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NEW POSSIBILITIES FOR PROCESS ANALYSIS IN AN UNDERGROUND MINE

Abstract. The paper presents selected issues related to process and risk management in mining companies. For the purpose of identification and analysis of processes in the underground mine, process mining techniques were proposed. An example of their application in analysis of roof support operation process in underground coal mine is presented.

Keywords: underground mining, process analysis, process mining, roof support operation process

NOWE MOŻLIWOŚCI ANALIZY PROCESÓW W KOPALNI PODZIEMNEJ

Streszczenie. W artykule przedstawiono wybrane zagadnienia dotyczące zarządzania procesami i ryzykiem w przedsiębiorstwach górniczych. Na potrzeby identyfikacji i analizy procesów w kopalni podziemnej zaproponowano wykorzystanie technik eksploracji procesów. Opisano przykład eksploracji procesu działania obudowy zmechanizowanej w kopalni podziemnej.

Słowa kluczowe: górnictwo podziemne, analiza procesów, eksploracja procesów, proces pracy obudowy zmechanizowanej

1. Introduction

In the context of organisation management, risk is very often considered mainly from a project management perspective. However risk is an inherent property of every business process in enterprise[1].

In the literature various definitions of risk can be found, *inter alia*[2]:

- risk understood as the danger of not fulfilling the stated purpose in taking a particular decision,
- risk defined as the likelihood of a negative event occurring,
- probability of loss,
- probability of a result other than expected.

One of the basic risk classification in company distinguishes two general groups[3]:

- specific risk (referring to the interior of the enterprise),
- systematic risk (related to the functioning of the enterprise in the changeable environment).

Other classification regarding the major types of risk in companies includes[4]:

1. *Strategic risk* related to execution of corporate and business strategies (e.g. growth of product innovation, mergers and acquisitions etc.);
2. *Business risk* related to periodic financial and operating results of business activities;
3. *Market risk* related to process and rates on the market;
4. *Credit risk* related to obligations between enterprise and customers, suppliers or counterparties;
5. *Liquidity risk* related to cash raising for company needs;
6. *Operational risk* related to actions and reliability of processes and systems in company;
7. *Compliance risk* related to law and regulations observance.

Considering the presented list, processes are the source of operational risk in a company. This perspective in process realisation is related to the incoming business objects (e.g. raw material with low quality), data (e.g. a vendor master record with outdated conditions), resources (e.g. employees, machinery) or information technology (e.g. a network transmission fails)[5]. In this context, process management is directly related to risk management in company and *vice versa*.

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[1] Rosemann M., zur Muehlen M.: Integrating Risks in Business Process Models. "ACIS 2005 Proceedings", 2005.

[2] Wodarski K.: Zarządzanie ryzykiem w procesie planowania strategicznego w górnictwie węgla kamiennego. Wydawnictwo Politechniki Śląskiej, Gliwice 2009.

[3] Jonek-Kowalska I.: Risk management in the hard coal mining industry: Social and environmental aspects of collieries' liquidation. "Resources Policy", Vol. 41, 2014, p. 124.

[4] Lam J.: Enterprise risk management: From incentives to controls. John Wiley & Sons, Hoboken 2014.

[5] Rosemann M., zur Muehlen M.: Integrating Risks…, op.cit.

In a mining company, process management is very challenging action due to specific conditions of mining process realisation, especially concerning underground mining.

Among the various sources of specific risk that do not occur in other companies (e.g. geology, raw material quality), natural hazards should be mentioned: gas, dust, rock burst, water, seismic and other[6].

To manage risk in the mining company, firstly, the processes should be identified and analysed. These stages are also familiar with BPM cycle in a classic Business Process Management approach.

If organization has engaged in BPM initiatives before, it is likely that an inventory of business processes is available. If not, identification phase should be performed. As result process architecture is created, which typically takes the form of a collection of processes with different types of relation[7]. The next stage is to understand the process in detail, which is a subject of so-called process discovery. In this stage a process model should be developed, which can be subject to further analysis. This model should reflect accurately a real process performance ("as-is" model type). After creation of a process model, further analyses could be carried out.

