Proceedings of the 34th European Modeling & Simulation Symposium (EMSS), 023
19th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0029 © 2022 The Authors.
doi: 10.46354/i3m.2022.emss.023

Digital Model of A Coalmine Face

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Abstract

The article presents the structure and implementation of a digital model simulating a face of a coalmine. The digital model takes into consideration the parameters of a mining seam, technical parameters of the mining machines used, and economic indicators. The model can be used to support decision-making on increasing the productivity of the longwall of a coalmine, assessing the effect produced by using of the new equipment or new technology. We gave an example of its use to determine the dependence of economic indicators of longwall operation on the length of the face and flow scheme of shearer operation.

Keywords: Digital model; simulation; coalmine; longwall; productivity

1. Introduction

Today many coalmines have problems in making decisions to increase productivity, to improve coal production planning, to use new mining equipment and new perspective technologies for coal mining. The most suitable way to solve these problems is simulation. Many publications support this statement (Gospodarczyk, 2016; Anani et al., 2016; Muniappen and Genc, 2020). There are also many publications about using simulation to solve problems for longwall mining (Ahmed et al., 2018; Dziurzyński et al., 2020; Kęsek et al., 2018). These articles investigate certain aspects of longwall mining. In this work, an attempt is made to develop an integrated parameterized longwall digital model that takes into account many aspects of the longwall mining.

The longwall digital model was developed using the MTSS simulation system (Okolnishnikov and Rudometov, 2014). It is a visual interactive and process-oriented discrete simulation system intended to develop and execute the technological mining processes models.

With the help of MTSS the models of the underground conveyor network and pumping subsystem of a coalmine in Kuzbass (Kuznetsk Coal Basin, Western Siberia, Russia) were developed (Okolnishnikov et al., 2016). New longwall digital model also intended for simulation longwall mining processes in coalmines of Kuzbass.

2. State of the art

At present, the tasks of joint design, monitoring of the technical condition and management of subsystems of a coalmine has arisen. To solve this extended set of tasks, it is required to use new information technologies implemented within the framework of "Industry 4.0" concept. One of the most promising technologies is the technology of digital twins (Qi et al., 2018; Uhlemann et al., 2017).

Concisely, a digital twin is a virtual representation of a physical system associated with it throughout the life cycle of a physical system (Grieves and Vickers, 2017). Currently there exist numerous publications revealing this definition. The publications are devoted to the classification of digital twins, their structure and implementation, their use for various industries, a review of the literature on digital twins, etc. The following is a selective review of the literature on digital twins in order to justify the use of this technology for a longwall of a coalmine.

The classification of digital twins is based on the following main types of digital twins: Digital Twin Prototype, Digital Twin Instance, Digital Twin Aggregate, and Digital Twin Environment (Grieves and Vickers, 2017; Jones et al., 2020). Digital twin "prototype" is a virtual description of the prototype of a physical object, containing all the information necessary to create a physical twin. A digital twin "instance" is a digital twin of a specific physical object, which remains associated with this physical object throughout its entire life. The digital twin "aggregate" is an interconnected set of all instances of digital twins. Digital twin "environment" is a software environment for working with digital twins.

Digital twins are also divided into digital twins of a product, a process, and a system. The digital twin of a "product" is a virtual model of a specific product, for example, some machine. The digital twin of a "process" simulates manufacturing processes. The digital twin of a "system" is a virtual model of an entire system, such as a coalmine. This article discusses the manufacturing process of underground coal mining at the longwall of a coalmine.

Michael Grieves (Grieves, 2014) presented the conceptual structure of a digital twin, consisting of three main parts: a physical product, a virtual product, and the relationship between the physical and the virtual product. In (Tao et al., 2019) the conceptual structure of a digital twin is expanded. The digital twin must include five parts: a physical part, a virtual part, a connection, data and a service part. In doing so, it is emphasized that every part of the digital twin is equally important. The implementation described below uses this concept. In (Enders and Hoßbach, 2019), basing on a systematic literature review, 77 applications of digital twins in various industries are considered and a classification scheme is proposed to describe the identified applications. The article notes that digital twins are used in various industries and lists the industrial sectors that use digital twins (ordered by number in brackets): manufacturing (54), aerospace (5), energy (4), automotive (3), marine industry (3), oil (2), agriculture (2), healthcare (2), public sector (1) and mining industry (1).

