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Intensive underground mining technologies: Challenges and prospects for the coal mines in Russia

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Abstract
The article presents the key features of underground coal mining that influence the development of mining technologies and mining equipment design. It covers the most important challenges faced by underground coal mining companies and discusses growth areas in mining technology that are aligned with the paradigm of sustainable development. Using the example of underground coal mining operations, it illustrates such concepts as the intelligent mine and the invisible mine, discussing how they can be brought to life. It also shows how underground coal mining companies can improve their productivity, OSH management, and environmental indicators to make their products competitive. As mining operations are becoming more intensive and the average depth of mining is growing, which is accompanied by an increase in both methane emissions and risks associated with rock mechanics processes, it is becoming vital to accurately predict how the rock mass will behave and, by applying stress-strain analysis, to identify hazardous zones and their boundaries. The article discusses several mine layouts and how their parameters are adjusted to ensure intensive mining. Among the factors that hinder growth in coal production, it highlights the underutilisation of high-performance mining equipment. It also contains a list of key principles aimed at fostering production growth in the underground coal mining sector and improving its competitiveness.

Keywords
underground coal mining, sustainable development, longwall panel, productivity, mining equipment, downtime, risk management, intelligent mine, invisible mine.

Introduction

In terms of the reserves-to-production ratio, coal remains the most common energy resource in comparison with oil and natural gas, and, despite the general trend towards decarbonisation, the coal industry is still among the most important ones. According to the Statistical Review of World Energy by BP (BP Statistical Review of World Energy 2019, 2019), global coal production amounted to 8129.4 million tons in 2019 (an increase of 0.5% compared to the previous year). About 60% of coal is produced by the underground mining method, and the depth of mining is growing, which creates a more complex mining environment. In 2020, Russia produced 398.3 million tons of coal, including 102.9 million tons from 58 underground coal mines (Tarazanov, 2021). At the same time, competition is increasing in the global and regional resource markets, with coal prices heavily fluctuating. All this makes coal companies search for solutions to improve their underground mining operations. These factors also indicate possible growth areas in underground mining technology that can result in improving overall performance, workforce productivity, OSH management systems, and environmental indicators. The development of mining methods led to the emergence of longwall mining systems that are the most productive and promising ones in underground coal mining. However, the application of such systems is limited to medium and thick flat-lying coal seams. As flat or gently inclined coal seams, such seams become the primary target, with steeply inclined seams being left behind as there is no technology that could be used to mine them with the same level of productivity. At Russian coal mines in 2020 were operating 52 longwalls with an average daily production of 4,710 tons (Tarazanov, 2021).

The need to compete with the less costly open-pit mining method, especially in the area of steam coal mining, requires that underground mining costs should be dramatically reduced. One of the ways to increase production and improve economic performance at underground coal mines is to use state-of-the-art, powerful equipment for longwall mining (Meshkov et al., 2018), (Kopylov et al., 2019). The fact that it is possible to reach new heights in coal production has been proven by some coal mining companies breaking coal production records (Meshkov et al., 2018), (Kazanin et al., 2019). However, by analysing the experience of these companies in detail, it can be seen that their production figures and economic indicators fluctuate a lot, which, in our opinion, results from equipment underutilisation.

The purpose of this article is to provide a rationale for the development of the underground coal mining sector through unlocking the potential of longwall mining equipment. The article provides information about the current challenges and trends in the development of underground coal mining technology, shows the importance of a qualitative forecast of mining and geological conditions as well as the choice of layout and parameters of longwall panels and the organisation of production to ensure high productivity of longwalls.

Current challenges and trends in technology development

As a result of the growing demand in the global community for low-carbon, green economies, there has been an ongoing tightening of environmental standards regulating coal extraction, processing, and use. Current standards require that mining companies should minimise or eliminate their impact on the environment.

To sum up, underground coal mining is currently facing several major challenges:

- a decrease in demand for coal in the energy market;
- volatility of the coal market;
- competition with countries that have better conditions for reducing production and transportation costs and are more attractive to investors;
- competition with open-pit mining in the production of steam coal;
- more stringent environmental regulations.

To make the coal that is extracted by underground mining competitive and to develop the underground coal mining sector, it is necessary to tackle these challenges.

