Identification of Priority Areas of Digitalization of Underground Coal Mining to Enhance the Stability of Mining Regions

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Abstract. The study solves the problem of choosing the most promising, effective digital technologies to increase the sustainability of the development of coal enterprises that mine opencast mining. The classification of digital technologies for underground coal mining in four blocks is used. Specific technologies are subjected to expert evaluation by the method of medians of ranks with the control of the coefficient of concordance and the chi-square test. In geological exploration and mining planning, the most effective technologies are the use of drones, the compilation of 3D models of subsoil and work, and the formation of large data bases. For coal mining, priority technologies are a deserted mine, an intellectual mine, automated monitoring, mining and geological information analytics. In the direction of coal and waste processing, an expert assessment has not been agreed; priority technologies have not been identified. The research results expand the understanding of the impact of various digital technologies on the sustainable development of the coal industry and can be used by coal companies and authorities in the development of the technical policy of the coal industry.

1. Introduction

Improving the sustainability of the development of mountain areas is one of the main requirements for the modern development of mining, including underground coal mining. Underground coal mining causes significant risks for sustainable development: air pollution, including greenhouse gas emissions [1, 2]; increased risks of morbidity and mortality from diseases caused by dust pollution [3, 4]; injury and loss of life in open pit mining [5, 6, 7]; accumulation of past environmental damage during the mine operation and incomplete repair after the mine closure [8, 9]; reduction of non-renewable mineral reserves, irretrievable loss of coal in mining [10].

Traditional technological and organizational-economic methods of damage reduction, compensation of accumulated damage in the mining industry require large amounts of investments. For many countries and regions, they are not available and cannot be implemented at this level of economic efficiency and social responsibility. In addition, for many coal enterprises, the approach to reducing the risks of sustainable development “at the end of the pipe” is unacceptable in terms of
design solutions. Consequently, the existing technologies and means of reducing damage to true savings in the mining industry, in particular, underground coal mining, cannot provide a transition to sustainable development. We need fundamentally new solutions that reduce damage to the environment, the degree of risk, provide cost-effective processing of stocks. These principles are implemented in practice subject to the introduction of digital technologies for underground coal mining. The “Industry 4.0” methodology needs to be actively implemented in the coal industry.

The introduction of digital technologies of underground coal mining is being actively studied. For the regions of Russia, the experience of the Chinese mining industry is interesting, since it is closer in technical level than the USA, Germany or Australia. The main result of the twelfth five-year plan in China (2011-2015) was the introduction of intellectual mining technologies in the development of coal seams using long-column technology. In particular, unmanned shearsers controlled from the surface were introduced. This made it possible to reduce the number of underground workers in the clearing face from 30–50 to 5–7 people, and to increase production rates by 15–17% [11, 12]. At present, the Internet of Things technologies are being introduced in China’s coal industry to monitor the state of mining. Another method of improving security is digital technologies that allow tracking the location of personnel and quickly finding it in case of emergency situations [13, 14].

Another important area is the creation of digital models of processes occurring in mines, for example, digital flow sheets. In the Republic of South Africa, these digital maps allow you to accumulate and process a large amount of data that mining companies have not previously used. As a result, it is possible to more productively manage the main cost factors (geotechnology and geotechnological planning) [15]. A number of semi-smart mines have been built in India’s coal industry in recent years. They combine corporate information systems such as Enterprise Resource Planning and data from mining machines, sensors in the workings. Seeing the state of mining in real time leads to a significant increase in safety and productivity [16]. The development of the Internet of Things in a coal mine is largely based on the already existing information infrastructure - industrial Ethernet, 3G and Wi-Fi wireless networks, wireless sensor networks [17]. Thus, the availability of next-generation info communication infrastructure (4G, especially 5G) is not a prerequisite for the introduction of digital technologies in the mining industry.

The principles of Industry 4.0 can also be used to integrate into a single value chain the main mining enterprise and outsourcing partners [18]. This involves such an important aspect of sustainability as the balance of business interests and the development of human capital in the value chain. The advantages of the digital mine are in forming a complete information base in real time, the possibility of using unmanned or autonomous equipment, automating decision making and transferring working teams, predicting the state of the “mountain environment – technology” system [19-24]. This is directly related to the prevention of accidents and catastrophes, the most productive use of reserves with minimal losses (maximum production in specific mining and geological conditions). In the environmental aspect, digital technologies help prevent excessive emissions, determine the most productive areas of environmental investment.