Recently, there appeared publications on applications of digital twins in the mining industry, for example, the digital twin of hydraulic supports (Xie et.al., 2019) and the digital twin of the Mining Shaftand Hoisting System (Kalinowski et al., 2021)

Different authors give different definitions of a digital twin; this list is most fully presented in (Enders and Hoßbach, 2019). Basing on the various definitions of a digital twin, we can formulate a general concept of digital twins as digital twins of physical objects. Within these definitions, the terms "digital model", "digital shadow" and "digital twin" are often used interchangeably (Kritzinger et al., 2018). However, these terms differ in the level of data integration between physical and digital counterparts. In (Kritzinger et al., 2018), a classification of digital twins is proposed in accordance with their level of data integration: digital model, digital shadow, and digital twin.

A digital model is a digital representation of an existing or planned physical object that does not use any form of automatic data exchange between the physical object and the digital object. A digital representation can include more or less comprehensive description of a physical object. These models can include both simulation models and other models of a physical object or technological process. Digital data from existing physical systems are used to develop such models, but all data exchange is done manually. A digital shadow is a digital representation of a physical object that uses an automated one-way flow between the state of an existing physical object and a digital object. An alteration in the state of a physical object leads to an alteration in the state of a digital object, but not vice versa. A digital twin is a digital representation of a physical object that uses two-way communication between the physical and digital object. In this combination, the digital object can also act as the controlling part of the physical object. Depending on the degree of integration, an alteration in the state of a physical object leads to an alteration in the state of a digital object and vice versa.

In order to make the virtual part of the digital twin be something more than a digital model, it must receive data about the external environment in real time. The conveyor, ventilation and other subsystems of a coalmine require obtaining values of environmental parameters that can be measured such as temperature, methane content, etc. Unlike them the external environment of a working face is a coal seam, mining geological and geotechnical parameters, which at the point of location of the shearer is difficult to measure in real time. Therefore, it is impossible to implement a digital twin of the working face in the classical form, and a more suitable solution is a digital model that uses the data of the corresponding geological model (Hodgkinson and Elmouttie, 2020). All this determined the choice of a digital model for implementation in this work.

3. Materials and Methods

3.1. The mathematical model of the productivity of a shearer

The formula for the theoretical productivity (1) of the shearer when moving on a straight section of the longwall is derived in (Ordin et al., 2019).

$$A = \frac{\gamma m r C \eta K_1}{f P \cos\alpha \pm P \sin\alpha + S m K_2} \tag{1}$$

The productivity depends on two types of parameters. The first type is the constant technical parameters of the shearer. The second type is the parameters of the coal seam, which can change.

In (1) the constant technical parameters of the shearer are: *m* is the cutting height of the shearer, *r* is the cutting width of the shearer, C is the capacity of the shearer drive, η is the efficiency of feed drive gearbox, n is the number of picks in a cutting line, K_1 is the coefficient taking into account a part of capacity of the shearer drive to move of the shearer, f is the coefficient of sliding friction between the shearer and the scraper conveyor, P is the shearer weight, K_2 is the coefficient, taking into account the decreasing of the cutting resistance of coal under the influence of rock pressure.

In (1) the parameters of the coal seam are: γ is the coal density, α is the dip angle of coal seam, "plus" and "minus" in front of the shearer weight specify the shearer movement up and down the longwall face respectively, S is the cutting resistance of coal.