The Global Sustainable Development Report 2016 by the UN contains a number of general goals for the development of technologies by 2030 (Ioris, 2016):

- continuous improvement in industrial efficiency and resource consumption accompanied by the pursuance of economic growth without compromising the environment;
- striving for better performance through diversification, technology upgrades, and innovation;
- upgrading infrastructure and outdated technologies to make them sustainable, with increasingly efficient use of resources and greater adoption of clean and environmentally sound technologies and industrial processes.

Several trends in coal production reflect the movement towards these goals:

- Intensification of mining operations. This strategy implies reducing the number of working units and increasing their productivity, concentrating mining operations within one coal seam and one longwall, and using the single longwall layout where all the coal produced at the mine comes from one longwall supported by several development entries.

• Implementation of the intelligent mine concept. It involves the use of IT tools at all development stages starting from exploration and 3D modelling to designing and managing production processes, logistics operations, and support systems. A digital model of the deposit serves as a foundation for all subsequent mining operations. Geographic information systems, TBMs, shearers, hauling equipment fitted with location-tracking devices, and safety system sensors generate data flows that are processed and presented in a convenient and understandable form (for example, online analytics or risk assessment).

• Implementation of the invisible mine (green mine) concept. It implies that the mine has a minimum impact on the environment due to the use of zero-waste technologies that include the multipurpose use of ores, mining waste processing and disposal, and the use of underground voids for waste disposal.

The quality of the mining and geological conditions forecast

When mining flat-lying coal seams, several factors pose challenges to applying the longwall mining method: a large depth of mining (Gendler et al., 2020), mining-induced seismic hazards (Kovalsk et al., 2018), gas hazards (Kabanov, 2019), geological heterogeneity, high gas contents (Rudakov et al.,2016), thin seams (Zuev et al., 2019), spontaneous combustion propensity (Zubov, 2017), as well as conducting mining operations under natural and man-made objects such as water bodies, buildings, and structures (Meshkov et al., 2018). It should be noted that the number of factors hindering longwall mining operations ranges for each mine (Chemezov et al., 2019). Also, the number of such factors and the degree of their impact change significantly within the same mining panel with an increase in the depth of mining. This is why making accurate predictions of how the rock mass will behave, which includes applying stress-strain analysis, becomes of key importance in ensuring coal mining efficiency and safety.

To adequately utilise mining equipment and minimise the mining-related geodynamic risks, the mine layout should be divided into large blocks with a minimum number of faults, fractures, coal seam irregularities, and variations in roof conditions and rock mass properties. It is necessary to identify in advance the properties and the structure of the coal seam, those of the enclosing rocks, and the directions of major stresses.

Data covering the period from 2010 to 2019 on fifteen longwalls operated by SUEK-Kuzbass show that some high-production working faces are unstable in terms of monthly production (Fig. 1).

