Approach to effectiveness evaluation of robotics technology in mining using discrete event simulation

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***Abstract*—**This paper reports the approach to effectiveness evaluation of robotics technology in mining which encloses the identification of both the technologies best prepared for the robotic automation in terms of their complexity and sources of the effectiveness of robotic technology via computer model simulations.

***Keywords*—**discrete event simulation, queuing system, robotic technology of mining, the effectiveness of robotics.

THERE are objective factors for the use of robotics in the technology of mining [1]:

1) The major share of manual labour in the mines is associated with the tunnel works where 36% of manual labour workers are engaged in installation of roof support, 25% - in delivery of roof support, 12% - in loading coal and rock, 10% - in blasting, 17% - in other works.
2) Working conditions in the tunnel faces are extreme for a human being. The amount of injuries caused by rock pressure increases with the transition to greater depths. Injury rate among underground workers is 4.4 times, and in deep mines 7.2 times, that on the surface. With the widespread introduction of mechanization the number of accidents connected with the operation of mining machines began to increase. High dust, humidity, temperature and pressure drop, noise and vibration in the workplace lead to occupational diseases.
3) The complexity of geological conditions of tunneling intensifies the objective contradiction of work in underground conditions. On the one hand, the complexity of tunneling requires greater human intervention in the process. On the other hand, the costs for safety and health precautions in the work area increase (fixing, airing, cooling, scheduled downtime).

An analysis of the achievements of the leading companies in the field of automation and robotics in underground mining has been carried out: Atlas Copco, GIA Industry, Sandvik (Sweden), Caterpillar (USA), Dyno Nobel (Norway), Normet (Finland), PAUS (Germany), Siamtek (Canada) [2]. The analysis has shown that all the proposals for robotics come down to commissioning of the robotic equipment such as drilling rigs, loaders, anchor-installers and chargers into technologies adapted for humans. However, many operations such as excavating the face, extending lines of communication, connecting the detonators, etc. cannot be performed by robots. As a result, the effect of commissioning of robots can be lost.

This approach concerns the effectiveness evaluation of robotics technology in mining which encloses the identification of both the technologies best prepared for the robotic automation in terms of their complexity and sources of the effectiveness of robotic technology via computer model simulations [3-7].

From the perspective of preparedness for robotics manufacturing operations can be divided into three groups: I - moving items between the fixed start and end points (loading and unloading buckets of cargo transport machines, drilling holes by drilling rigs, managing the effector of the combine, delivery of equipment); II - moving items with the search for the origin (purging and loading holes, positioning the elements of roof support, conducting a drainage groove); III - recognition of objects in non-oriented environment (marking holes, assessing the state of a face, assembling the elements of roof support, excavating the face, extending lines of communication).

This preliminary estimate is not complete because of the diversity of proposals for robotics, the manifold conditions of mineral occurrence and mining and multi-variant ways of work organization. It is expedient to research technology of mining with computer models to determine the sources of the effectiveness of robotic technology via simulation experiments.

Most of the operations in mining are discrete with a finite number of variables. These operations include beginning and end of drilling, loading and unloading of coal, beginning and

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end of the combine work, and others.

To model these operations it is expedient to use the mathematical apparatus of queuing systems (QS) [8-10].

There have been developed models of mining technology in the form of multi-channel closed multiphase QS where applications are the moments of readiness of the equipment for the next cycle. The applications are considered to be handled if they are delayed for the time duration of the processes of a drifting cycle in devices that simulate the appropriate equipment. The process duration of a technological cycle is displayed by entering random time delays in the QS devices. The length is specified in the ongoing development of QS by a number of applications arriving at the input of the system (1)

$$m = L / l \qquad (1)$$

where L – the face length; l - face advance per cycle.

