A Review of Computer Simulations in Underground and Open-Pit Mining

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Abstract

The article presents the role of computer simulations in present times and discusses aims and benefits of using such solutions. It was established that by conducting simulations and building virtual models it is possible to increase the efficiency of analysed processes while minimizing the costs of production, logistics, storage, etc. What is more, simulation models allow for scenario analysis of various solutions, and thus making the appropriate decisions based on the obtained results. Therefore, they become the basis for the analysis of various technological and process changes. Simulation and modelling tools are increasingly used in the mining industry. Computer models of mining processes supplied with real data are a useful tool for testing planned changes, an investment risk analysis or a quality assessment of accepted solutions. The authors cited and discussed selected simulations of mining processes made in various tools, and also proposed a method of simulation the process of coal production with a longwall complex in the 3D dimension using FlexSim Simulation Software. The simulation model was built on the basis of the ProcessFlow technology, allowing for building the logic of the system in the form of block diagrams, and thus significantly shorten the time of modelling extensive processes.

Keywords: computer simulation, mining, FlexSim, modelling

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Introduction

Computer simulation is increasingly used by enterprises with a view to analysing and extending their production capacities, as well as improving the quality of finished products, with a simultaneous minimisation of incurred costs. Changes introduced to real processes entail a high risk of failure. Such activities require decisions concerning high capital investments and are often extremely time-consuming. In addition, there is a risk that the operation of a real (physical) model will slightly deviate from the original assumptions or will not generate the expected outcomes, thus generating substantial financial and working-time losses. For this reason, is seems highly important to conduct computer simulations before any changes are actually made. The creation of a virtual model makes it possible to assess the future process operation, analyse its performance and efficiency, evaluate the finished product quality and precisely adjust all the parameters, aiming at production optimisation [7].

Owing to computer process modelling, a large number of factors can be considered, such as determining the adequate setting and workload [17], defining the best parameters for individual devices, estimating the optimum number of workers, and selecting means of transport. At the computer simulation stage, any irregularities can be immediately identified, along with an early detection of any bottlenecks in the entire production process and prompt introduction of appropriate model changes. Simulation provides wide opportunities for experimenting on a virtual model and creating multiple scenarios from which the most suitable one can be selected, fostering the achievement of expected efficiency. The possibility to account for any breakdowns and inspection-related downtimes constitutes a considerable advantage of such modelling, making the modelled process fully correspond to the real one and contributing to shorter working times with given parameters [2,12].

Computer simulation and modelling is successfully used also in the mining industry. To date, several mining process simulations have been performed, both in underground and open-pit mines. New integrated modelling methods have also been proposed. The mining industry is characterised by considerable investment outlays made as part of new investments. Therefore, modelling is a frequently-applied method of planning and solving the existing investment challenges [1,8]. Moreover, the solutions in question can be used to analyse the occurring threats, rock mass behaviours and land deformations within roadways, and also to improve workers' safety.

A review of computer simulations performed so far in the mining industry is presented below, along with various authors' approaches and an author's method for performing a simulation of a longwall system operation.

A review of computer simulations in relation to the mining industry

A simulation of an open-pit mine production system

Open-pit mining is characterised by a relatively steady production technology which does not change throughout a plant's life cycle. That is why the production parameter changes result mainly from the need to modify machine and device settings. It is thus important to adequately design the plant so as to ensure that the extraction process is efficient enough and conducted with the lowest possible cost. To this end, simulation technologies can be used, which enable testing the functioning of a plant which does not exist yet and selecting the best possible solution. There are several computer programs on the market designed to analyse the functioning of open-pit and underground mines, e.g. HAULSIM released by RPMGlobal. The software serves the purpose of analysing transport operations in the extraction industries. It acts as a simulator of discrete events, enabling the reliable mapping of mine operation principles, the analysis of variability impact and the estimation of risks posed by certain decisions [19].

Nonetheless, simulation tools can also be used in the already-existing open-pit mines, with the aim of reducing costs or optimising selected parameters. In their articles, Chęciński and Witt [5,6] proposed the use of 3D simulations to determine the best production and transport system for a defined progress of exploitation fronts. Using the FlexSim Simulation Software, they mapped an open-pit mine production system, assuming that the extraction process would utilise an explosive, whereas dump trucks would transport the output for crushing. The model comprised the following elements: a charging hopper, a primary crusher, a conveyor system and a crushing system with a sieving device. The principal objective of the simulation was to minimise the risk of idle operation of the crushing system. The authors used the capacity of dump trucks as a variable for analytical purposes. The simulation model itself was developed using the drag&drop technique. The authors used the library of 3D objects available in the FlexSim software, combining the objects in line with the flow logic. In addition, object layers were changed by preparing the adequate 3D shapes, dedicated to the analysed problem.