A large variety of digital technologies that can be applied to improve the efficiency and sustainability of the coal industry, determines the scientific and practical task of identifying priority areas. This is a multi-criteria task, the solution of which requires taking into account the economic, environmental and social aspects of the impact of certain digital technologies on sustainable development. Therefore, the purpose of this article is to select priority areas for the digitalization of underground coal mining to increase the sustainability of mountain areas in Russia, such as the Kemerovo Region.

2. Materials and methods

The material for determining the priorities of the digitalization of the mining industry are the classifications of digital technologies that can be used in the coal industry (morphological box of options). The study used a classification developed by the Energy Research Institute of the Russian Academy of Sciences in 2018. Digital technologies allow us to form a multitude of options for their
use at the level of individual coal enterprises and regions. Therefore, it is necessary to compare the possible options among themselves according to the above criteria. The task of evaluating options is classical for the theory of control of technical systems. There are a number of methods for its solution, including clear and fuzzy, expert and rigorous quantitative. This study uses quantitative rankings based on expert estimates using the median rank method. The assessment of the consistency of expert opinions was carried out on the basis of the coefficient of concordance (the Kendal consistency coefficient). The choice of these methods is determined by the need to rank various digital technologies. This is more correct than assigning scores to them, since ranking is a simpler and less subjective task for an expert. The calculation of the coefficient of concordance is a standard procedure for checking consistency. When evaluating the statistical significance of the obtained concordance coefficients, Pearson's agreement criterion (chi-square, $\chi^2$) was used. The method of collecting information is a simple correspondence questionnaire. The number of experts – 12. The processing of the results of the expert survey was carried out in the program “Statistica 13.0” (module “Non-parametric statistics and distributions”).

### 3. Results and discussion

Table 1 presents the results of expert ranking of digital technologies for underground coal mining in the direction of “Exploration of reserves and mining planning”.

**Table 1.** The results of expert ranking of digital technologies of underground coal mining in the direction of “Exploration of reserves and mining planning”.

| Technologies                                      | Sum of ranks | $d$  | $d^2$ | Median of ranks |
|--------------------------------------------------|--------------|------|-------|-----------------|
| Using drones                                     | 27           | -45  | 2025  | 2               |
| 3D modeling of the geological environment during exploration | 24           | -48  | 2304  | 2               |
| Spatial planning solutions                       | 50           | -22  | 484   | 3               |
| Digital Internet Integration of Spatial-Time Data| 58           | -14  | 196   | 4               |
| Simulation and simulation                        | 72           | 0    | 0     | 5               |
| The use of satellite surveying systems           | 84           | 12   | 144   | 6.5             |
| Online planning and analysis                     | 74           | 2    | 4     | 6.5             |
| The combination of virtuality and reality        | 85           | 13   | 169   | 7               |
| Planning of working off autonomous production units | 96           | 24   | 576   | 9               |
| Environment of interactive well design           | 105          | 33   | 1089  | 10              |
| Curved mine field development                    | 117          | 45   | 2025  | 10.5            |

According to table 1, the coefficient of concordance is calculated, which is 0.569. The consistency of expert opinion is average. With this value of the concordance coefficient, the obtained estimates can be considered quite consistent. At the same time, the value of the concordance coefficient is statistically significant, since the Pearson's matching criterion was 68.3. In this direction of the assessment, there are 11 degrees of freedom. The tabular value of the chi-square test at a significance level of $\alpha = 0.05$ is 18.3. Therefore, the results of expert evaluation are statistically significant.

Priority areas for the introduction of digital technologies in the exploration of mineral resources and the compilation of mining plans are the use of unmanned aerial vehicles (drones) to obtain geological information, the compilation of 3D models of subsurface resources and work for the subsequent digitization of mining plans, the formation of large databases of mining information. In addition, at the stage of exploration and mining planning, it is most expedient to provide for the use of autonomous (unmanned) mining equipment. The complex of these technologies allows the first stage of digitization of the mining industry to be carried out most effectively. Technologies such as the curvilinear development of mine fields, an interactive mining planning environment are not rated as priorities. They can be seen in the long run.