In real conditions the equipment may start execution of the next cycle after the previous cycle and the time interval between the beginning and the end of tunneling depends on the random cycle time of manufacturing operations. This feature is displayed in the model by the feedback input, whereby the next application enters the input of QS after the handled application appears at the system output. Thus, the feedback forms the input stream of applications. The rate of submitting applications is equal to the speed of their handling, so there is no queue at the system input and the objectives of the research are reduced to the estimation of the total time of handling the application and utilization of equipment.

The average duration of a cycle is defined in the model as the sum of random variables (2)

$$t_{\mu} = \left(\sum_{i=1}^{m} t_{pi} + \sum_{i=1}^{m} t_{ni} + \sum_{i=1}^{m} t_{ki} \right) / m \qquad (2)$$

where t_{pi}, t_{ni}, $t_{\kappa i}$ - random time values for handling the application by the devices simulating equipment for the destruction of the rock mass, rock mass loading and mined-out area supporting at the *i*-th cycle.

Fig. 1 shows an example of the technologies of drilling and blasting in a closed-channel multiphase queuing system.

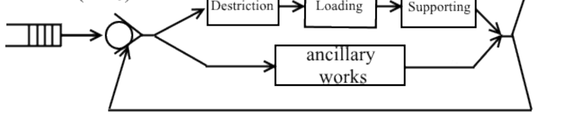

Fig. 1 mapping the model of the robotic technology of drilling and blasting in QS

The application is the moment when the equipment is ready for the next drifting cycle, and devices are the tunneling machines that handle applications at a random time; the rate of submitting the applications in the system is determined by the speed of handling the applications. On one channel the application is handled by drilling rigs, loaders and a roof support installer. Other channels perform additional operations. At the end of the drifting cycle the application, which has been handled, is fixed by a cycle counter and allows the unhandled application to enter the input of the system. The time of handling applications with the devices is presented in the form of functional dependencies (3):

$$\begin{aligned} t_d &= f\left(n_h, l_h, P^{dr}, f_r, S, n^{dr}\right) \\ t_l &= f\left(S, f_r, l_h, \eta, P^l, n^l, k_s, V_v\right) \\ t_s &= f\left(S, l_f, n_d\right) \end{aligned} \qquad (3)$$

where t_d, t_l, t_s - random variables of the time needed for destruction of the rock mass, rock mass loading and excavation support; S - section of a face; f_r - rock hardness ratio; n_h - the number of holes per cycle; l_h - the length of the holes; η - coefficient of hole utilization; k_s – softening coefficient; P^{dr}, P^l – capacity of drilling and loading machines; n^{dr}, n^l – the number of drilling and loading machines; Vv - the volume of a vehicle; l_f - the length of the face fixed in a single cycle; n_d - the number of the drifters employed in the installation of roof support.

A cycle counter, which increases the delivery time depending on the cycle number, is introduced to the system. It fixes the changes in time made by cargo transport machines as preparatory works move forward (4):

$$t_{li} = f(l_l), \qquad i = (1, m) \qquad (4)$$

where l_l - the haul length of the rock mass; m - the number of cycles required for mine development.

As a means of software implementation of the models of mining technology, the most suitable language version of the modern simulation is GPSS - GPSS World. The GPSS language is currently one of the most effective and common software tools for modeling complex discrete systems on the computer and it is successfully used for the simulation of various industries [11-13], including mining operations, formalized as queuing systems [14-17].

In GPSS World, there are two basic types of objects: blocks and transacts. Blocks set the logic for the model operations and determine the path of the transacts on it. The blocks are the analogues of QS devices that display a processor, drilling rigs, loaders, roof support installers. The delays of transacts in the blocks simulate mining operations such as snapping and distilling drilling rigs, loading of the vehicle, excavating the face, etc. The transacts are analogues of applications. In QS these applications are connected with performing operations of a drifting cycle. In the process of system simulation there are changes of the attributes of transacts in the blocks of a model as well as conversions of arithmetic or logical values. Such transformations are called events.