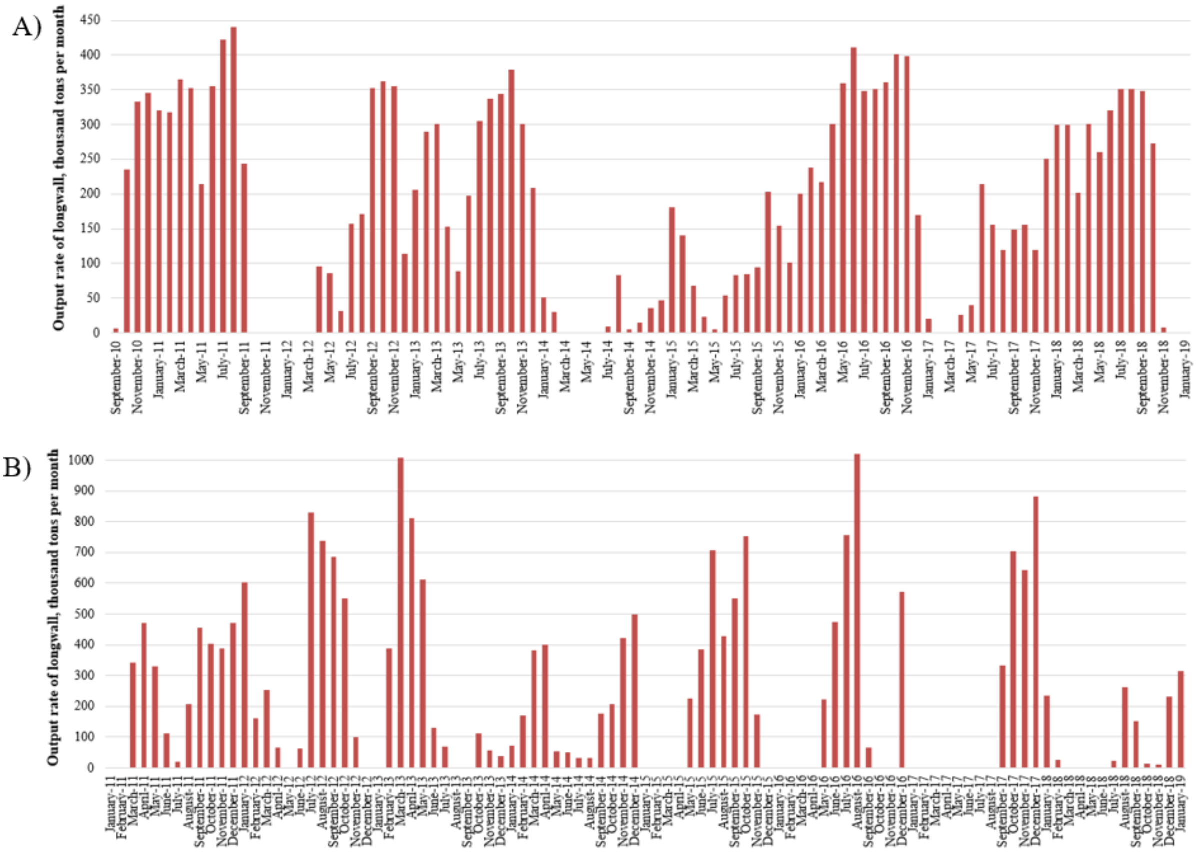

Fig. 1. Fluctuations in the output rates of longwalls: A) Taldinskaya-Zapadnaya-2 coal mine; B) Taldinskaya-Zapadnaya-1 coal mine

It is worth noting that in most cases, downtime and drops in output rates were caused by obstacles associated with rock mechanics processes that were not predicted at the design stage. As can be seen from Fig. 1, the average output rate was two times lower than the planned one, which caused significant economic losses.

Early detection of seismic event sources includes the following stages:

• identifying zones associated with geodynamic risks;

• developing the mine layout and planning mining operations based on the parameters of the identified zones;

• seismic monitoring and ongoing analysis of geodynamic risks;

• taking various preventive measures (for example, changing the mining sequence or adjusting the output rate) both on-site and at the regional level.

These procedures, including ongoing monitoring and forecasting geodynamic risks, should be carried out using modern instruments, software, and hardware and should be part of a multifunctional safety system at a coal mine.

The role of longwall panels layout for increasing the intensity of underground coal mining

The choice of a mine layout and longwall panel dimensions has a significant impact on production capacity. Currently, mining companies all over the world use different panel layouts (Figure 2). To save on costs associated with development operations, Layout A (Figure 2) can be used, which implies that a panel is outlined by two entries, and conveyor entries are later reused when mining an adjacent panel. However, difficulties associated with roof control and abutment stresses growing in the working area of the adjacent panel lead to a significant increase in resource costs and time spent to ensure safety at work, hindering intensive mining.

