

DE GRUYTER
OPEN

GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2017

Volume 33

Issue 2

Pages 113–128

DOI 10.1515/gospo-2017-0015



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An expert system for underground coal mine planning

Introduction

The deepening crisis in the global coal market has an undeniable impact on the domestic producers. Mining enterprises are faced with the need to take actions to improve the efficiency of the mining process. Among these activities the joining of the mines is also undertaken, that enforces a centralization of activities in the field of deposit economy and the planning of mining operations in these companies. The production process in an underground coal mine is characterized by high financial expenditures to conduct mining operations, the high costs of salaries and the engagement of expensive technical equipment. Therefore, the maximum possible utilization of technical equipment, the proper use of staff potential and to assess the level of risk of meeting the assumed production plans should be taken into account during the mine planning. Relevant knowledge is required, especially on the part of the designers, which could be completed with various data bases and informatics systems, for proper completion of this process.

The uniqueness of the mining conditions in underground hard coal mines requires, in the planning process, paying more attention to experience and knowledge acquired during continuous and past mining works. This knowledge can be of two types – evident knowledge and tacit knowledge. The second one is related to the people employed in the company, is difficult to obtain and not formalized. This intellectual human capital (skills, extensive experience and intuition) used in the planning solution brings certain production and economic

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advantages for the mining company. Decisions undertaken at the planning stage of the mining process have a great impact on the future of the mine. At this stage, designers develop variants of coal mine production process, determine the schedule of operations and assign equipment to the planned excavations. Decisions made at this stage, according to the deposit development or operations schedule are largely irreversible. Therefore, it is important to use knowledge about the production results obtained in certain mining conditions, allowing for selection of the optimal solutions in the scope of the mine production planning.

For the mining companies, it is important to create solutions taking the uniqueness of the mining process and efficient use of the experience and knowledge gained during mining operations into account.

The currently observed continuous development of new technologies and forms of business involves huge amounts of data. Thus, newer forms of decision-support development are continuously demanded (Hosack et al. 2012). Reviewing these sources can help create a firm foundation for enhancing knowledge in IS research (Pare et al. 2015). From a decision support perspective, the reasoning knowledge formulates decision parameters and perspective rules, and thus contributes to making informed decisions (Miah, Kerr and von Hellens 2014).

The development of technology in the mining industry also needs to be managed on the basis of decision support systems. The latest examples of work on such systems include a demand-responsive decision support system which integrates the operations of coal shipment, stockpiles and railing (Kozan et al. 2012) or simulation based decision support system for sustainable coal mining operations (Nageshwaranier et al. 2012).

The abilities to store and use knowledge are provided by expert systems (Liebowitz ed. 1997). Expert systems have been already implemented in the global mining industry. One of the earliest is PROSPECTOR (Hart and Duda 1977), designed to solve problems associated with the exploration and mining of minerals, which allowed for the discovery of rich molybdenum deposits. Another example is SHEARER, developed for a British Coal mine, described in (Perkin, Pitt and Price 1986), which diagnoses failures of the longwall shearers. Selected expert systems for coal mining are related to *inter alia*: planning construction or reorganization of the coal mine (Samantha and Samaddar 2002), identification of stratigraphic layers in the mine (Plumer 1992), selection of the operating systems and methods for mining and geological conditions (Zhang and Zhao 1999), selection and monitoring of mining machinery (Basu, Yuejin and Singh 1991; Streichfuss and Burgwinkel 1995; Basu and Lineberry 1995; Liu et al. 2010), management of the coal mine (Britton 1987; Grayson et al. 1990), coal mine safety (Liu and Huang 2008; Yingxue and Hongguo 2010).

The latest solutions in the area of expert systems in mining regard mine efficiency estimation (Golak and Wieczorek 2014), machinery system management (Stefaniak et al. 2014), monitoring processes, devices and hazards in a coal mine (Kozielski, Sikora and Wróbel 2015) or fire hazard monitoring (Grychowski 2014). There is also research on expert system shell for the coal mining industry (Przystalka et al. 2016).