Using GPSS World, standard software modules have been

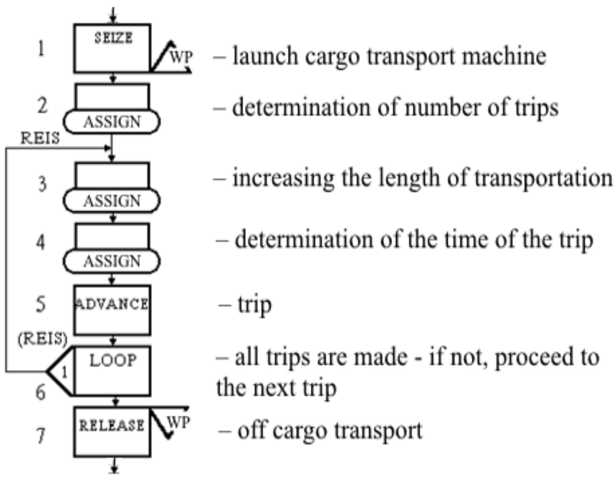

Fig. 2 mapping block diagram of the loading module

developed for the construction of models of mining technology: "cut with loading", "drilling", "loading", "pickup", "support". Fig. 2 shows an example of the module "loading"

Block 2 (ASSIGN) is determined by the desired number of hauls for the removal of the split rock (5)

$$\begin{aligned} Q &= Sl_h k_s \\ n &= Q / Vk_f \end{aligned} \tag{5}$$

where Q - the volume of split rock; S - section of a face; l_h – the length of the holes; k_s – softening coefficient; n - the number of hauls required for exporting split rock by a vehicle; V – the capacity of the vehicle; k_f – filling factor.

The duration of the haul of the cargo transport machine is simulated by the delay in ADVANCE block for the period (6):

$$t_{Li} = 2\left(\frac{l_i}{v}\right) + t_l + t_{un} \tag{6}$$

where t_{Li} – duration of the i-th load cycle; l_i – the amount of advance in the i-th cycle; v – vehicle speed; t_l – loading time; t_{un} – unloading time.

The increase of the distance of rock transportation is determined in block 4 (ASSIGN) with the (7):

$$l_i = l_{i-1} + l \tag{7}$$

where l_i – the amount of advance in the i-th cycle; l – the value of the face advance.

Turning off the cargo transport unit with the RELEASE block takes place after all the hauls of that unit have been done. This is determined by the LOOP block, which reduces the number of required hauls for one unit and checks the condition $n_0 = 0$. If this condition does not work the cycle repeats loading.

The developed model program modules allow us to create models of existing and robotic technology of mining which can be used to conduct research on the effectiveness of robotic technology, to choose the optimum bucket volume of cargo transport machines, to determine the maximum length of transportation of the mined rock with the capacity of a drifting cycle being limited, to choose the desired volume of the vehicle, and others.

As an example of the proposed approach for evaluating the effectiveness of robotics there have been selected three technologies of drill and blast, and combine driving methods tested in the same conditions: the mine working is 600 m long, the section is 25.1 m^2, the tunneling is 29.05 m^2 on the rock with strength factor 6, the support is metal frame SVP-33.

For the first technology of drilling and blasting method with individual machines the following equipment is used: Drilling rig 1SBU-2K (1); cargo transport vehicle MPKT (2); trolleys VG-3.3 (3) and electric AM-8D (4). The cycle begins with the drilling of 114 holes by drilling rigs 1 (Fig. 3).

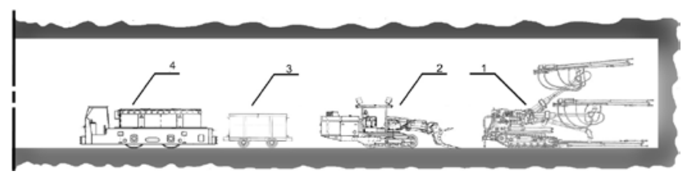

Fig. 3 mapping the technology of mining with individual machines

After loading and blasting the holes the face is brought into a safe condition. The cargo transport vehicle 2 uses several hauls to load the mined rock in the trolleys 3, after which the goaf is supported with the constant metal arch support by the manipulator of the drilling rig with a cradle.