In the paper we would like to present new possibilities for analysis of processes in a mining company. We focus on specific underground process, which is strongly related to chosen exploitation system and applied technology solutions. In analysis of selected process we use various process mining techniques.

2. Characteristic of selected process

Two main mining methods are used in practice: underground and, more common, surface method. In some geological conditions (especially due to deposit's depth) only underground method is possible. As an example hard coal or copper mining in Poland can be given.

In the underground method raw material is transported from underground through mining excavations to the surface. After vertical and horizontal access to deposit, cutting of deposit surface is carried out and deposit exploitation. Exploitation phase could be executed with use of room-and-pillar system (more popular on the world) or longwall system (most often used in Polish coal mines).

Our research concerns a mining process and production results of longwall faces in an underground coal mine. These results depend on mining conditions (especially geological conditions and mining hazards) and used equipment.

[6] Jonek-Kowalska I.: Risk management…, op.cit.

[7] Dumas M., La Rosa M., Mendling J., Reijers H.: Fundamentals of Business Process Management. Springer-Verlag, Berlin 2013.

Monitoring and analysis of longwall's operation and working equipment were objectives of various researches, presented *inter alia* in[8].

In Polish coal mining lack of initiatives for wide using of monitoring data in process management can be observed. Functioning systems in this area are rather used by machinery vendors to monitor the machinery operation on the site. Whereas monitoring data, after preparation phase, can be easily used for process modelling and analysis. As example in this area we present analysis of roof support operation process. Roof support ensures safe movement of persons operating and servicing the equipment. Automated mining roof support of a longwall consisting of a line (up to a few hundred) of hydraulic roof supports[9] (Fig. 1).

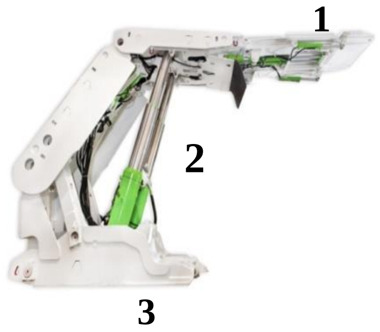

Fig. 1. Basic elements of roof support (1 – roof-bar, 2 – props (legs), 3 – footing)
Source: https://famur.com/produkty/frs-fazos-1441-2x3380/

The basic cycle of roof support operation process starts from the shearer passage. After this passage a hydraulic system decreases the pressure in the props to break the contact with the roof. Then moving of support and shifting is performed. Afterwards a rapid pressure

[8] Balaba B., Ibrahim M.Y., Gunawan I.: Utilisation of data mining in mining industry: Improvement of the shearer loader productivity in underground mines. "10th IEEE International Conference on Industrial Informatics", Beijing, China 2012.; Duan C.: Stochastic availability analysis and modeling of longwall mining operations. Virginia Polytechnic Institute and State University, ProQuest Dissertations & Theses Global, Blacksburg 1990; Frith R.: Development and demonstration of longwall monitoring system for operational decision ma king. ACARP, Project Report No. 4017, July 1996; Gąsior S.: Diagnosis of Longwall Chain Conveyor. "Mining Review", Vol. 57, No. 7-8, 2001, p. 33; Gibiec M.: Data mining w systemie monitorowania pracy kombajnów górniczych. „Wiadomości Górnicze", t. 62, nr 7-8, 2011, s. 398; Frith R.: Development and demonstration of longwall monitoring system for operational decision ma king. ACARP, Project Report No. 4017, July 1996; Gąsior S.: Diagnosis of Longwall Chain Conveyor. "Mining Review", Vol. 57, No. 7-8, 2001, p. 33; Gibiec M.: Data mining w systemie monitorowania pracy kombajnów górniczych. „Wiadomości Górnicze", t. 62, nr 7-8, 2011, s. 398; Hoseinie S.H., Ataei M., Khalokakaie R., Ghodrati B., Kumar U.: Reliability analysis of drum shearer machine at mechanized longwall mines. "Journal of Quality in Maintenance Engineering", Vol. 18, No. 1, 2012, p. 98; Kępski P., Barszcz T.: Validation of vibration signals for diagnostics of mining machinery. "Diagnostyka", Vol. 64, No. 4, 2012, p. 25; Michalak M., Sikora M., Sobczyk J.: Analysis of the longwall conveyor chain based on a harmonic analysis. "Eksploatacja i Niezawodność", Vol. 15, No. 4, 2013, p. 332; Plush B., Ren T., Cram K., Aziz N.: Dust Monitoring and Control Efficiency Measurement in Longwall Mining. "11th Underground Coal Operators' Conference", University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2011; Sottile J., Holloway L.E.: An overview of fault monitoring and diagnosis in mining equipment. "IEEE Transactions on Industry Applications", Vol. 30, No. 5, 1994, p. 1326.