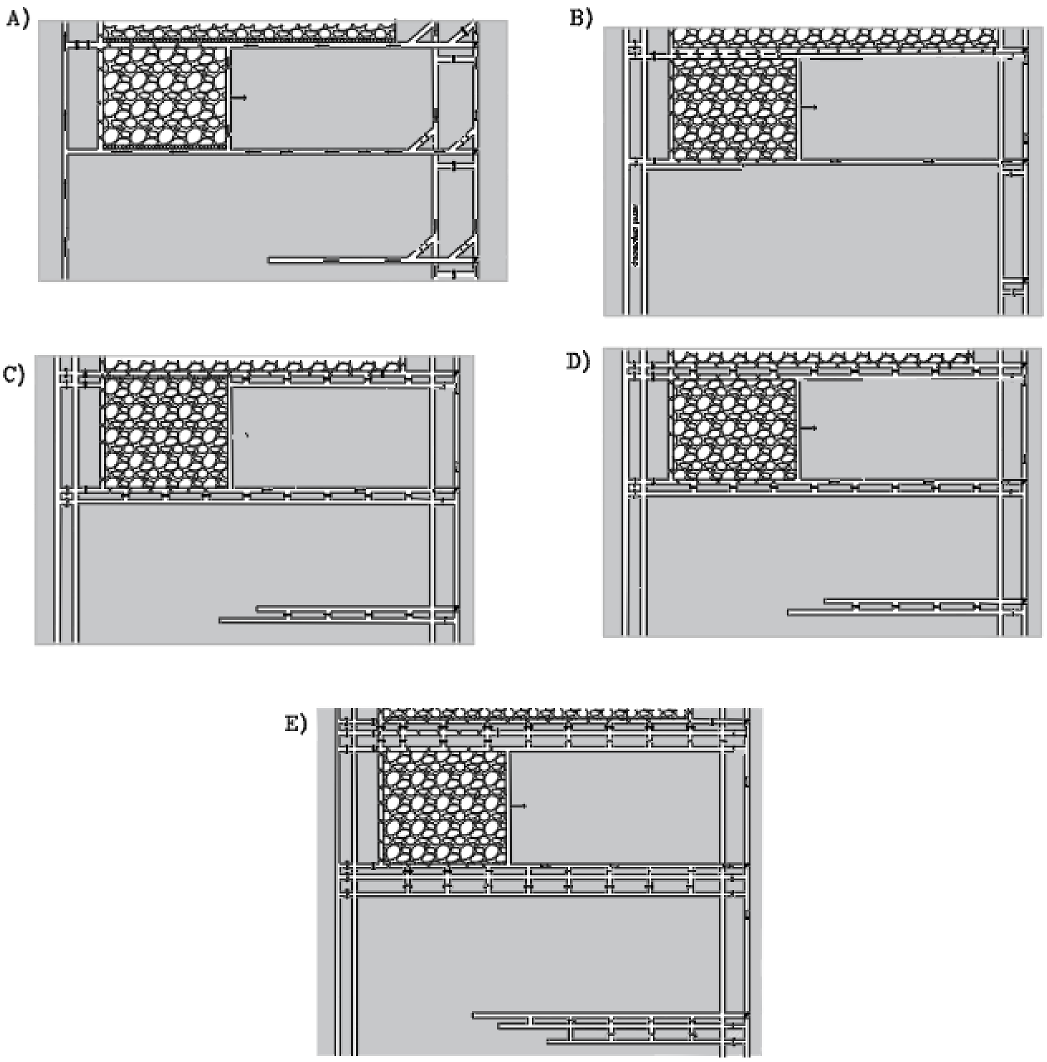

Fig. 2. The most common panel layouts in longwall mining

Layout B eliminates the need for entry support behind the working area, but it requires that one more entry should be driven and a narrow pillar should be left to mine the adjacent panel. The disadvantages of this layout include difficulties associated with support the extra entry protected by the narrow pillar and an increase in ventilation costs when driving a single entry. Consequently, this layout does not create conditions favourable for intensive mining. Layout C implies driving dual entries, leaving wide pillars that are later extracted. In this case, wide pillars provide favourable conditions for entry support in the adjacent area, and the use of dual entries facilitates ventilation operations in the course of development operations. However, pillar extraction worsens the working conditions near the gob, which leads to a decrease in both the advance rate and the intensity of mining operations, exposing miners to greater dangers.

Conditions that are favourable for increasing the intensity of longwall mining operations are created only with the use of two-entry (Layout D), three-entry (Layout E), and, less often, four-entry developments. Wide pillars minimise the impact of mined-out areas and create favourable conditions for ground control, as they make it possible to use roof bolts, which is the most flexible type of roof support. These layouts facilitate methane emission control in working areas, allowing for the use of the most effective ventilation designs, degassing methods, and methane drainage techniques and improve the quality of haulage operations.

Most of the longwall panels in the coal mines of Russia have a two entry layout (D), only a few – one entry (A).

The disadvantages of three- and four-entry developments include an increase in development costs and significant coal losses due to the use of pillars. However, such developments provide conditions for improving methane control and haulage operations by means of separating production and auxiliary operations.

It should be noted that in most coal-mining countries, two-entry developments are the most common, with the exception of the USA, where three-entry developments dominate (Longwall lead the way underground, 2020). As multi-entry developments have indisputable advantages, they can be recommended as the most promising ones for ensuring intensive mining. At present, transitioning to such developments is considered a promising option for the development of intensive coal mining practices in Russia.