For the second generation technology of drilling and blasting method the tunneling complex Siberia-2TM, trolleys VG-3.3 and electric AM-8D are used.

The cycle starts with drilling holes by two drilling rigs 1 (Fig. 4). After blasting and ventilation the loading machine 2 loads the mined rock with two buckets to the loader 3. Then, using roof support Installer 4, the goaf is supported. Along with the basic operations of the drifting cycle some additional operations are carried out such as extending lines of communication, rock splitting and others.

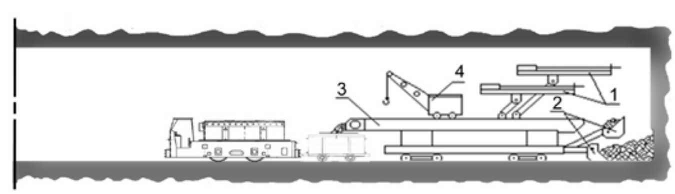

Fig. 4 mapping mining with the drilling and blasting complex Siberia-2TM

There are six people in the shift. Drilling holes is combined with marking holes (one person) and extending lines of communication (two people). When filling the shot holes the blasting area is being protected (by one person).

Simultaneously with the work of loading machines the shunting operations, splitting the rock and supervision of loading take place (three people). The control of the roof support stacker is combined with the installation of support elements (four people). Throughout the cycle some other additional works take place (one person).

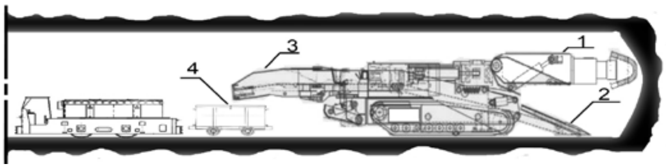

Fig. 5 mapping the technology of mining with combine KP-25

The third generation technology uses the selective heading machine (combine) KP-25. Simultaneously the effector 1 processes the face and the loading body 2 loads the mined rock to the loader 3 which transports it into the trolley 4 (Fig. 5). At the same time there are works connected with extending lines of communication and constructing the drainage grooves. Then combine stops and the work on powered support construction starts. Then the cycle is repeated.

As a result of evaluating the effectiveness of robotics in terms of the complexity of the automation of the process operations it has been found that the technology of the production with individual machines is the most suitable for robotics as in this technology the proportion of operations hardly suitable for robotics does not exceed 37% (Fig. 6).

When evaluating the effectiveness of robotics technology in mining with discrete-event models the suggestions for robotics were selected and then the results of simulations of robotic and existing technologies were compared. As a result, we have received a number of recommendations and approvals. Concerning the robotic technology of drilling and blasting with individual machines and with a drilling and blasting complex it has been proposed to mount the system of the positional control for directing the drill head at the hole as well as of automatic rotation speed control and feed rate of the drilling rig. The system can provide the movement of the drill head at a variable pattern of holes, the drilling of the face with manipulators according to the reprogrammable drilling pattern and controlling the feed rod and the position of the head in space. Automatic guidance program for the drill head excludes the operation of marking holes as well as shortens the time needed for transposition of the drill head from one hole to another. The possibility of serving several robots by one