In the course of their analyses, the authors tested six scenarios of dump truck capacities, repeating each of them five times. The Experimenter tool for scenario analyses, embedded in the FlexSim software, was used for this purpose. The conclusions formulated on the basis of the performed calculations appear rather obvious – the higher the capacity of the dump truck, the larger the quantity of the transported material at a given time, and thus the higher the coefficient of the effective use of the crushing system operation. Nevertheless, as reported by the authors, once the highest value of the dump truck box capacity's impact on the coefficient of idle operation was achieved, an increased dump truck box capacity no longer triggered any efficiency growth. It can, therefore, be concluded that the simulation allows to determine the maximum profitable dump truck capacity and, hence, to avoid unnecessary costs.

The authors emphasise that the simulation approach can be effectively adjusted for supporting the design process of production systems in open-pit mines, and for managing deposits exploitation. However, in order to achieve the expected outcomes, the course of the actual process needs to be accurately mapped and real data must be delivered to the model. In addition, the obtained results may be used as the basis for analyses performed in other industrial software.

A simulation of a mining process in an underground hard coal mine

The requirements specified for simulation tools are becoming increasingly higher. One of the attempts is to develop very detailed and widely applicable simulation models with the minimum use of software and the maximum use of experience derived from various fields of expertise. The growing requirements, coupled with the need to consider specific parameters, often make engineers develop simulation programs for very specific parameters in a given plant. The articles [14,15] include a description of the Manufacturing and Transportation Simulation System (MTSS) developed at the Design Technological Institute of Digital Techniques (DTIDT) of the Siberian Branch of Russian Academy of Sciences, which is used for developing process steering systems for underground hard coal mines in the Kuznetsk Coal Basin (Russia, Western Siberia).

MTSS is a process-oriented discrete simulation system, the aim of which is to develop and create models of technological processes. It enables both the creation of elementary structures and complex system simulations. In the context of this tool, elementary structures should be understood as ready-to-use objects (or groups of objects) with a low-level steering option, i.e. unconstrained parameterisation of the available settings. Complex models are developed by combining elementary structures in line with the flow logic. The MTSS enables 2D and 3D visualisations. The division of the simulation model's logic into logical low and logical high levels is one of the MTSS' distinguishing features, which not only makes it possible to map the object operation principles but also fosters hardware emulation and communication with steering systems.

The hard coal extraction model described by the authors can communicate well with the new DTIDT-developed process steering system, and may be the source of input signals, allowing hardware emulation and the testing of the actual steering process with the simultaneous visualisation of the entire extraction process. This enables debugging and tuning the new process

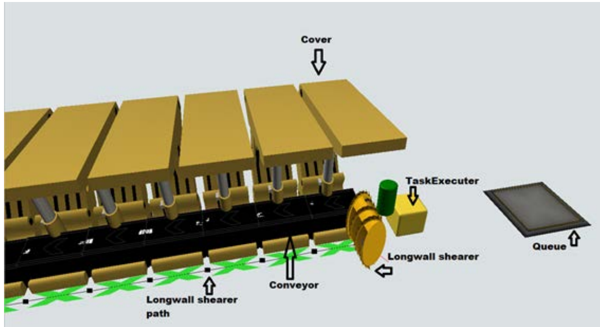

Fig. 1. A longwall shearer model developed in FlexSim (Source: author's own elaboration)
Rys. 1. Widok modelu kombajnu ścianowego w programie FlexSim (Źródło: opracowanie własne)

