage of milling – the most energy-intense process in mines. Nowadays, considering the critical nature of process efficiency, reliable and high-capacity crushing and milling methods are in the spotlight of major business players.

Dynamic modeling of the grinding process in drum mills, for instance, enables the implementation of the drum rotation speed control with a view to optimizing the existing process of milling. The benefits connected with reliability, complex function, with reduced wear of mill elevators and with maintenance can be reached using the advanced technologies of variable speed drives and dynamic modeling. Introduction of such systems can put the milling process at the next level of higher capacity and profitability [22, 23].

The major question to be answered by each production design engineer is: how to get the maximal profit in drum milling? Such parameters as water flow rate, size, and number of balls, or material feed can be adjusted so that to optimize the milling chain output. However, such adjustment always takes much time, assuming the use of a process installation while setting and inducing wear or downtime of equipment. Thus, the parameters which can be adjusted to the maximal efficiency of milling usually remain unchanged. In the meanwhile, such parameters can be varied easily, without extra time or problems connected with wear. The milling process mainly depends on the velocity of a mill, which conditions the type of the mill feed and has a direct influence on the

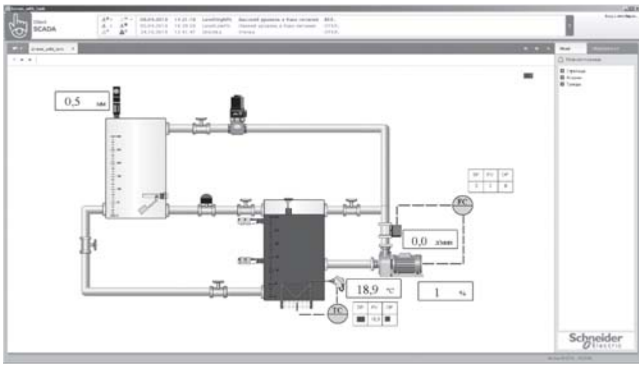

Fig. 2. Operator's display

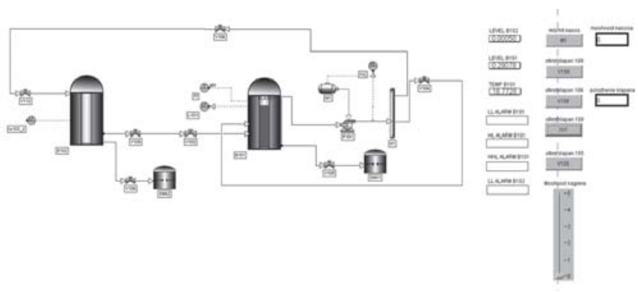

Fig. 3. Trainer's display

process variables such as fracture velocity, bulk discharge, and mill capacity. Finally, the size of the output product and, accordingly, the mill efficiency change. A digital twin of semi-autogenous mill includes a few stages and is implementable using dedicated programs [24–28]. Later on, the obtained results can be sent to the environment of dynamic modeling of process flows.

Dynamic modeling

An example of dynamic modeling is the simulator based on Schneider Electric software and designed at the Mining University. As an advantage of the simulator, operators are trained in the mode of accelerated simulation and in the real-time mode [29, 30]. This contributes to skills to operate in emergency situations. In case of an emergency, a number of preset scenarios should be executed, which allows the experience of behavior in off-normal situations [31].

The master environment was selected as DYNSIM as a practically approved and integrated dynamic modeling software which allows a user to handle the tasks of engineering and safe operation of modern process plants. The systems of dynamic modeling of process flows in DYNSIM are described in [32–34].

By combining the in-built equipment models with precise thermodynamics models of control elements and electrical models, DYNSIM enables the simulation of different process installations, including control system, shutdown lockout and power supply. Moreover, DYNSIM can [35–37]:

- add equations and other user's objects;
- add different libraries and equations of reaction kinetics;
- develop special control modes for a process plant.

The presented CSS simulates the simplified process of thickening and filtration. The main operator's display shows

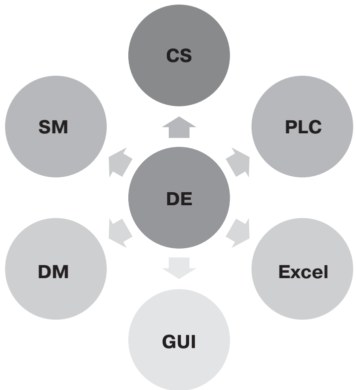

Fig. 4. Modular dynamic modeling system:
DE — development environment; CS — control system; PLC — programmable logic controller; CUI — graphical user's interface; DM — dynamic modeling; SM — simulation models

a mnemonic diagram of the filtration with options of calling different pop-up windows for setting of controllers and effectors (**Fig. 2**).