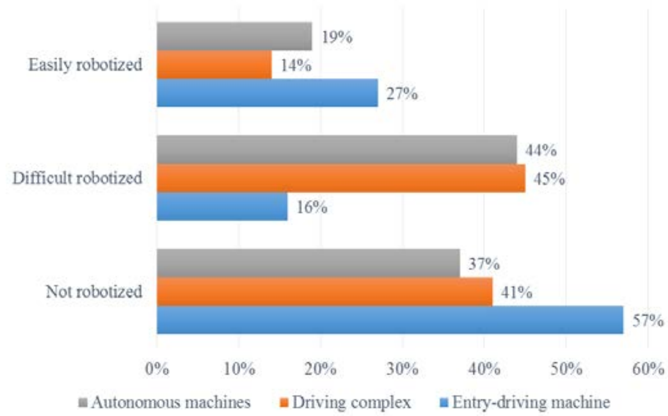

Fig. 6 mapping the distribution of labor intensity of the operations in the drifting cycle in terms of complexity of robotics

operator will reduce the number of people employed in the process of drilling rigs control.

To fill the holes with explosives it has been proposed to use self-propelled (hinged) filling machines with a remote control which are additionally equipped with filling hose feeders and the filling control panels. This will reduce the time of loading the holes as well as the number of miners.

To robotize the loading process to the loading machines it has been proposed to install remote or automatic control of loading. This will provide the loading of the rock mass by a loading machine during the face ventilation. The reduction in loading time by 10-15% is possible due to the stabilization of loading cycles and human factor exception.

It has been proposed to replace metal arch support with anchoring using self-propelled robot (mounted) roof-bolters. This will reduce the duration of the process and exclude the operations connected with the installation of the elements of arch support.

The automatic control of the effector of the combine has been offered for the technology of mining with a combine. Due to the automatic processing of the face by the combine arrow, the excessive section can be excluded, which results in the reduction of time needed for the destruction of the face by 20-30%.

Using the developed software modules, the models of existing technologies of mining and of the proposed robotic technologies have been made.

In the simulation experiments computer models identify the sources of the effectiveness of robotics in technological operations.

The results of comparison the parameters of the existing and robotic technologies are presented in Table I.

Table 1. Indicators of the drifting cycle for existing robotic technologies of mining

Cycle parameters	Existing technology			Robotic technology		
	Combine	Complex	Individual machines	Combine	Complex	Individual machines
Duration, min	523	673	718	443	418	380
Labor intensity pers.-min.	1968	3687	4676	1310	1252	685

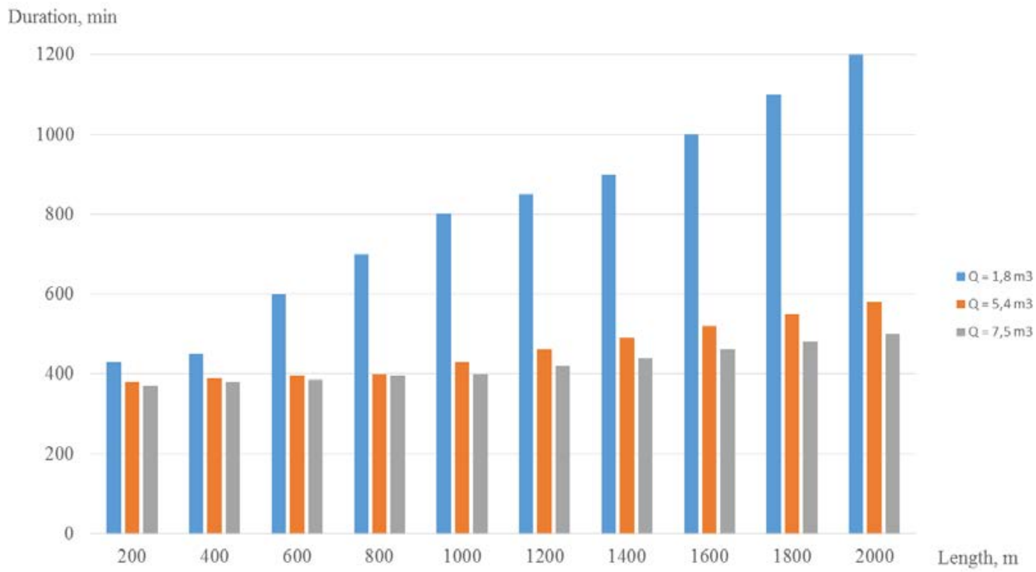

Fig. 7 mapping the impact of the length of the drift on the cycle time for the technology with robotic machines with a different bucket capacity of cargo transport vehicles

It has been found that the most effective option for the use of robotics technology is mining with individual machines. Switching to this technology will reduce the cycle time by 27-47%, and the labor intensity - by 65-84%.