[9] Novák P., Babjak J.: Roof support control in longwall technology. "14th Coal Operators' Conference", University of Wollongong, The Australasian Institute of Mining and Metallurgy & Mine Managers Association of Australia, 2014, p. 34.

increase in the props is performed to restore the contact with the roof[10]. To overcome rock mass pressure on the roof support, the hydraulic system increases the pressure in props (by actuation of overflow valve). Hence, the following stages in a working cycle of roof support can be defined:

- overbuilding,
- overflow valve actuation (open, closed),
- folding.

The mentioned stages regarding time and pressure perspectives are presented in Fig. 2.

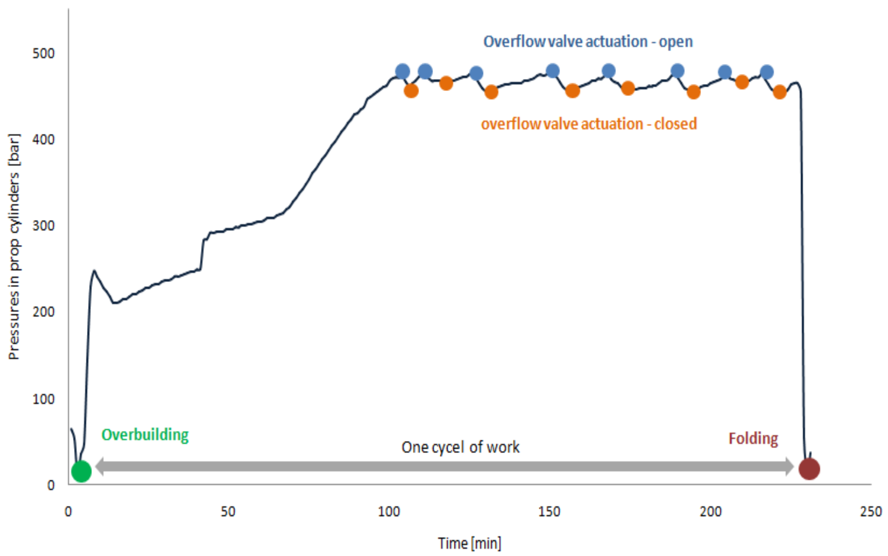

Fig. 2. Cycle of roof support operation
Source: Author's work.

The working cycles of roof support differ in progress and duration (Fig. 2) and raw data are characterized by high degree of variation.

Mathematical models for distinguished phases of the roof support operation cycle describing the changes in pressure in the props can be found in[11]. Research on this subject and various analytic approaches can be also found in[12].

[10] Michalak M.: Modelling of Powered Roof Supports Work. "World Academy of Science, Engineering and Technology International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering", Vol. 9, No. 5, 2015.
[11] Michalak M.: Modelling of Powered…, op.cit.
[12] Howie W.L.: Mobile Roof Support Load Rate Monitoring System. "IEEE Industry Applications Conference", Thirty-Fourth IAS Annual Meeting, Vol. 1, 1999, p. 234; Hoyer D.: Early warning of longwall roof cavities using LVA software. "12th Coal Operators' Conference", University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2012, p. 69; Peng S.: What can a shield leg pressure tell us? "Coal Age", Vol. 103, No. 3, 1998, p. 41; Płonka M., Rajwa S.: Assessment of powered support loadings in plow and shearer longwalls in regard to the pressure measurements in props. "Proceedings of the International Mining Forum", Bogdanka, Poland 2011; Zhao Y., Zhang N., Si G.: A Fiber Bragg Grating-Based Monitoring System for Roof Safety Control in Underground Coal Mining. "Sensors", Vol. 16, No. 10, 2016.