Similarly, a trainer's station is switched-in (**Fig. 3**). A trainer's workplace is a set of tools for simultaneous administration and teaching of a few operators, and includes estimators of skills.

A trainer can simultaneously set the implementation of a process flow scenario with automated teaching exercises or with monitoring of teaching. In this mode, the actions of an operator are described using different estimators of efficiency scores or weights, and the trainer is capable of unbiased assessment of the operator's activity, following the operator's actions and administering the process of teaching.

The dynamic models of a process plant are integrated with the modeling program of the related control system. The main environment is the modular dynamic modeling software. The modular architecture allows the development of scalable integrated systems of operator's training packages [38].

The development environment, including executive dynamic modeling, can switch to different subprocesses such as simulation models, emulation models of control systems, emulation of programmable logic controllers, graphical user's interface, applications of outside suppliers (e.g., Excel) and many others [38, 39]. The whole system is united by the common environment which synchronizes data transfer (**Fig. 4**).

Concurrently, with the advancement of digital technologies, computer-aided simulators experience upgrading. Increasingly larger power computers and progressive software enable 3D visualization, extended and virtual reality, and interaction of different programs. Advanced technologies become more available and cost-efficient and ensure the correct operation of simulators in the complex production environment.

DYNSIM integrates with the Schneider Electric's PRO/II modeling program of stationary processes and includes modular thermodynamic principles, frameworks, and algorithms. Using the general architecture, the software is readily integrated with a variety of control systems, which offers a platform for engineering solutions, control adjustment and higher reliable software development, including operator's training [40, 41].

The information technology of the kind can substitute hardware elements of a real-life control system (process flow chart, controllers, computers) for program equivalents in the mining industry [42–45]. This, in its turn, can make it possible to create smaller-size, mobile, and simpler operating simulators.

Conclusions

Digital twin modeling is much more than a simple creation of an operator's board. This approach is critical in the optimization of control both in the mining and chemical industries. The data of measurements, statistics, and numerical modeling are the framework for machine learning. A set of unuted digital twins can be optimized within a unified control system.

Such technologies as virtual and extended reality for the visualization of project solutions and hidden elements of process flows help in the training of personnel and in the enhancement of labor safety as they offer visual presentation and literally let trainees and operators into a real-life process flow or a production object while being remote and inside training rooms, which is of special concern at present.

It is a necessity of today to introduce digitalization in the mineral mining and processing industry. Management of many mining companies realize that digital technologies can bring actual advantages and profits. The concept of digital transformation enables advanced technologies to stimulate the transparency and earning power of a real sector of economy. This happens owing to the virtualization of business systems, visualization of data and knowledge on resources (mineral, equipment, labor), updating of data in real time, improvement of project solutions, and smooth control, as well as analysis and automation of managerial decision-making.

For the efficient and economic operation of new equipment, the current systems of personnel training and development are insufficient. In this case, the spotlight is on the skills of an operator in control over a specific process or equipment, while such skills can be independent of the qualification, theoretical knowledge, and work experience of the operator.

The solution to this problem is the engineering of a training set based on a mathematical model which is maximally similar to a real-life object.

The use of computer-based simulation can greatly improve the practical knowledge and skills of university graduates, young specialists, and personnel in the field of mineral mining, which, in its turn, can essentially enhance production safety. Qualification of engineers certified based on their operation results in computer-aided simulation can be acknowledged in all countries of the world. The urgency of such highly professional certification of specialists, especially those who recently obtained diplomas of higher education, is governed by the heavy deficit of skilled personnel in the mining industry, especially considering the exclusive standards of production safety.

It has been proved that digital twins based on numerical modeling and modern software are applicable in any industry: transport, power engineering, production, aviation, etc. Some companies are already saving millions of dollars through the integration of information, digital modeling, simulation platforms, cloud technologies, and machine learning.