In this paper we present an expert system (MinePlanEx) with new language version of the interface, allowing for the use of the system by the wider user community. Our system,

due to its scope of application and possibilities of equipment multi variant analysis in the planning of mining operations in underground mines, is a new proposal in the mentioned area.

1. Architecture of the MinePlanEx system

The aim of the the MinePlanEx system is to support the designers of production planning in hard coal mines within the scope of (Brzywczy et al. 2011):

- ◆ equipment selection with respect to geological and mining conditions of the planned excavations,
- ◆ mining machinery combining into equipment sets (including shearer, conveyor and only for longwall faces – mechanized support),
- ◆ determining characteristic curves regarding the production results in the planned excavations (rate of advance of the mining operations).

The system consists of the following components (Brzywczy et al. 2013):

- ◆ knowledge base,
- ◆ knowledge-acquisition module,
- ◆ inference module.

The main element of the MinePlanEx system is a knowledge base that integrates data related to the geological, mining, technical and organizational conditions of conducted excavations, equipment specification and models of the mining operations' advance achieved in excavations. A detailed description of the MinePlanEx system components is presented below.

1.1. Knowledge base

The knowledge base consists of: database, rule base and model base.

The database includes detailed information related to mining operations conducted in the past. Current data of 272 longwall faces and 870 openings is gathered. These excavations were conducted in two multi-plant mining companies.

The database is divided into two parts:

1. Part I – includes the data on openings.
2. Part II – includes the data on longwall faces.

In each part three segments are separated according to the scope of the data and information contained in the database. These are:

- ◆ excavation conditions (described by list of parameters – 42 for longwall faces and 33 for openings),
- ◆ equipment used,
- ◆ rate of the mining operations' advance.

The rule base contains a set of different rules for equipment selection according to mining conditions of the excavation and the rules of combining mining machinery into equipment sets.

The general form of the rule is as follows:

IF (fact 1 exist) and (fact 2 exist) and ... and (fact n exist) THEN (conclusion is W)

Rules are qualified by a certainty factor (CF).

Rules were formulated by using manual and computer-based acquisition techniques.

The knowledge acquisition from the experts was carried out through interviews and the observation of the problem solved by the professional project team.


An example of the questionnaire is presented in Fig. 1.

Knowledge acquisition using the questionnaire was conducted in the following steps:

1. The questionnaire was presented with an explanation of its contents.
2. The designer (expert) began conceptual work.

Form of questionnaire

THE QUESTIONNAIRE OF ACQUISITION OF KNOWLEDGE FROM EXPERT

	Data	
	seam thickness	1.7–2.0 m
	hazards:	
	coal dust explosion	class A
	fire	group V
	tremor and rock burst	I degree
	water	I degree
methane	-	
gas and rock outburst	-	
roof class	I class	
workability	I group	
roof control: caving	roof cut	
production rate	1000 Mg/day	

1. Please choose the equipment for longwall faces in the presented operating panel.
2. Please estimate advance of the mining operations, which is possible to achieve (according to your knowledge) in the given geological and mining conditions, with the accepted number of shifts that equals 3 and with 6-hour effective working time.

Fig. 1. Questionnaire for expert knowledge acquisition – sample

Rys. 1. Kwestionariusz dla pozyskania wiedzy od eksperta – przykład

3. During problem solving the expert was asked (i.e. Why?, and What if?, What does this result from?, What would you point out? etc.).
4. The expert answers were recorded in order.
5. The acquired knowledge was organized.
6. After checking by an expert, the rules were introduced into the knowledge base.

Algorithms of classification trees and association rules were used in the computer-based knowledge acquisition process. Classification trees were used to determine the rules for the selection of equipment for different excavation conditions, while the association rules were used in the analysis of combining mining machinery into equipment sets.

The best models of classification trees were created with the C5.0 algorithm (concerning accuracy of the classification). The selection of variables for analysis was based on the expert survey that identified relevant factors for the equipment choice for mining operations.