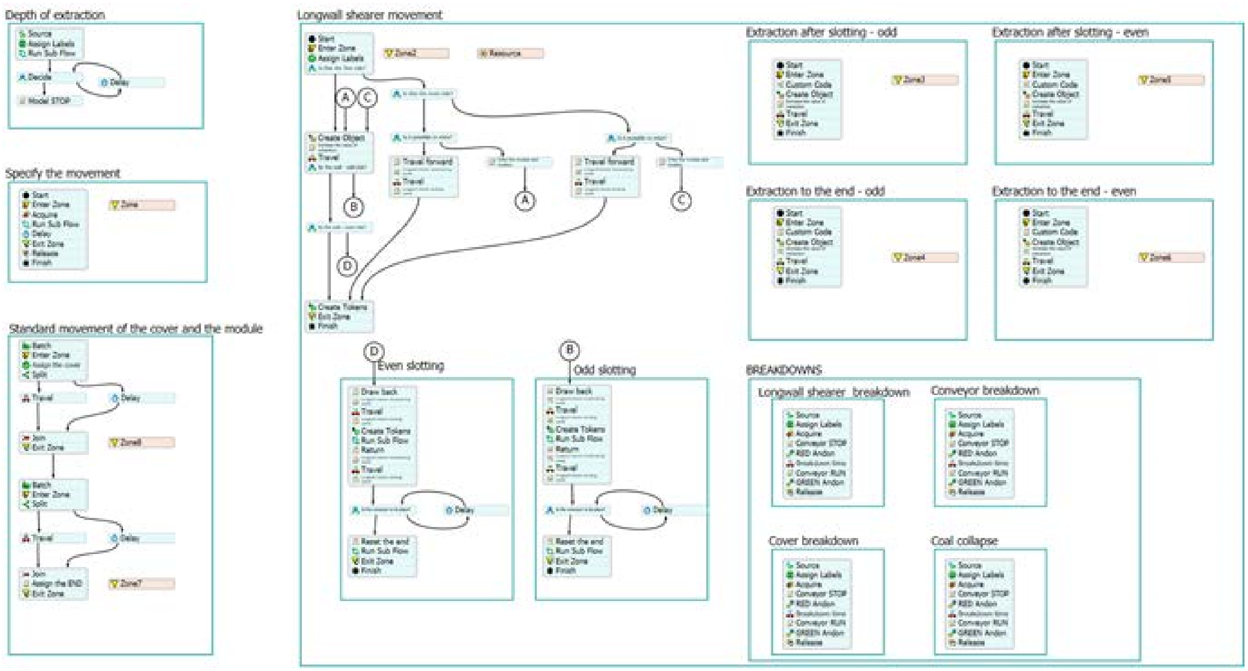

Fig. 2. The simulation model operation logic in ProcessFlow (Source: author's own elaboration)
Rys. 2. Logika działania modelu symulacyjnego w ProcessFlow (Źródło: opracowanie własne)

steering system based on the simulation model responses and outputs. It, therefore, leads to the minimisation of the on-site system launching costs and time.

The authors presented simulation models for three hard coal extraction aspects:

- Simulation of the conveyor system

The conveyor model makes it possible to map transport processes and steering algorithms, as well as to simulate real information signals and steering signals for the process steering system. It also allows to test system work parameters and to stop/start the conveyor when specific conditions occur.

- Simulation of the pumping subsystem

The pumping subsystem model comprises pumps, pipes, containers, water flows and electricity subsystem elements. The simulation is based on two elements, i.e. fluid distribution and energy consumption. The simulation model of the subsystem in question takes into account the technological and underground water pumping processes, and the simulation of energy consumption, thus fostering, inter alia, the pump steering mode optimisation.

- Simulation of the extraction of various types of coal

The principal objective of this library is to enable interactive simulation and visualisation of various extraction aspects in shallow coal beds. The longwall system simulation algorithm was developed on the basis of real steering algorithms used in mining, thus ensuring the accurate mapping of the coalmine operation principles and related processes. This makes it possible to analyse traps and bottlenecks related to using various longwall configurations for different coal layers. In other words, the longwall system itself can be analysed.

As stressed by the authors, the MTSS can be used not only for simulations of the existing hard coal extraction techniques, but also for prospective work techniques. The library of available objects is gradually extended. There is a possibility of establishing detailed simulation models for underground mining plants, including conveyor systems, power supply systems, ventilation systems and various longwall models that may be used for solving the "what if" queries and for steering system development.

An integrated simulation of mining processes

In the industry, certain correlations are always found between product quality, process performance and production costs. An increase in one of these factors automatically leads to a decrease in another. For instance, product quality affects productivity and vice versa. In this situation, it appears necessary to take well-matched process optimisation decisions in order to achieve the highest quality and performance at the lowest possible cost. In the mining industry, there is a risk of an erroneous estimation of potential gains, given the diversified composition of the deposit, which may lead to a quick loss of the competitive edge.