Current regulatory documents, methods and instructions for calculating the productivity of production faces, as well as publications, imply that when calculating the theoretical productivity of the shearer, invariable values of the parameters of the coal seam should be used. These values are calculated in one way or another. The scientific novelty of the proposed approach is the use of variable values of the parameters of a coal seam, which correlates with the actual system to a greater extend. With this approach, the parameters of the coal seam are considered as functions of the current position of the shearer with coordinates (x, y) in a some coordinate system. To calculate the productivity of the shearer, instead of formula (1), the authors used modified formula (2).

$$A(x,y) = \frac{\gamma(x,y) m r C \eta n K_1}{fP\cos\alpha(x,y) \pm P\sin\alpha(x,y) + S(x,y) m K_2} \quad (2)$$

Values of functions $\gamma(x, y)$, $\alpha(x, y)$, $S(x, y)$ are calculated with the Inverse Distance Weighting (IDW) method according to the following general function (3).

$$F(x,y) = \begin{cases} \frac{\sum_{i=1}^{n} d_i^{-2} F_i}{\sum_{i=1}^{n} d_i^{-2}}, \text{if } d_i \neq 0 \\ F_i \quad\quad\quad , \text{if } d_i = 0 \end{cases}, \quad (3)$$

where: F_i are values of the corresponding parameters of the coal seam in i_{th} geological prospecting well, n is the number of geological prospecting wells nearest to longwall face that are taken into account while calculating, d_i is the distance between the i_{th} geological prospecting well and current position of the shearer *(x, y)*.

3.2. The structure of the digital model

The proposed digital model is intended for to support decision-making on increasing the productivity of the face of a coalmine, assessing the effect produced by using of the different mining machines and different mining technologies.

The structure of the digital model of a coalmine face is shown in Figure 1. The structure of the digital model includes three interrelated levels: model, information, and user levels. The lower model level contains interconnected mining machine models and a coal seam model. The main model is a shearer model that allows calculating the speed and the productivity (the amount of extracted coal per time unit) of the shearer.

When simulating the movement of the shearer in the operating mode, at each moment of the model time, the model of the shearer coordinates with the model of the coal seam, transmits the coordinates of the shearer and receives the calculated values of the parameters of the coal seam at the point where the shearer is located. When calculating the variable values of the parameters of the coal seam, we used IDW method (3). This method uses the values of the parameters of the coal seam in exploration wells. The mathematical models and algorithms for the interrelated functioning of the shearer, the face scraper conveyor, and the support sections are presented in (Okolnishnikov et al. 2018; Ordin et al. 2019). In this work, the mathematical models were transformed into simulation models of these mining machines.

The simulation model of the shearer calculates the speed and productivity of the shearer (2). At the same time, such factors that affect the performance of the shearer are taken into account:

- The distributed mining-geological and geo-mechanical state of the coal seam.
- The technical parameters of mining machines.
- The flow schemes of shearer operation.
- Movement of powered support sections.
- Operation of a face scraper conveyor.
- Calculation of methane release from the seam.

The information layer contains a database that includes the following information:

- Geographic coordinates of underground workings.
- Geographic coordinates of exploration wells and geological data obtained during their drilling.
- Technical parameters of mining machines.
- Technological schemes of coal extraction.
- Technical parameters determining by the work procedure and safety requirements.
- Economic data, etc.

The user level with the help of the implemented interface includes the ability to set the model parameters, set the model execution modes, launch the model for execution, 2D and 3D visualization of the modeling process, document the simulation results.