References

1. Availabe at: http://static.government.ru/media/files/WXRSE-Bj6jnRWNrumRkDakLcqfAzY14VE.pdf (accessed: 27.03. 2020)
2. Available at: http://www.garant.ru/products/ipo/prime/doc/70484380/#ixzz4aP1zXHhy (accessed: 27.03.2020)
3. Available at: https://spmi.ru/sites/default/files/imci_images/univer/bloks/napr_iiul_2019_s.pdf (accessed: 27.03. 2020)
4. Litvinenko V. S. Digital Economy as a Factor in the Technological Development of the Mineral Sector. *Natural Resources Research.* 2019. Vol. 28, Iss. 28. pp. 1–21.
5. Litvinenko V. S.The Role of Hydrocarbons in the Global Energy Agenda: The Focus on Liquefied Natural Gas. *Resources.* 2020. Vol. 9, Iss. 59. DOI: 10.3390/resources9050059
6. Berman S. Digital transformation: Opportunities to create new business models. *Strategy & Leadership*. 2012. Vol. 40, Iss. 2. pp. 16–24.
7. Gukovskiy Y. L., Sychev Y. A. and Pelenev D. N. The automatic correction of selective action of relay protection system against single phase earth faults in electrical networks of mining enterprises. *International Journal of Applied Engineering Research*. *Research India Publications*. 2017. Vol. 12, Iss. 5. pp. 833–838.
8. Rylov S. A., Sofiev A. E., Tarakanov Yu. V. Mobile computer-based simulator for training process flow operators. *Pribory*. 2010. No. 3. pp. 19–24.
9. Dozortsev V., Nazin V., Oboznov A., Mironova A. Structural knowledge as an evaluation instrument of trainess progress in learning. *11th IEEE International Conference on Application of Information and Communication Technologies*. 2017. Vol. 2. pp. 275–279.
10. Alvarez A., Fernandez E., Prokofeva E. N., Vostrikov A. V. The building of effective systems of training and development for mining engineers with the basis of digital technologies. *Eurasian Mining*. 2019. No. 1. pp. 49–52. DOI: 10.17580/em.2019.01.12
11. Gurskaya T. V., Krasavin A. V., Fedorova S. V., Khudyakov P. Y. Practice-oriented approach to mining engineer training. *Gornyi Zhurnal*. 2018. No. 2. pp. 97–103. DOI: 10.17580/gzh.2018.02.14
12. Dozortsev V. M., Kreidlin E. Y. State-of-the-art automated process simulation systems. *Automation and Remote Control*. 2010. Vol. 71, Iss. 9. pp. 1955–1963.
13. Dozortsev V. M. New Challenges to industrial safety — Will computer simulators help? *Bezopasnost' Truda v Promyshlennosti*. 2019. No. 9. pp. 31–38.
14. Corbetta M., Grossmann I. E., Manenti F. Process simulator-based optimization of biorefinery downstream processes under the Generalized Disjunctive Programming framework. *Computers & Chemical Engineering*. 2016. Vol. 88. pp. 73–85.
15. Alekseenko V. A., Pashkevich M. A., Alekseenko A. V. Metallisation and environmental management of mining site soils. *Journal of Geochemical Exploration*. 2017. Vol. 174. pp. 121–127.
16. Pashkevich M. A., Petrova T. A. Development of an operational environmental monitoring system for hazardous industrial facilities of Gazprom Dobycha Urengoy. *Journal of Physics: Conference Series*. 2019. Vol. 1384. pp. 1–7.
17. Koptev V. Y., Kopteva A. V., Improving paraffin deposits detection methodology for better ecological safety during