Sample rules from the classification tree are presented below:

```

Rule for JOY 4LS22
  if Height > 1,800
  and Height <= 2,400
  and CuttingDepth = 0.8
  and LongitudinalInclination <= 7.400
  then shearer = JOY 4LS22

Rule for RYBNIK 850
  if TransverseInclination > 5
  and LongitudinalInclination > 6
  and LongitudinalInclination <= 10
  and Length > 154
  and Length <= 247
  then conveyor RYBNIK 850

Rule for TAGOR 12/31 POZ
  if FloorClass = III
  and RoofClass = I
  and Height > 2,450
  and Height <= 3,320
  then mechanized support TAGOR 12/31 POZ
  
```

The association rules were created with use of the A'priori algorithm. A sample of the rules is presented below:

```

If TAGOR 12/35           then KGS 600S
If KSW 475W             then RYBNIK 850
If GLINIK 12/24 POZ    then KSW 880EU
If JOY 7LS6            then GLINIK 21/46 POZ
If JOY 7LS6            then RYBNIK 1100
If TAGOR 14/32.5 POZ   then JOY 4LS20
  
```

The model base includes functions of the mining operations' advance, in particular excavations. This rate is one of the most important factors determining the production results that can be achieved in specific geological and mining conditions. For the purpose of the better modelling of the mining process, it has been assumed that the model of operations' advance in the knowledge base will be stored as a probability density function of the specified distribution.

Distributions of the mining operations advance have been determined by a statistical analysis of data related to excavations from the database. The fitting of the distribution function to the data was confirmed by the results of the statistical tests. There is a possibility of introducing parameters, inter alia, the following distributions: normal, log-normal, Chi-Square, beta, triangular in the model base, as popular in the description of real data collections.

1.2. Knowledge acquisition module

The knowledge acquisition module includes forms for entering, recording and editing knowledge in the system.

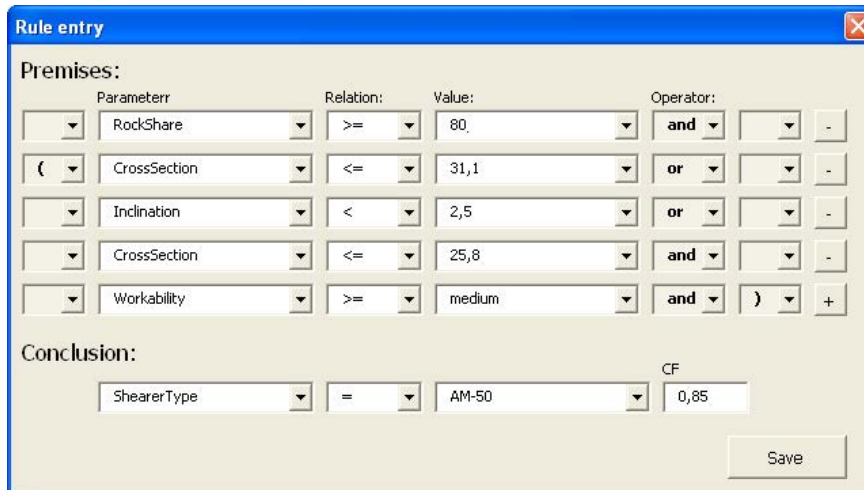
An example of form for entering data of excavation equipment is shown in Fig. 2.

In Fig. 3 a form for defining rule, with the possibility of expanding the premises list, is presented.

Field	Value
Type	RYBNIK 850
Chute height	260
Chute width	850
Chute thickness	45
Chain number	2
Chain speed	1.3
Drive power	3x250/85
Productivity	1500
Dump type	Sideway
Condition	after inspection
Ownership	leasing

Fig. 2. Form for entering data of a longwall conveyor

Rys. 2. Formatka dla wprowadzenia danych o przenośniku ścianowym



Premises:				
Parameter	Relation	Value	Operator	
RockShare	>=	80	and	-
(
CrossSection	<=	31,1	or	-
Inclination	<	2,5	or	-
CrossSection	<=	25,8	and	-
Workability	>=	medium	and) +

Conclusion:			
Parameter	Relation	Value	CF
ShearerType	=	AM-50	0,85

Fig. 3. Form for entering the rule into the rule base

Rys. 3. Formatka dla wprowadzenia reguł do bazy reguł

There is also the possibility of introducing rules from other programs in the form of an xml file. This allows for the easy exchange of data between different systems, especially data mining software.