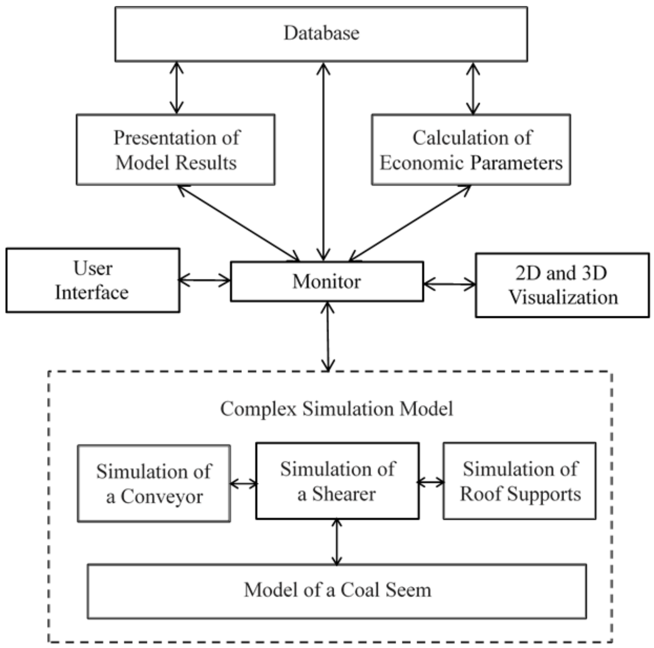

Figure 1. The structure of the digital model of a coalmine face

3.3. The implementation of the digital model

The simulation models that are the part of the digital model of the face in a coalmine were developed using the MTSS simulation system.

To meet the challenges of increasing productivity and safety of coal mining it is required to integrate simulation models of independent mining machines and coalmine subsystems within the framework of a digital model. This work is devoted to this task presenting the example of the digital model of a coalmine face. The digital model of a coalmine face can be used to solve the following tasks:

- Justified evaluating of the productivity of the face, including financial values.
- Assessing the effect of using new mining machines and new technologies.
- Decision support during the modernization of existing faces and design of new faces.

To solve such problems, the user must perform the following actions using the implemented interface: set the model parameters, set the model execution modes, running the model in debug mode, observe the model execution process using 2D and 3D visualization, running the full model with the possible disabling of visualization to speed up the simulation.

When specifying the parameters of the model, the user must specify the number and coordinates of exploration wells, as well as the values of mining-geological and geo-mechanical parameters of the coal seam in these wells.

The database contains information about exploration wells for several under-ground coalmines in Kuzbass. When you select a mine, these data are automatically loaded into the model parameters.

Then, the user sets the list of mining machines (shearers, face scraper conveyors, roof supports) and specifies the technical parameters of these mining machines. A distinctive feature of the developed digital model is the possibility for the user to choose from the database mining machines. Currently 53 mining machines (shearers, face scraper conveyors, roof supports) are available in the database. The user can expand the database and include a new existing mining machine or a hypothetical prospective mining machine. This procedure requires using of the implemented interface and filling in the corresponding data fields. When the user selects a certain mining machine, all the technical parameters of this machine are automatically loaded into the model parameters.

After that, the user sets the linear dimensions of the face, and selects the flow scheme of shearer operation. The face length significantly affects the productivity of the face. The performance of the face is also influenced by the selected flow scheme of shearer operation. Comparison of the performance of various flow schemes of the shearer operation, made in this work, can be used to make decisions when modernizing faces or when designing new faces.

Then the user sets a logical condition to end the simulation. In particular, such a condition can be the value of the model time, upon reaching which the execution of the model ends. The user sets the modes of execution of the model, forms of presentation of the output parameters of the model, and launches the model for execution. The following execution modes are implemented in the model: 2D visualization, 3D visualization, no visualization. When the model is executed, the values of the output parameters are calculated. These values can be dynamically displayed either numerically or graphically.

Figure 2 shows a 2D visualization of the digital model execution. Longwall boundaries are shown in green. The shearer is shown in yellow. Figure 3 shows a 3D visualization of the digital model execution.