In work [4], the authors developed the Method of Integrated Process Simulation (MIPS), the aim of which is to foster the development of the Decision Support System (DSS), taking into account all the aforementioned factors, i.e. finished product quantity and quality, efficiency, and production costs. The purpose of the DSS is to introduce improvements in the entire production chain in an enterprise. It enables the development of many simulation scenarios responsible for taking decisions concerning performance changes in more than one production process, stocks changes and potential changes at various stages of the production chain, as well as exploitation plans and bottleneck identification. In their work, the authors described the use of this method by referring to iron ore extraction, in response to the shortage of methods that would serve the purpose of assessing the extent to which various decisions impact on the entire production chain [3,4].

The proposed method comprises five steps:

- Step 1 – involves understanding major correlations between productivity and quality,
- Step 2 – involves developing a conceptual system model, taking into account all the production chain operations, following the previous analysis of the productivity/quality relation,
- Step 3 – involves collecting the relevant DSS data and identifying individual variables necessary for determining the calculation model parameters,
- Step 4 – involves data processing,
- Step 5 – the final stage, involving model validation.

The authors applied the MIPS in respect of a Brazilian iron ore mine and performed an in-depth analysis of all five steps in twelve months. In the reference period, major decision-making problems faced by the enterprise were identified, the correlations between productivity and quality were determined, and several DSS applications were implemented. The use of the adequate scenario led to the conclusion that the enterprise was capable of significantly increasing granulate production, achieving fast return on investment, avoiding substantial financial loses, and improving its condition through adequate investment decisions.

The MIPS application brought an array of benefits, including in particular the ability to analyse and justify capital investments, and the possibility of conducting simulations and forecasting production volumes, finished product quality, as well as revenues and financial outlays. The method also facilitated the identification of bottlenecks within the production chain and the ordering of scattered data. Despite these benefits, the authors also noted some weak points of the method, including the significant amount of time required for its implementation, the high number of people involved in the project and the need to re-introduce updates with time, given the variable character of the iron ore and the complexity of processes [4].

A simulation of the dynamic impact of a rock-mass shock on the excavation corridor

Simulation also opens the way for analysing potential threats that may appear in individual mines. Underground hard coal mines are often characterised by high seismicity which may result in shocks and rock bumps. These, in turn, entail several dangers, including fatal accidents. Owing to the more accurate calculations generated by gradually improving computer programs, tests can be conducted, enabling in-depth analyses of mining conditions and, thus, taking the adequate measures to improve workers' safety.

In work [18], the authors conducted a numerical simulation of the dynamic impact of a rock-mass shock on the excavation corridor, using the "Marcel" mine as an example, due to a high risk of bumps occurring in the excavation process. The simulation was performed with the use of the Fast Lagrangian Analysis of Continua (FLAC) software which is mainly employed for simulating rock mass and groundwater behaviours, and for dealing with rock engineering issues. Its purpose is to solve complex problems related to the occurrence of both large deformations and dislocations, and unstable systems. It also enables taking into consideration the issue of rock mass plasticity in the model creation process.

The authors developed a rock mass model in a plane strain state and performed the modelling of a coal bed, along with the excavation corridor. Assumptions regarding rock layer parameters were made on the basis of the mine examination results. To assess the existing

Tab. 1. Percentage downtime shares in disposable time. Source: author's own elaboration based on [1]
Tab. 1. Procentowe udziały przestojów w czasie dyspozycyjnym. Źródło: opracowanie własne na podstawie [Herezy et. al., 2015]

mining breakdowns	55:27	40.62%
technical breakdowns (mechanical)	2:16	1.66%
technical breakdowns (electrical)	11:11	8.19%
technical breakdowns (hydraulic)	2:35	1.89%
technical breakdowns (haulage-related)	9:04	6.64%
efficient system operation time	**39:11**	**28.71%**
organisation and maintenance time	16:46	12.28%
	136:30	

deformations within the excavation, a ubiquitous joint model of anisotropic plasticity was used.

The simulation was performed by the authors in two stages. The first one focused on estimating rock structure damage and rock mass plasticity within the excavation area. The obtained results were used as input data for the second stage involving the conduction of a dynamic simulation, the aim of which was to assess the loads effect on the rock mass and its post-shock reconstruction. This analysis made it possible to estimate the causes of deformations occurring within the excavation area [18,20].