hydrocarbon transportation. *International Journal of Applied Engineering Research.* 2017. Vol. 12(5). pp. 618–621
18. Katuntsov E. V., Kultan Y., Makhovikov A. B. Application of electronic learning tools for training of specialists in the field of information technologies for enterprises of mineral resources sector. *Journal of Mining Institute*. 2017. Vol. 226. pp. 503–508. DOI: 10.25515/PMI.2017.4.503
19. Dozortsev V. M. Computer-based simulators for training process flow operators. Moscow : SINTEG, 2009. pp. 29–31, 42–44.
20. Sganzerla C., Seixas C., Conti A. Disruptive Innovation in Digital Mining. *Procedia Engineering*. 2016. Vol. 138. pp. 64–71.
21. Rylov S. A., Sofiev A. E. Applicaton of Virtual Machine Technology in engineering of computer-based simulators for training of process flow operators. *Pribory.* 2020. No. 5. pp. 22–25.
22. Skorych V., Dosta M., Hartge E.-U., Heinrich S. Novel system for dynamic flowsheet simulation of solids processes. *Powder Technol*. 2017. Vol. 314. pp. 665–679.
23. Vasilyeva N. V., Nikitina L. N. Using Modern Technologies in Research Complexes and Laboratories of Saint-Petersburg Mining University for Improving the Preparation Efficiency of Specialists in the Mining Industry. *IOP Conference Series: Materials Science and Engineering.* 2020. Vol. 753. DOI: 10.1088/1757-899X/753/6/062031
24. Monov V., Sokolov B., Stoenchev S. Grinding in ball mills: Modeling and process control. *Cybernetics and Information Technologies.* 2012. Vol. 12, Iss. 2. pp. 51–68.
25. Cleary P. W., Owen P. Effect of operating condition changes on the collisional environment in a SAG mill. *Minerals Engineering*. 2018. DOI: 10.1016/j.mineng.2018.06.027.
26. Kiangi K., Potapov A., Moys M. DEM validation of media shape effects on the load behaviour and power in a dry pilot mill. *Minerals Engineering*. 2013. DOI: 10.1016/j.mineng.2013.03.025.
27. Cleary P. W., Owen P. Effect of particle shape on structure of the charge and nature of energy utilisation in a SAG mill. *Minerals Engineering*. 2019. Vol. 132. pp. 48–68.
28. Beloglazov I. I., Stepanyan A. S., Feoktistov A. Yu., Yusupov G. A. Disintegration process modeling for a jaw crusher with complex jaws swing. *Obogashchenie Rud*. 2018. No. 2. pp. 3–8. DOI: 10.17580/or.2018.02.01.
29. Savchenkov S. A., Nikitina L. N., Bazhin V. Y. Experience of mining specialists training at the chair of process and production automation of the mining university. *Eurasian Mining.* 2017. No. 1. pp. 42–44. DOI: 10.17580/em.2017.01.11
30. Voronina M. V., Tretyakova Z. O., Krivonozhkina E. G., Buslaev S. I., Sidorenko G. G. Augmented Reality in Teaching Descriptive Geometry, Engineering and Computer Graphics – Systematic Review and Results of the Russian Teachers' Experience. *Eurasia Journal of Mathematics, Science and Technology Education*. 2019. Vol. 15, Iss 12. DOI: 10.29333/ejmste/113503
31. Dong P., Shi L. Emergency pressure relief simulation of diesel hydrogenation unit. *Petroleum Refinery Engineering*. 2019. Vol. 49, Iss. 11. pp. 55–59.
32. Available at: https://download.schneider-electric.com/files?p_enDocType=Customer+success+story&p_File_Name=SuccessStory_SE-LIO-SimSci_Intermountain-Power_11-16.pdf&p_Doc_Ref=Intermountain_Power (accessed: 27.03. 2020).
33. Dave D., Arnold W., Timothy S., Reed M. Dynamic simulation studies for boiler draft. *Applied Thermal Engineering*. 2017. Vol. 121. pp. 255–293.
34. Gani R., Soerensen E. L., Perregaard J. Design and analysis of chemical processes through DYNSIM. *Industrial & Engineering Chemistry Research*. 1992. Vol. 31, Iss.1. pp. 244–254.
35. Corbetta M., Grossmann I. E., Manenti F. Process simulator-based optimization of biorefinery downstream processes under the Generalized Disjunctive Programming framework. *Computers & Chemical Engineering*. 2016. Vol. 88. pp. 73–85.
36. Potapov A. I., Kulchitskii A. A., Smorodinskii Ya. G., Smirnov A. G. Evaluating the Error of a System for Monitoring the Geometry of Anode Posts in Electrolytic Cells with Self-Baking Anode. *Russian Journal Nondestructing Testing*. 2020. Vol. 56. pp. 268–274.
37. Slastenov I., Tasanbaev S., Dozortsev V. First principles simulation model identification based on real industrial process data. *21st European Concurrent Engineering Conference.* 2015. pp.11–14.
38. Marcano L., Haugen F. A., Sannerud R., Komulainen T. Review of simulator training practices for industrial operators: How can individual simulator training be enabled? *Safety Science*. 2019. Vol. 115. pp. 414–424.
39. Patle D. S., Manca D., Nazir S., Sharma S. Operator training simulators in virtual reality environment for process operators: a review. *Virtual Reality*. 2018. DOI: 10.1007/s10055-018-0354-3
40. Kluge A. The acquisition of knowledge and skills for taskwork and teamwork to control complex technical systems: A cognitive and macroergonomics perspective. Springer, 2014. 196 p.
41. Overchenko M. N., Marinin M. A., Mozer S. P. Quality Improvement of Mining SpecialistsTraining on the Basis of Cooperation Between Saint-Petersburg Mining University and Orica Company. *Journal of Mining Institute.* 2017. Vol. 228. pp. 681–687.
42. Litvinenko V. S., Tsvetkov P. S., Dvoynikov M. V., Buslaev G. V., Eichlseder W. Barriers to implementation of hydrogen initiatives in the context of global energy sustainable development. *Journal of Mining Institute*. 2020. Vol. 244. pp. 428–438. DOI:10.31897/PMI.2020.4.5
43. Boikov A. V., Savelev R. V., Payor V. A., Erokhina O. O. The control method concept of the bulk material behavior in the pelletizing drum for improving the results of DEM-modeling. *CIS Iron and Steel Review*. 2019. Vol. 17. DOI: 10.17580/cisisr.2019.01.02
44. Golubev V. O., Chistiakov D. G., Brichkin V. N., Litvinova T. E. Systems and aids of mathematical modeling of the alumina refinery methods: Problems and solutions. *Non-ferrous Metals*. 2019. No. 1. pp. 40–47. DOI: 10.17580/nfm.2019.01.07
45. Beregovoi D. V., Younes J. A., Mustafin M. G. Monitoring of Quarry Slope Deformations with the Use of Satellite Positioning Technology and Unmanned Aerial Vehicles. *Procedia Engineering*. 2017. Vol. 189. pp. 737–743. EM