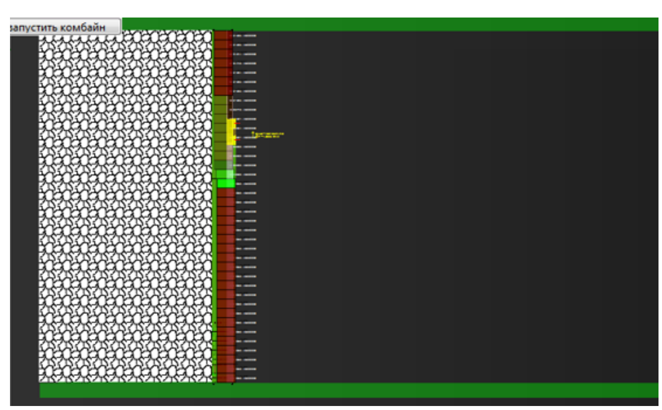

Figure 2. 2D visualization of the digital model execution

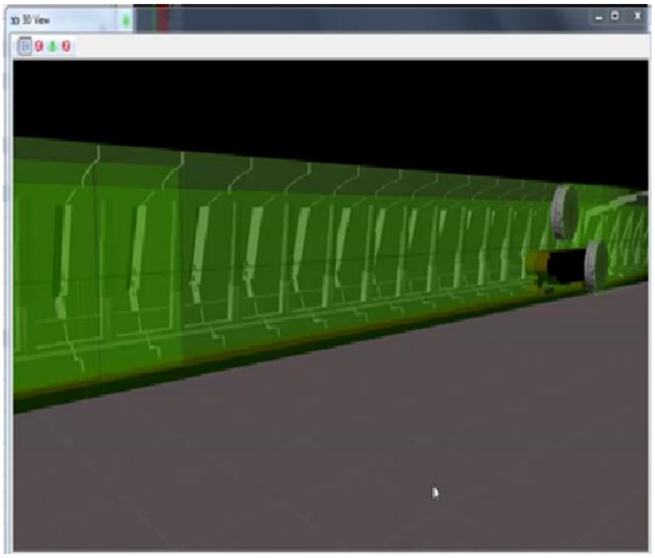

Figure 3. 3D visualization of the digital model execution

4. Results

The Yalevsky mine in Kuzbass was selected as an example of using the digital model of a coalmine face. The purpose of the simulation was to determine the annual profit of the face operation, equal to the cost of extracted coal minus depreciation costs, depending on the length of the face and on the flow scheme of shearer operation. The model was validated on actual data from Yalevsky mine. The amount of coal extracted per year, obtained by the model, coincides with the data in (Meshkov et al., 2018).

The model used the technical parameters of mining machines: shearer SL-900, scraper conveyor SH PF 6/1142, roof support DBT 220/480. To calculate the profit of the face operation, the following economic parameters were used: wholesale price of 1 ton of coal in rubles, depreciation rates, respectively, for a shearer in rubles, powered support and scraper conveyor in rubles/m. In the model, there are parameters that set the operating schedule for the face. In the considered example, the work of the face was simulated for a year. Daily work was carried out in two work shifts (coal mining) and one technical shift (routine maintenance). To calculate the net profit from the operation of the face you should take into account the cost of materials, electricity, and wages. The relevant parameters are included in the model, but the values of these parameters were not available and were not used in this example.

The following flow schemes of shearer operation used in longwall mining were simulated: the one-way flow scheme, the two-way flow scheme, and the bench flow scheme. In the one-way flow scheme, the cycle of operation of the shearer consists of its forward motion in the operating mode and in the reversely motion in the mode of the cleaning-up.

In the two-way flow scheme, the cycle of operation of the shearer consists of its forward and reversely motion in the operating mode. In the bench flow scheme, first, the upper layer with a thickness equal to drum diameter of the shearer is cut and then, when the shearer moves reversely, the remaining lower layer of the coal seam is cut.

The subject of the research was the detailed simulating of the one-way flow scheme, the two-way flow scheme, and the bench flow scheme of the shearer operation together with movement of the face scraper conveyor, and power roof supports.

Figure 4 shows the results of simulation the dependence of the annual profit of the mine on the face length in the range from 95 to 495 m and on the flow scheme of shearer operation. Red solid curve is the curve corresponding to the bench flow scheme of shearer operation, blue dashed curve is the curve corresponding to the one-way flow scheme of shearer operation, and the green dash-dotted curve is the curve corresponding to the two-way flow scheme of shearer operation. The figure shows that the greatest profit can be obtained using the two-way flow scheme of shearer operation and the length of the face in the range of 345–395 m. The further increase in the face length insignificantly affects the increase in profit.