The intensity of mining operations in longwall mining is greatly influenced by such parameters as panel length and panel width. When these dimensions increase, the number of assembly and disassembly operations decreases, which reduces the number of planned breaks. In addition, an increase in the panel width reduces the frequency of operations associated with reversing the cutting direction, thereby reducing operating time losses and development costs per panel.

A retrospective analysis of panel dimensions in the top coal-mining countries shows a steady upward trend accompanied by an increase in equipment dependability. For example, in the USA, the average panel width increased from 150 to 360 m over the period from 1984 to 2020. From 2005 to 2019, panel lengths in the USA also steadily increased, reaching a maximum value of 6,960 m (Peng, 2019).

However, this growth cannot be endless. We believe that the maximum possible dimensions that ensure a balance between costs and productivity growth have already been reached. These limits stem from the nonlinear relationship between costs and the effect produced by increasing the panel width. For example, an increase of 25% in the panel width leads to an increase of only 10 to 15% in the output rate, with an increase of 20 to 22% in equipment costs. Further growth in the panel width after reaching values of 400 to 450 m is restrained by a sharp increase in the cost of the armoured face conveyor (as a result of an increase in chain weight and the need to use special materials as well as more powerful drives) and the fact that a significant increase in capital costs and energy consumption associated with haulage in the working area results in an insignificant increase in the output rate (Figure 3).

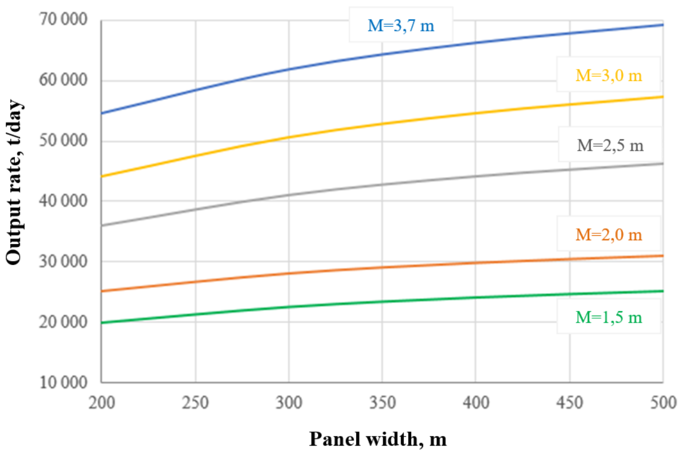

Fig. 3. The impact of the panel width on the output rate

As a result of high dependability indicators that are characteristic of modern mining equipment, panel lengths have grown significantly, in some cases reaching 7 or 8 km (Peng, 2019). Over their service lives, modern shearers produce 25 to 30 million tons of coal or more, longwall shields endure 40 thousand cycles, and armoured face conveyors transport 20 million tons of coal. Thus, when mining a 4-m-thick seam with a panel width of 450 m, the amount of coal within a panel with a maximum length of 8 km will be approximately 19.5 million tons. However, taking into account that maximum panel lengths are usually used in medium seams (with a thickness of up to 2.5 m) as they produce the greatest effect of reducing development costs per panel, the longest panels do not contain more than 15 million tons of coal, with the average values ranging from 7 to 12 million tons.

The reasons for equipment underutilisation in underground coal mining that has been identified indicate the following growth areas in production engineering through which mining intensity can be significantly increased:

- using multi-entry (three-entry) developments to improve methane control and create conditions for efficient haulage operations;
- assessing the feasibility of longwall panels dimensions (width and length) and increasing these dimensions if possible;
- developing an efficient mine layout aimed at improving methane emission control and ground control when mining adjacent coal seams (especially if geodynamic and methane risks are present);
- eliminating the impact of previously mined-out seams by coordinating mining operations conducted in separate seams;
- conducting preliminary degassing operations in mining areas and using stress-relief techniques in developing multiple coal seams containing methane;
- maintaining a reserve of time for panel development.