Further, the study looked at digital technologies directly related to coal mining. The results of the expert assessment are shown in Table 2. The coefficient of concordance was 0.7. Consequently, the
consistency of expert opinion is high. The coefficient of concordance according to the chi-square test is statistically significant, since it is 151.27. The tabular value of this coefficient with 18 degrees of freedom and significance $\alpha = 0.05$ is 28.87.

**Table 2.** The results of expert ranking of digital technologies of underground coal mining in the direction of “Coal mining”.

| Technologies                                      | Sum of ranks | $d$  | $d^2$ | Median of ranks |
|--------------------------------------------------|--------------|------|-------|-----------------|
| Deserted recess                                  | 42           | -78  | 6084  | 2               |
| Integrated information management structure       | 45           | -75  | 5625  | 3               |
| Technologies of geodynamic, geomechanical, upper-air and technical monitoring | 46           | -74  | 5476  | 3.5             |
| Technologies of geoinformation support and automatic control system at mining enterprises | 51           | -69  | 4761  | 4.5             |
| Highly efficient coal mining technologies using flexible second- and third-generation robotic systems | 65           | -55  | 3025  | 5               |
| Cloud technologies                               | 61           | -59  | 3481  | 5               |
| Big Data Analysis                                 | 75           | -45  | 2025  | 7               |
| Digital modeling of geomechanical processes       | 98           | -22  | 484   | 8.5             |
| Integration of information technology systems     | 124          | 4    | 16    | 10              |
| Innovative technologies of physical, chemical, hydraulic, electromagnetic methods of rock destruction | 120.5        | 0.5  | 0.25  | 11              |
| Use of autonomous alternative energy sources      | 159.5        | 39.5 | 1560.25 | 13         |
| Robotic frontal units                             | 151          | 31   | 961   | 13.5            |
| Automation and robotization of workings based on geohods | 165          | 45   | 2025  | 13.5            |
| Mining technologies using high-performance self-propelled equipment | 168.5        | 48.5 | 2352.25 | 14         |
| Deserted coal mining with scraper circular robotic devices | 167          | 47   | 2209  | 15              |
| Automation of deserted auger notch                | 181          | 61   | 3721  | 15.5            |
| Downhole coal mining                              | 182.5        | 62.5 | 3906.25 | 15.5       |
| Innovative types of explosives                    | 178          | 58   | 3364  | 15.5            |
| Gamification processes and analytics              | 200          | 80   | 6400  | 18.5            |

These expert estimates suggest that the introduction of digital technologies in underground coal mining should begin with the creation of complete digital mining complexes. It is advisable to apply the following design solutions: deserted mine, intellectual mine, automated monitoring, analytics of mining and geological information. According to a set of criteria, design decisions on auger-mining and well production are considered less appropriate.

Further, digital technologies in the direction of "Processing of coal and industrial waste" were considered. The results of the evaluation are presented in table 3.

**Table 3.** The results of expert ranking of digital technologies of underground coal mining in the direction of “Processing of coal and industrial waste”.

| Technologies                                      | Sum of ranks | $d$  | $d^2$ | Median of ranks |
|--------------------------------------------------|--------------|------|-------|-----------------|
| The use of nanotechnology, biotechnology         | 51           | 3    | 9     | 5               |
| Production of deep processing                     | 52           | 4    | 16    | 5               |
| Technology of nanoporous sorbents                 | 62           | 14   | 196   | 5,5             |
| Pyrolysis (coking) of coals                       | 46           | -2   | 4     | 3               |
| Thermocoke technology                            | 39           | -9   | 81    | 3               |
| Production of waste                              | 31           | -17  | 289   | 2.5             |
| “Intellectual Factory”, focused on creating “smart” processes | 55           | 7    | 49    | 5               |
According to the results of expert evaluation, it was concluded that in these conditions, the correct ranking of technologies for processing coal and waste products is impossible. The coefficient of concordance is 0.16. Consequently, the consistency of expert opinion is low. The expert group did not come to a common opinion. Practically for each technology, the sum of differences of ranks is large, the sum of ranks differ slightly. Thus, there are large discrepancies in experts' estimates of various technologies.