A simulation of the longwall system operation

The author's longwall system simulation model was developed with the aim to analyse the impact of selected parameters on the excavation process. The simulation model was created using FlexSim 18.0.3 software, whereas the logic of the longwall shearer work was mapped using the ProcessFlow technology embedded in that software, which had not been previously used for simulations in that area. It enables the construction of a simulation model as a block diagram. The ProcessFlow technology makes it possible to easily adapt the 3D model operation to current conditions which, in turn, fosters increased elasticity. This appears especially useful in creating large and complex models and enables a significant reduction in the model development time. The longwall system model was developed in such a way that it could be further extended by additional modules and analytic variants. To this end, the ProcessFlow logic was made fully independent of the shearer type and the assumed work parameters.

Using the library of 3D objects available in the FlexSim software, the basic arrangement of the longwall system was created. In the model, both the mining head itself and various conveyor and cover modules are mapped using TaskExecutors. In addition, a queue structure of data flow was used to map the excavation process. Figure 1 presents a longwall shearer using the FlexSim software.

The model operation logic developed using ProcessFlow comprises several interrelated blocks (sub-processes). The construction of the system operation logic using blocks considerably facilitates the analysis of various stages and the mapping of the work flow. A transparent description of the entire process provides an additional advantage. Figure 2 presents the ProcessFlow logic developed for the purpose of the model.

Model steering begins with the "Depth of extraction" area where the system sliding towards the longwall is calculated. The "Specify the movement" block serves the purpose of determining the number of movements made along the conveyor by the mining head. The "Longwall shearer movement" block maps the principle of the longwall shearer movement along the conveyor. However, certain specific manoeuvres were distinguished.

At first, it is verified whether the shearer has just launched. If not, the movement direction and the excavation possibility are verified. At the subsequent stage, the position of the mining head is checked. If it is not positioned next to the longwall, the rule responsible for the module movement is activated in the "Standard movement of the cover and the module" block, and the logic begins from the start. It should also be noted that the standard movement of the cover and the conveyor was arranged by taking into account the delayed movement of those elements in relation to the mining head movement. In order to map the real working conditions of the longwall system, several types of breakdowns were also taken into account in the model creation process. The breakdowns logic is presented in the "Breakdowns" block.

The model was developed so as to enable the analysis of the longwall system operation depending on both wall parameters (height) and longwall shearer parameters (working speed, manoeuvring speed, cutting range). The purpose of this approach is to enable verification of various extraction scenarios, depending on the available equipment, and to support investment decisions concerning equipment purchase/modernisation. Users may freely change these parameters, depending on their actual needs. Moreover, due to frequent breakdowns occurring within the longwall system, a possibility to enter various breakdown parameters (such as the mean time between failures and the mean time to repair) was envisaged. Once the data are entered to the control panel, and the model is re-launched, the results for current assumptions are displayed. The model, therefore, provides information on the longwall shearer work efficiency and on the impact of various breakdowns on shearer work. In addition, coal extraction values in m3 and tonnes are displayed. Figure 3 presents examples of simulation analysis results.

The presented approach to longwall system modelling has only entered an initial stage of the analysis. The authors are planning to extend the model by including additional parameters related to both the properties of the extracted raw material and the shearer itself. The model developed to date is aimed at outlining the possible options and proving the ease of modelling mining processes by means of discrete event simulation software.

Factors reducing efficiency

The first objective of the implemented project, which envisaged the most accurate simulation of the longwall system exploitation, was to establish mutual correlations between the longwall shearer, conveyor and cover segments operations. This objective was accomplished with the use of the ProcessFlow technique. Along with the assumed values of the machine work parameters, such as shearer speed (i.e. excavation and manoeuvring speed), conveyor speed, cover section operational speed, etc., resulting from catalogue information, an array of factors reducing exploitation efficiency, which are mainly environmentally-conditioned, need to be taken into consideration in the process efficiency simulation.

In the excavation area, downtime may occur due to:

- geological and mining factors (roof and rock slides and collapses within the excavation area, bumps, bottom taking or excavation reconstruction before the wall face which stops or slows down the excavation progress, decompression blasting, breaking of rounds),
- technical factors (damage to longwall system elements, electrical faults, hydraulic faults and haulages) [10].

The rapid development of electronic technologies which has been observed in recent years, resulting in the growing availability of various methods of measuring machine work parameters, makes it possible, in particular, to monitor pressure in the racks of the powered support section [13]. This allows, inter alia, to forecast the volume of roof rock falls and rock slides into longwall working. In work [9], an increase in the monitored rack pressure was associated with roof rock compressive strength, vertical convergence of drifts and the speed of wall advance, which allowed to develop nomograms for projecting vertical convergence both in front of and behind the wall face.