As high-performance mining equipment has become extensively used, average panel advance rates have increased. However, entries advance more slowly, with rates that are insufficient for the timely preparation of working areas (Yutyaev et al., 2017), (Kazanin et al., 2019). To provide for sufficient float time, it is rational to reduce the panel advance rate by increasing the panel width. As can be seen from Figure 3, an increase in the panel width from 300 to 400 m (i.e. by 33%) leads to an increase in the output rate of only 7 to 15% and a decrease in the advance rate of 18 to 26%. However, this method has its limits that have already been reached, and development operations lagging behind remains the main reason for equipment downtime. Consequently, some mines opt for conducting production operations only five days a week, which means that they can use the term “planned breaks” to describe their downtime periods, but it does not solve the problem.

In complex mining conditions, we believe that a prerequisite for sufficient float time that helps to eliminate equipment downtime is to improve planning efficiency by factoring in significant reserves of time or extra panel development operations that will compensate for actual performance rates lagging behind.

Methods for increasing the intensity of underground coal mining operations

As an analysis of technologies used by Russian coal mining companies has shown, there are at least three promising methods for increasing the intensity of underground coal mining operations: equipment upgrades, technology utilisation improvement, and process streamlining (Figure 4).

We believe that the utilisation of reliable and powerful equipment is the main condition for increasing the intensity of underground coal mining operations. However, it is often underutilised, with the equipment utilisation ratio not exceeding 25-32% (Kazanin et al., 2019).

The following reasons can be identified that cause equipment underutilisation (Figure 4):

- the imperfection of the technologies being utilised;
- complex mining conditions;
- the human factor.

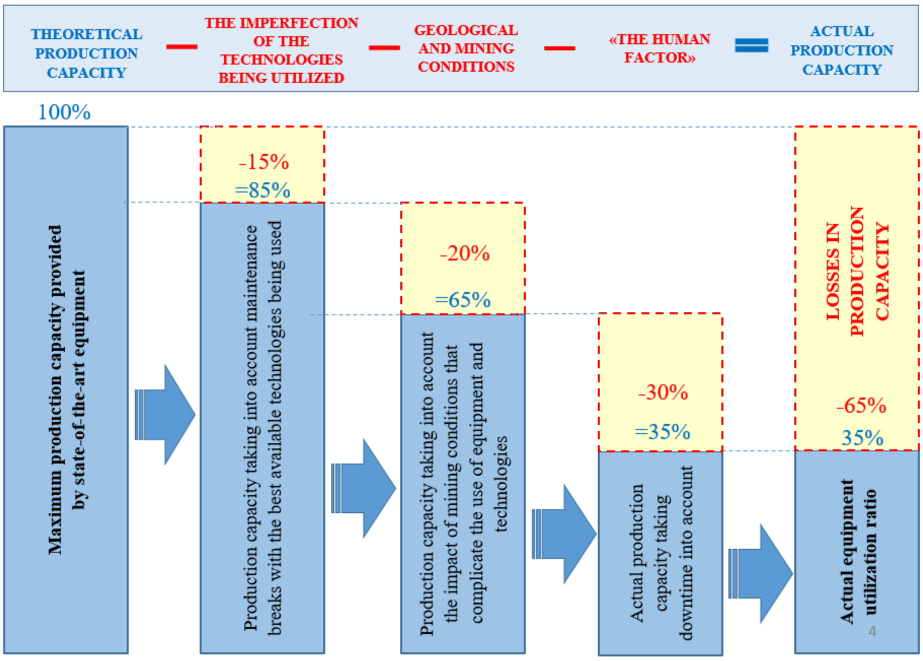

Fig. 4. The main reasons for equipment underutilisation

The imperfection of the technologies being utilised stems from the fact that their application ranges are limited, and their utilisation ratio is influenced by a number of factors (Ma et al., 2020), (Qiao et al., 2018) that reduce production capacity in particular mining conditions. As production at each mine is influenced by several factors and mining conditions can vary within one production panel, it makes it a nontrivial problem to choose the right technology solutions. The human factor means that decisions taken by the management have an impact on coal output. If their decisions regarding production engineering issues do not match the mining conditions, it makes production operations more hazardous even with state-of-the-art technology being used.

Longwall equipment utilisation

Modern shearers produced by the world's top manufacturers of mining equipment have power capacities ranging from 2 to 2.9 MW, with a dependability indicator of 0.98. Theoretically, their production capacity can range from 15 to 30 t/min when mining thin seams and from 60 to 108 t/min when mining thick seams. However, as a rule, the actual production capacity does not exceed 25 or 30% of the theoretical value.