This is explained by the fact that coal processing in the Kemerovo Region did not receive serious development, although attempts to stimulate it began in the 1990s. The products of coking, semi-coking, and hydrogenation of coal are not produced to date in quantities worthy of attention. Existing developments in the region to create carbon materials, in particular, sorbents, have not been brought to large-scale mass production. Therefore, the technology of deep processing of coal is perceived by the professional community extremely skeptical. Slightly higher marks were received only by the production of waste products.

At the final stage of the study, the efficiency of digital coal industry logistics technologies was evaluated. The results are presented in table 4.

Table 4. The results of expert ranking of digital technologies of underground coal mining in the direction of “Transport of coal and other goods”.

| Technologies                                               | Sum of ranks | d  | d^2  | Median of ranks |
|-----------------------------------------------------------|--------------|----|------|-----------------|
| Using navigation systems                                  | 24           | -18| 324  | 2               |
| Unmanned vehicles                                         | 21           | -21| 441  | 2               |
| The use of “smart” cars with on-board telemetry           | 35           | -7 | 49   | 3               |
| Use of cargo drone                                        | 44           | 2  | 4    | 4               |
| Complexes “intellectual transport and control centers”   | 60           | 18 | 324  | 5               |
| (information and management logistics structure)          |              |    |      |                 |
| Use of autonomous and alternative energy sources          | 68           | 26 | 676  | 6               |
| Checksums                                                 | 252          | -  | 1818 |                 |

Here, the consistency of expert opinion is quite high. The coefficient of concordance is 0.721. It is statistically significant, since the value of the chi-square test is 43.29, with a tabular value for 5 degrees of freedom and significance level α = 0.05 11.07. The most promising digital technologies for building logistics systems for coal enterprises are navigation systems and unmanned vehicles. It should be noted that they are already quite actively used in the coal enterprises of the regions of Russia, including the Kemerovo Region.

The advantages of these technologies (reduction of unlawful behavior, elimination of the problem of toxic personnel, increased operational control) became obvious to the owners and management. The closest prospects for the development of logistic systems in the coal industry are wagons with on-board telemetry and cargo unmanned aerial vehicles to replace traditional cargo transport when delivering material and technical resources to remote areas. Consequently, expert assessments of the effectiveness of various digital technologies made it possible to identify specific priorities in the areas of exploration and mining planning, coal mining and logistics itself. In the direction of processing coal and coal industry waste, expert judgment cannot be considered due to inconsistency. This is due to skepticism towards deep coal processing, and negative experience in implementing projects in this area.

4. Conclusions

The study allows systematizing the existing digital technologies of underground coal mining, ranking them by efficiency in the context of the sustainable development of the industry. The ranking of the most promising digital technologies is necessary for reasons of limited investment resources, the need for a comprehensive account of the economic, environmental, social aspects of various digital technologies.
Technologies were considered in four directions. For the three, agreed, statistically significant expert estimates were obtained (except for technologies for processing coal and coal waste). The most effective technologies for improving the sustainability of the coal industry (under the conditions of the Kemerovo Region) are the following. In the sphere of exploration of the subsoil and planning of work: the use of unmanned aerial vehicles for obtaining information, the compilation of 3D-models of the subsoil and work, while it is necessary to envisage the possibility of using autonomous mining equipment at the stage of mine operation. In the area of coal mining: the creation of unified intellectual mining complexes – a deserted mine, an intellectual mine, as well as automated monitoring, analytics of mining and geological information. In the field of logistics is the use of unmanned vehicles and navigation.

The results of the study provide additional information when justifying decisions on technical development, investment policy of coal enterprises. They can be taken into account by public authorities when developing measures for the strategic planning of the coal industry. Prospects for the study associated with a more detailed assessment of the consistency of opinions of a wider range of experts, the use of more complex productive methods for constructing complexes of mining digital technologies (for example, fuzzy assessments).

5. References

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