In previously research conducted by author[13] data mining methods (e.g. multiple regression, decision trees and association rules) were used. Received models have described the main cycle features (e.g. duration of the cycle, medium pressure, number of the safety valve actuation), but do not give the possibility of in-depth quantitative and qualitative analysis of roof support operation in a process manner. Therefore, an attempt to use the process mining approach has been undertaken.

3. Process mining

Process mining is a relatively young research discipline which brings together capability of several known disciplines e.g.: data mining, machine learning, modelling and analysis of processes[14]. The most important idea of process exploration is to discover, monitor and improve real processes. It is one of the most important innovations in the field of business process management.

Process mining aims to provide methods and tools which allow: discovery of real process models, identification of bottlenecks, conformance checking by monitoring deviations, prediction and history-based recommendations and automated construction of simulation models.

The basis of process mining is to extract knowledge from event logs that contain structured data relating to the performance of the process. Events log include: information about events and their time of occurrence and also additional information (e.g. resources involved in the process – people or devices).

In Figure 3 simplified scheme of process mining with several important stages is presented.

[13] Trzcionkowska A.: Zastosowanie wybranych technik eksploracji danych w analizie procesu wydobywczego kopalni podziemnej. Praca magisterska (niepublikowana), Akademia Górniczo-Hutnicza, Kraków 2015.
[14] van der Aalst W.: Process Mining: Data Science in Action. Springer-Verlag, Berlin 2016.

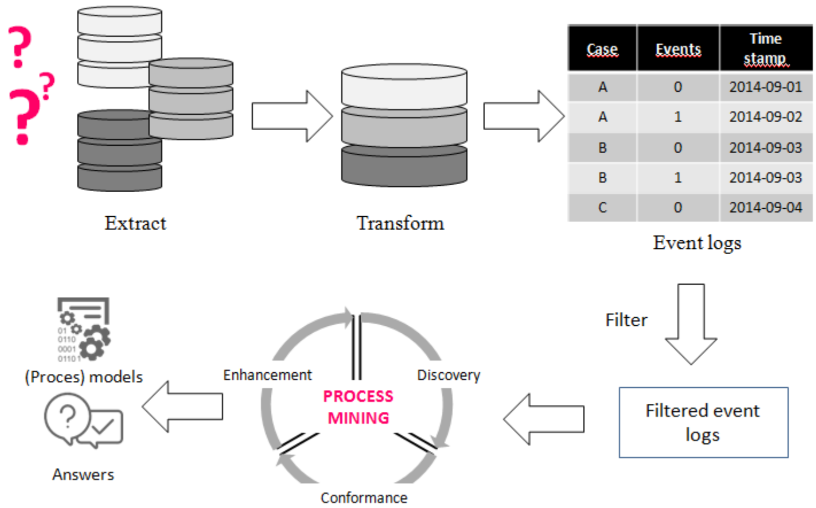

Fig. 3. Overall process mining workflow
Source: Author's work.

Starting point of process mining is the acquisition, merging and preparation of event data, which very often come from different sources or databases. After the initial preparation of data, next step is data cleaning. In this stage selection of the most interesting events, removing rare or unusual events, as well as adding missing actions are carried out. Final event log can be used to perform the following process exploration tasks[15]:

1) Process model discovery – transformation of input data from event logs into a process model without using *a priori* information. This is the most promising process mining technique. The process model can be expressed in different notations (Petri net, BPMN, process tree).
2) Conformance checking – comparing of an existing, formal model with an event log-based model. This task allows checking whether the process recorded in the event log is consistent with the formal models (procedural, organizational, declarative, business rules).
3) Enhancement – in-depth analysis of the process through using contextual information stored in the event log, which is used to extend and refine the existing process model (e.g. by indicating process bottlenecks, bandwidths, frequencies).