1.3. Inference module

In the MinePlanEx system, the inference process works as forward chaining. After loading a list of facts concerning the planned excavation and available equipment, the database is searched to find an excavation similar to the planned one in terms of mining conditions and equipment. If such an excavation is found, a message is generated and the inference process ends. When the program cannot get an answer, the following steps are taken.

Rules with true premises are specified. All rules which can be used at the inference stage supply the memory of the system. Then, rules are activated based on the selected reasoning strategy (freshness, specificity, the highest CF). This process is continued until the final answer is reached or when no more rules can be activated.

After selecting a set of equipment for the planned excavation and its acceptance in the system, the estimation of the mining operations' advance using taxonomic procedures is carried out.

Taxonomic procedures enable searching for the object most similar to the model. After finding such an object, designers can validate their own assumptions based on previously observed values. Taxonomic procedures also allow for the defining of a group of such objects – clustering (Webb 1999).

The results of clustering can be represented as a hierarchical graph, where the taxonomic tree represents the distance between objects. The length of the vertical branches of the tree corresponds to the distances between the clustered objects. The hierarchical tree allows for the easy distribution of the objects in a predetermined number of groups.

After determining the group of similar objects, the value of the searched parameter could be estimated. These estimates, in accordance with the taxonomy procedures, can take place for example, by the adoption of a parameter value from the object that is representative of the group.

2. Example of the system operation

The system operation scheme is presented in Fig. 4.

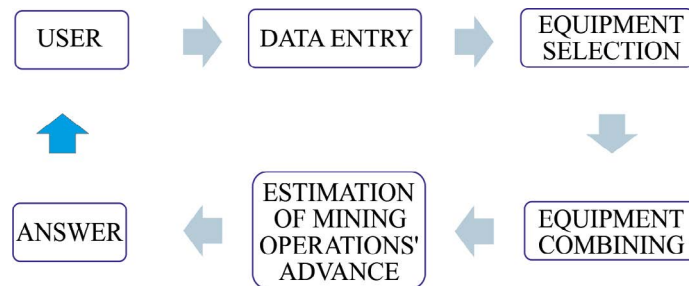


Fig. 4. Scheme of the system operation

Rys. 4. Schemat działania systemu

After entering the data following steps are carried out:

1. The system proposes machinery that can be used in the conditions of the planned excavation.
2. The possibility of combining machinery in the equipment sets is checked.
3. The advance of the mining operations is estimated for selected sets of equipment and conditions of the planned excavation.

The system operation starts by selecting an option from the start window.

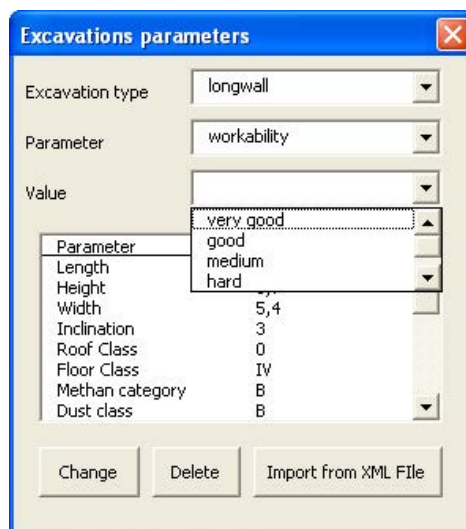
To illustrate the system operation, an example of longwall face is given with the following parameters:

- ◆ seam thickness: 3.0 m
- ◆ transverse inclination: 4.2°
- ◆ longitudinal inclination: 7.3°
- ◆ longwall face length: 230 m
- ◆ longwall face height: 2.7 m
- ◆ longwall face workspace width: 5.1 m

- ◆ coal workability: easy
- ◆ rock share in longwall cross-section: 15%
- ◆ floor class: II
- ◆ roof class: I
- ◆ methane category: II
- ◆ dust class: B
- ◆ degree of rock burst hazard: I
- ◆ roof control: caving

These parameters were identified by domain experts as having a significant impact on the selection of equipment for excavation conditions.