The reasons for equipment underutilisation become clear after considering how the equipment is operated (Figure 5). Over a calendar year, significant amounts of operating time are lost due to planned breaks, downtime, and a decrease in production capacity even if production operations are streamlined, and the mining conditions are favourable (Brodny, 2019).

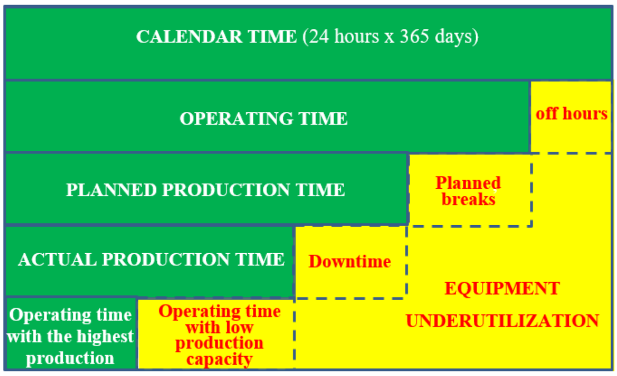

Fig. 5. Equipment operating time

The main reasons for planned breaks are associated with the specific features of the longwall mining method and its production and panel development operations, including longwall move operations (Gantry, 2013). Shearer downtime periods are associated with the following reasons (Kazanin et al., 2019), (Stebnev et al., 2017): auxiliary equipment malfunctions, faulty methane emission control (Palyanova et al., 2017), faulty ground control, and faulty production engineering.

Thus, an increase in the intensity of coal mining operations can be achieved by reducing planned breaks and downtime, using the best available technologies, and improving production engineering practices.

The specific features of underground coal mining operations make it necessary to modify the information technologies that are already available for open-pit coal mining. Modern systems for collecting, transmitting, processing, and storing information make it possible to analyse information flows that contain data on the location of workers and equipment and the parameters of various processes taking place in mines.

The application of information technologies in the mining sector is associated with the concepts of the intelligent mine and the digital twin, the use of which at both the design stage and the production stage will make it possible to predict changes in the conditions and indicators of coal production and, ultimately, to streamline mining operations, which will make it possible to achieve maximum output results and have the best possible economic, OSH, and environmental indicators.

If adequate mine models are to be developed, it should be noted that it is necessary to have a complete and accurate understanding of the processes occurring in both the mine workings and the rock mass affected by mining operations. First of all, gas hazards and rock mechanics processes need to be taken into account. Despite the fact that they have been studied and analysed for a long time, the existing models are simplified and describe these processes with sufficient accuracy only if the parameters and initial data are constant. However, the processes under consideration are not only non-stationary (as their parameters change vary in both time and space) but also periodic. In addition, the sharp increase in the intensity of underground coal mining operations that has been observed in the world over the past two decades makes it impossible to use the previously obtained data on various dependencies and patterns as the parameters have changed and the processes have become more intensive.

There are several software systems (Ansys, Abaqus, etc.) that rely on the principles of continuum and discrete mechanics. However, such systems usually serve single purposes, solve a particular class of problems, or find the parameters of processes that occur in a limited space and over a limited period of time, with the main input parameters remaining constant.

Further research is needed into gas hazards, and rock mechanics processes that mining engineers may deal with over the course of mine life. This will help to create adequate mathematical models that can accurately predict how non-stationary and periodic processes will develop in order to assess mine planning in terms of efficiency, safety, and rationality. As there are a lot of factors involved and the processes vary in time and space, this problem is complex and difficult to solve, which makes the application of the digital twin technology in the mining sector possible only in some distant future.

In our opinion, a more promising approach is to develop intelligent mines, which are self-learning information systems that can adequately respond to changes in operating conditions and the main process parameters at a mine. However, it should be noted that this concept has so far been applied only in the optimisation of individual mining processes.

An example of how the intelligent mine concept has been successfully implemented by Russian mining companies is the operations control centre at SUEK-Kuzbass, the main functions of which include:

- the automatic control of parameters, indicators, and characteristics of production facilities;
- displaying information on the operations to all the participants in the process;
- the automatic generation of emergency alarm signals;
- the automatic generation of reports, comparative analyses, and recommendations;
- collecting, standardising, and storing information in a convenient format;
- analysing and predicting process parameters;
- the continuous monitoring and archiving of all signals;
- granting data access based on a specific algorithm;
- distributing information by designated individuals within their jurisdiction.