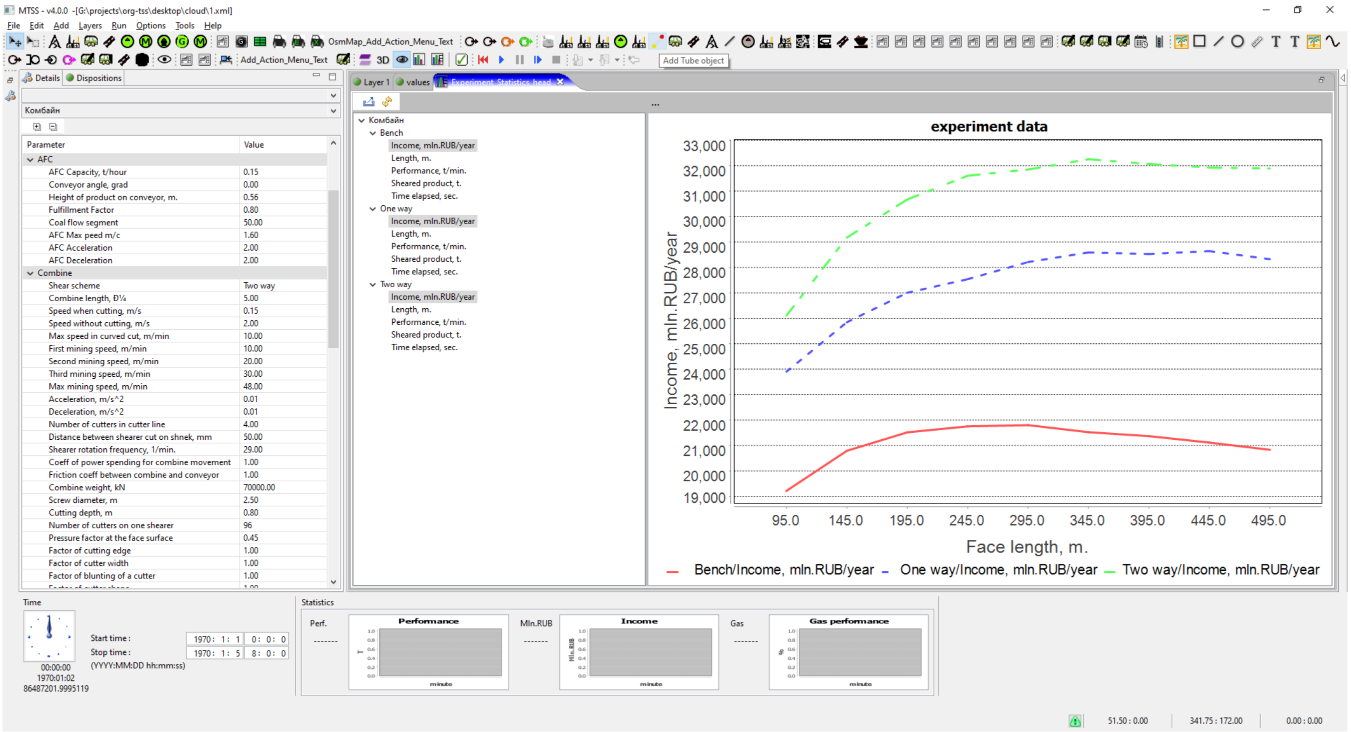

Figure 4. The dependence of the annual profit of the mine on the face length and on the flow scheme of shearer operation

5. Conclusions

The structure of the digital model of the face in the coal mine was developed. In accordance with the structure, the digital model was implemented. It includes the parameters of the coal seam, technical parameters of mining machines, flow schemes parameters, economic parameters, etc. The digital model allows solving optimization problems in order to increase the productivity of the face in a coalmine. It was validated on actual data from the Yalevsky mine. The simulation results can be used to support decision-making on the modernization of existing faces and to design new faces.

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