Firstly, the parameters of the planned excavation should be entered (Fig. 5) or an xml file with these parameters should be uploaded.



Parameter	Value
Length	
Height	
Width	5,4
Inclination	3
Roof Class	0
Floor Class	IV
Methan category	B
Dust class	B

Fig. 5. Form for entering the parameters of the planned excavation

Rys. 5. Formatka dla wprowadzenia danych o planowanym wyrobisku

Then, based on the data stored in the database of the machinery, the system presents a list from which the user can choose the equipment that is available to the designer (Fig. 6).

Before starting the inference process, the user makes setting of the inference algorithm, using the form shown in Fig. 7.

As a result, the system generates list of machines and equipment sets that can be used in the planned excavation. The system allows the user to see the rules, which were used during the inference process (Fig. 8). Left side triangles mark available equipment, which was declared by the designer, while an unmarked element contains alternative equipment found by the system.

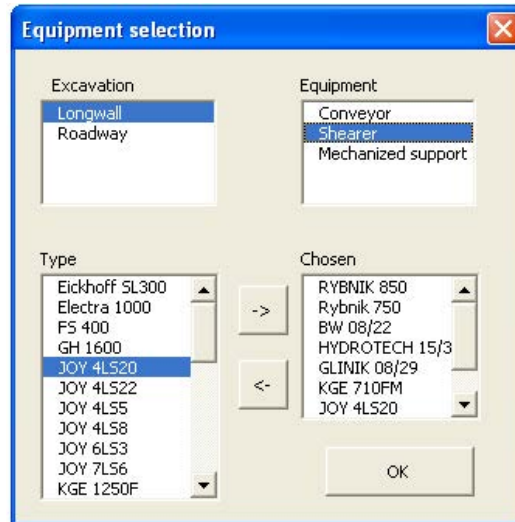


Fig. 6. Selection of equipment available to the designer

Rys. 6. Wybór wyposażenia dostępnego dla projektanta

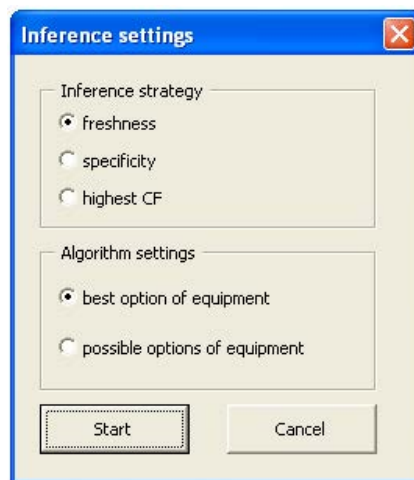


Fig. 7. Inference algorithm settings

Rys. 7. Ustawienia algorytmu wnioskowania

Once the user selects a particular set of equipment, the system enables to estimate the advance of the mining operations in the planned excavation.

The result of system operation is presented in the window (Fig. 9), where the equipment set is presented and the estimated value of the advance in the planned excavation is provided. The designer can go back to select other optional equipment set using the *Back* option.