The development of the operations control centre and the introduction of multifunctional safety and automation systems at SUEK began in 2010. Starting from 2010, the number of accidents at SUEK-Kuzbass has fallen by two thirds, while total coal production has increased by more than 34%, and the average daily output rate from one longwall face increased by 43%.

By introducing several technological and methodological solutions, SUEK secured the best longwall performance indicators in Russia, including the record set in August 2018 at the mine named after V.D. Yalevsky (1,627 thousand tons of coal per month).

Further development in this area is associated with the application of fully automated robotic equipment that will make it possible to extract coal without the constant presence of workers on site.

Conclusions

The global energy problem that is associated with the need to meet the ever-increasing demand for cheap energy resources makes coal a popular commodity even though there is a trend toward decarbonisation and switching to renewable energy resources. However, the economic crisis that the world is experiencing today led to a decrease in both demand and prices for energy resources, which poses a number of new challenges for underground coal mining companies as they have to compete with companies operating in other countries with more favourable mining and transportation conditions and comply with stringent environmental regulations. Overcoming these challenges is essential for the development of the underground coal mining sector and making its end products competitive in both local and international markets. It can be done only by improving the productivity of underground coal mining operations, which, in our opinion, can be achieved only by the efficient utilisation of modern mechanised equipment in mining flat-lying coal seams using longwall systems.

To maintain today's high advance rates and further increase the intensity of underground mining operations, it is necessary to observe the following production guidelines for Russian coal mines.

1) Intensive mining is possible only if the quality of coal reserves is high, which means that mining conditions should provide for coal extraction using longwall systems and state-of-the-art equipment. Factors that hinder the use of longwall systems include mining at depths exceeding 600 m, irregular coal seams, high gas contents of the seams being mined (over 15 m3/t), low seam thickness (less than 1.3 m), and conducting mining operations under such natural and man-made objects as water bodies, buildings, and structures.

2) The development and mining layouts used should create favourable mining and ventilation conditions for high panel output rates, i.e. the impact of mined-out areas on adjacent panels should be minimised, and the entries should be maintained for the whole period of extracting a panel. Production operations should be conducted, leaving chain pillars between longwall panels, the dimensions of which will depend on the depth of cover, seam thickness, and the presence of geodynamic hazards as well as gas hazards.

3) Longwall panel dimensions (length and width) should ensure that longwall move operations are kept at a minimum, with their number being calculated based on the cost, service life, and capacity of the production equipment. Panel widths and lengths recommended for intensive coal mining range from 300 to 500 m and from 4 to 8 km, respectively.

4) The number of development entries on each side of the panel depends on whether adequate ventilation and service operations can be provided. It is recommended to use two or three entries for intensive development. The exception is panels located on the edges that can be developed using a smaller number of entries.

5) Technological, organisational, and planning solutions aimed at ensuring the high intensity of mining operations should be selected based on the need to ensure the highest equipment utilisation rates possible. The ultimate goal is that shearers should operate 24 hours a day, 7 days a week at the highest capacity. The main problem to solve on the way to achieving this goal is finding ways to reduce downtime and planned breaks. Planned breaks stem from the need to carry out longwall move, ground control, and methane drainage operations. The reasons for downtime include development operations lagging behind, high gas contents, flooding, disruptions in transport and power supply operations, etc. To eliminate downtime, it is recommended to increase the number of entries on each side of the panel from two to three to create better conditions for transportation, methane emission control, and longwall move operations. To ensure that development operations do not lag behind (especially with an increase in the number of entries), it is necessary to factor in sufficient float time that will make it possible to start extracting new panels as scheduled. However, when striving for the highest production rates, it should be borne in mind that there are some limits that result from the need to find a balance between production costs and productivity.

Following these guidelines will ensure the high intensity and safety of underground coal mining operations, making them competitive and viable even when prices for coal and other energy resources are highly volatile. The presented results are consistent with the results of studies by other authors (Peng et al., 2019) with respect to longwalls.

The scope of application of the research results is limited to the underground development of shallow coal seams in favourable mining and geological conditions. Due to the increase in the depth of mining operations and the resulting increase in the methane content of the coal seams, the development of research is expected in the direction of improving the efficiency and safety of gassy coal seams mining during the transition to greater depths.

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