Questionnaire surveys conducted among employees of Polish coal mines, concerning geological factors which affect the occurrence of roof falls in longwalls with cavings were described in work [16]. Among the most important factors, the survey participants listed geological distortions, stability of the coal side wall, roof rock strength parameters, as well as the occurrence of weak rocks in the immediate roof. In addition, they mentioned rock dampness, cleavage and the degree of caved debris reconsolidation [16].

The problem of determining disposable time losses resulting from the above-mentioned factors has been hardly addressed in literature. However, contemporary methods of equipment work monitoring based on the continuous measurement of electrical parameters allow for a precise determination of machine utilisation factors [11]. The authors of work [10] focused on assessing the impact of automation on an improved efficiency of longwall. They conducted practical observations, based on which they distinguished several groups of downtime causes and determined percentage downtime shares in disposable time. These are shown in Table 1.

The presented conditions of the exploitation process and a number of other conditions connected with the impact of mining speed on methane generation or the width of exposed roof, provide a starting point for the next stage of work on the model which will take into consideration the above factors. At the current stage, the model assumed statistical arrangements of downtime parameters, reflecting breakdowns occurring for mining or technical and organisational reasons.

Concluding remarks

The articles mentioned above provide evidence that computer simulation can be successfully used both in underground and open-pit mining. As has been demonstrated, there is a wide range of simulation and modelling software available on the market, serving the purpose of improving the existing processes as well as designing new mines from scratch. Individual software solutions provide an opportunity for building elementary structures (ready-to-use objects or groups of objects) and performing complex system simulations. Both 2D and 3D visualisations of processes can be made.

The unquestionable assets of computer modelling include supporting the decision-making process, facilitating the understanding of certain correlations between productivity and the quality of finished products, introducing improvements in the entire production chain, and conducting integrated process simulations. The opportunity for supporting decisions concerning capital investments appears invaluable. Another advantage refers to analysing potential threats and assessing the rock mass state and land conditions within the excavation area, which facilitates taking the adequate measures to improve workers' safety. Simulations also enable creating variants and scenarios, from among which the most optimal solution can be selected.

The simulation method of hard coal extraction within a longwall system, based on the ProcessFlow concept, as proposed by the authors, is merely the first attempt and may be further improved. The presented model, once validated, may provide grounds for decision-makers to conduct various analyses concerning the performance and efficiency of the longwall system operation. The authors opted for the ProcessFlow concept due to its transparent presentation of existing correlations by means of block diagrams, a much shorter project development process and the ease of introducing changes.

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Przegląd symulacji komputerowych w górnictwie podziemnym i odkrywkowym

W artykule zaprezentowano rolę symulacji komputerowych w dzisiejszych czasach oraz omówiono cele i korzyści płynące z wykorzystania tego typu rozwiązań. Ustalono, że dzięki zastosowaniu symulacji i wirtualnych modeli możliwe jest zwiększenie wydajności analizowanych procesów przy jednoczesnej minimalizacji kosztów: produkcji, logistyki, magazynowania itd. Co więcej, modele symulacyjne pozwalają na analizę scenariuszową różnych rozwiązań, a tym samym i podejmowanie trafnych decyzji na podstawie uzyskiwanych wyników. Dlatego też stają się one podstawą do analizy różnych zmian technologicznych i procesowych. Narzędzia do modelowania i symulacji coraz częściej wykorzystuje się również w branży górniczej. Modele komputerowe procesów górniczych zasilone rzeczywistymi danymi są użytecznym narzędziem do testowania planowanych zmian, analizy ryzyka inwestycji czy też oceny jakości przyjętych rozwiązań. Autorzy przytoczyli i omówili wybrane symulacje procesów górniczych wykonane w różnych narzędziach, a także zaproponowali metodę symulacji procesu wydobycia węgla kamiennego kompleksem ścianowym w wymiarze 3D przy wykorzystaniu oprogramowania FlexSim Simulation Software. Model symulacyjny został zbudowany w oparciu o technologię ProcessFlow, pozwalającą na budowę logiki działania systemu w postaci schematów blokowych, a tym samym i znaczne skrócenie czasu modelowania obszernych procesów.

Słowa kluczowe: symulacja komputerowa, górnictwo, FlexSim, modelowanie