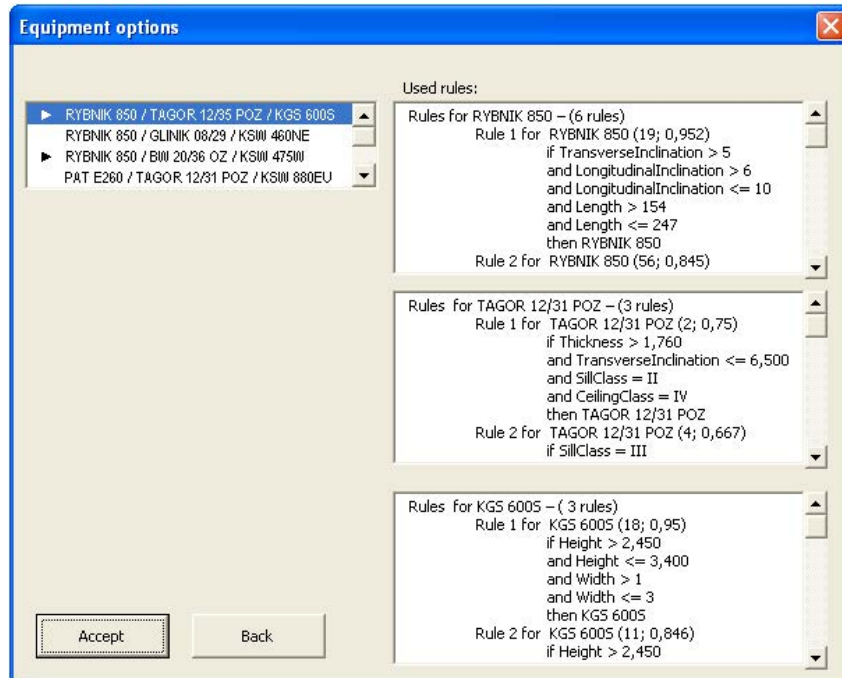


Fig. 8. Possibilities of equipment for planned excavation with the used rules

Rys. 8. Możliwości wyposażenia planowanego wyrobiska zgodnie z wykorzystanymi regułami

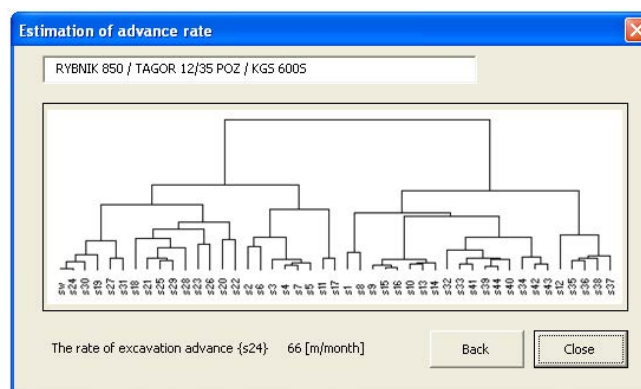


Fig. 9. Estimation of the mining operations' advance in the planned excavation

Rys. 9. Oszacowanie postępu robót w planowanym wyrobisku

The hierarchical tree contains planned excavation (sw) that has been assigned to a group of similar excavations. The estimated average value of the advance rate for this group is 66 m/months. The following equipment is proposed in the case of the analyzed longwall face:

- ◆ longwall shearer – KGS 600S,
- ◆ longwall conveyor – Rybnik 850,
- ◆ mechanized support – Tagor 12/35 POz.

The results regarding the proposal of the equipment set for the planned excavation and estimation of the advance rate value can be used in the planning of the mining production process conducted in a single mine or group of mines.

Summary

It is indispensable to use experiences and knowledge gathered during the mining process in the modern deposit economy and operational planning in mines. Proper use of this knowledge in the design process is essential to create design solutions and for their successful implementation.

Decisions which are undertaken at the planning stage have a great impact on the future results of the single mine as well as the results of the company. Unfortunately, most of the decisions, especially according to deposit development, are irreversible. Therefore, it is very important to use the proper tools, which could support the use of knowledge on the production results, obtained in certain mining conditions, in the mine production planning.

An example of such tool is presented in this paper in the form of an expert system that enables the collection, storage and use of knowledge related to deposit management and mine planning in an underground hard coal mine.