There has been investigated the influence of the bucket capacity of cargo transport vehicles, the capacity of haulage equipment and the length of mining on the indicators of the drifting cycle.

The robotic technology of mining with individual machines demonstrates the linear increase of the average cycle time according to the corresponding increase of the length of the drift from 200 to 1800 m. Reducing the bucket capacity of cargo transport vehicles from 7.5 to 1.8 m3 increases the duration of the drifting cycle by 24-56% depending on the length of the drift (Fig. 7).

Utilization in the robotic technology of mining is increased by 22-50% in comparison with the existing technology depending on the capacity of the vehicle (Fig. 8).

It has been found that up to the length of 600 m the robotic technology of mining with individual machines is the most productive in comparison with the existing technologies using combines with selective effect, individual machines and the complex "Siberia-2". For the length from 600 to 1800 m it is the traditional combine technology of tunneling that is the most productive, and the effect of individual machines robotics is lost (Fig. 9).

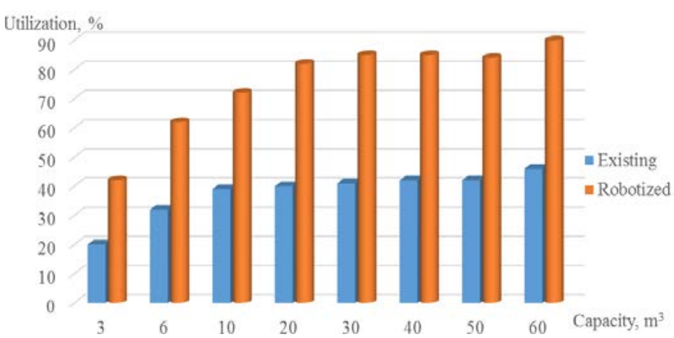

Fig. 8 mapping the impact of transport capacity on the combine utilization

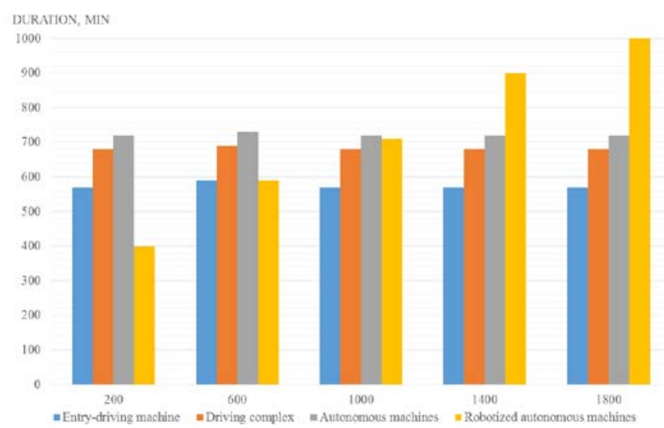

Fig. 9 mapping the impact of the length of the drift on the duration of a drifting cycle

a- combine excavation;

b- blasting excavation with complex "Siberia-2";

c- excavation with individual machines;

d- robotic excavation with individual machines

The paper illustrates the approach to evaluating the effectiveness of robotics technology of mining, which identifies the technologies most prepared to robotics by determining the degree of complexity of the automation of operations. The use of discrete event simulation with display of mining technology in the form of the QS and followed by software implementation in a specialized simulation language GPSS World makes it possible to determine the sources of the effectiveness of robotic technology by carrying out computer model experiments. All these things will help to reduce the significant loss of capital investment at the stage of mine design.

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