An essential element of the developed system is the knowledge base that integrates data describing the geological, mining, technical and organizational conditions of the conducted excavations and their equipment along with the models of the mining operations' advance. The knowledge base also includes rules related to equipment selection and machinery combining into equipment sets.

Expert methods and data mining techniques (such as decision trees, association rules, statistical and taxonomic methods) were used in the process of knowledge acquisition for the system purposes.

The system can be used in deposit management by facilitating the work of the designer who plans to develop and exploit the new deposit or new mining levels with the use of knowledge about excavations conducted in different geological and mining conditions.

It can also support, among others, the rational management of the equipment in the mine by identifying the various possibilities of the equipment allocation to the planned excavations. An important advantage of the system is the estimation of the mining operations' advance in the planned excavations, based on results achieved in real conditions.

Acknowledgements

This paper presents the results of research conducted at AGH University of Science and Technology – Contract no 11.11.100.693

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SYSTEM EKSPERTOWY DLA POTRZEB PLANOWANIA ROBÓT GÓRNICZYCH W PODZIEMNYCH KOPALNIACH WĘGLA KAMIENNEGO

Słowa kluczowe

system ekspertowy, górnictwo węgla kamiennego, planowanie, zarządzanie wiedzą

Streszczenie

W obecnej sytuacji rynkowej przedsiębiorstwa górnicze stają przed koniecznością podjęcia działań, mających na celu zwiększenie efektywności prowadzonego procesu wydobywczego. Wśród tych działań znajdują się również łączenia kopalń (lub ich części), które wymuszają pewną centralizację działań w zakresie gospodarki złożem i planowania robót górniczych w tych przedsiębiorstwach.

Dla poprawnej realizacji procesu planowania w takim zakresie wymagane jest posiadanie odpowiedniego zasobu wiedzy członków zespołu projektującego, który powinna uzupełniać baza wiedzy, zasilana informacjami i danymi uzyskanymi w miarę realizacji zaprojektowanych robót przygotowawczych i eksploatacyjnych oraz umożliwiająca wykorzystanie wiedzy ekspertów z innych jednostek organizacyjnych kopalni lub przedsiębiorstwa.

W artykule zaprezentowano oryginalny system ekspercki do planowania robót górniczych w podziemnych kopalniach węgla kamiennego (MinePlanEx). Celem systemu jest wspieranie projektantów planowania produkcji w kopalniach węgla kamiennego w zakresie doboru sprzętu do warunków

geologiczno-górnictwowych i określania charakterystyk dotyczących wyników produkcyjnych w planowanych wyrobiskach. Wiedza w systemie reprezentowana jest przez reguły wyznaczone z wykorzystaniem wybranych technik drążenia danych (reguły asocjacyjne oraz drzewa klasyfikacyjne) oraz uzyskane od ekspertów.

W pierwszej części artykułu przedstawiono bazę wiedzy, moduł akwizycji wiedzy i wnioskowania, które są głównymi składnikami systemu. Druga część zawiera przykład działania systemu.

AN EXPERT SYSTEM FOR UNDERGROUND COAL MINE PLANNING

Keywords

expert system, coal mining, mine planning, knowledge management

Abstract

In the current market situation, mining companies are faced with the necessity to take actions to improve the efficiency of the mining process. Some of these actions enforce a centralization of activities in the field of deposit economy and planning of mining operations in these companies. In the planning process with such scope the large knowledge of designers is required, which could be additionally supported by a knowledge base, supplied by information and data obtained during the completion of mining works, which also allows for use of the expert knowledge of other organizational units of the mine or the company.

The paper presents an original expert system for mining works planning in the underground hard coal mines (MinePlanEx). The aim of the developed system is to support the designers of production planning in hard coal mines within the scope of: equipment selection, mining machinery combining into equipment sets and determining characteristic curves regarding the production results in the planned excavations. Knowledge of the system is represented by the rules selected with the chosen data mining techniques (association rules and classification trees) and obtained from experts.

The first part of the paper presents a knowledge base, knowledge acquisition module and inference module which are the main components of the system. The second part contains an example of system operation.