It is worth mentioning that the diagram in Figure 3 does not reflect the repetitive character of process mining. Very often the achieved results will generate further questions and all steps need to be repeated several times. In-depth analysis of the process also uses classic data mining techniques (e.g. clustering or classification).

[15] Daniel F., Barkaoui K., Dustdar S. (eds.): The Process Mining Manifesto by the IEEE Task Force on Process Mining, BPM 2011 Workshops, Part I, LNBIP 99, Springer-Verlag, Berlin 2012, p. 169.

Process mining techniques have been applied in different industrial sector: service, manufacturing, healthcare, utility, construction and chemical[16]. There hasn't been recorded application of these techniques in the mining industry until now.

4. Modelling and analysis of roof support operation process

Process mining is supported by various tools, which have been developed. Released software includes commercial (e.g. Celonis, Disco, Minit, Perceptive, Rialto) and open-source software (e.g. ProM).

All presented analyses in the paper were performed with ProM 6.6 software (www.promtools.org). It enables not only control-flow or time analysis but also organizational mining, decision mining and many others.

In table 1 fragment of event log with single roof support operation data in a selected longwall face is presented.

Table 1

Event log of roof support operation process (fragment)

Case	Pressure	Event	Timestamp	Shift_work	Day_of_the_week	Month
1	459,6	valve_actuation	2017-01-10 23:33	C	tuesday	january
1	253,3	folding	2017-01-10 23:39	C	tuesday	january
2	72,1	overbuilding	2017-01-10 23:40	C	tuesday	january
2	207,4	folding	2017-01-11 02:00	D	wenesday	january
3	77,2	overbuilding	2017-01-11 04:26	D	wenesday	january
3	235,2	folding	2017-01-11 04:27	D	wenesday	january
4	77,2	overbuilding	2017-01-11 04:27	D	wenesday	january
4	461,4	valve_actuation	2017-01-11 09:03	A	wenesday	january
4	455,6	valve_closed	2017-01-11 09:14	A	wenesday	january

Source: Author's work.

This event log was created on basis of monitoring data including date, pressure measurements in roof support legs and event ID.

The first task in process mining is very similar to initial task in data mining as is preparation and cleaning of data. We used in this case *Filter Log using Simple Heuristic* option, which enables exclusion of non-completed traces and rare or unusual events. Then exploratory analysis of event log can be done with *Explore Event Log* (Fig. 4) options.

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[16] Gonella P.: Process mining: A database of applications. HSPI SpA – Management Consulting, Bologna, Italy 2016. http://win.tue.nl/ieeetfpm/lib/exe/fetch.php?media=casestudies:hspi_process_mining_database_20161207.pdf (20.03.2017).

Fig. 4. Explore Event Log view
Source: Author’s elaboration with ProM software.

The original event log includes 5279 events in 533 cases (cycles). The log contains 4 classes of events (“overbuilding”, “valve_actuation”, “valve_closed”, “folding”). All cases start with “overbuilding” event and all finish with “folding” event.

The most popular traces include the following order of events:

- overbuilding – folding (189 cycles – 35,46% of event log) it is the shortest trace in the log,
- overbuilding – valve_actuation – folding (58 traces – 10,88% of event log),
- overbuilding – (valve_actuation – valve_closed)^4 – folding (24 traces – 4,50% of event log),
- overbuilding – valve_actuation – valve_closed – folding (21 traces – 3,94% of event log).

In the 111 traces (20%) above 6 valve_actuation (and adequate valve_closed) events can be observed. The longest trace in the log includes 144 events (with 72 valve actuations). The most of these cases are related to days without longwall operation (weekend, holidays), but too intensive roof support operation during normal working days can be also noticed. These observations can be initial input to deeper analysis concerning causes of this phenomenon.

Discovery of process model was performed with *Mine Petri Net with Inductive Miner* option. Petri net created for analysed event log (Fig. 5) can be easily transformed into BPMN model (with *Convert Petri Net to BPMN diagram* option).

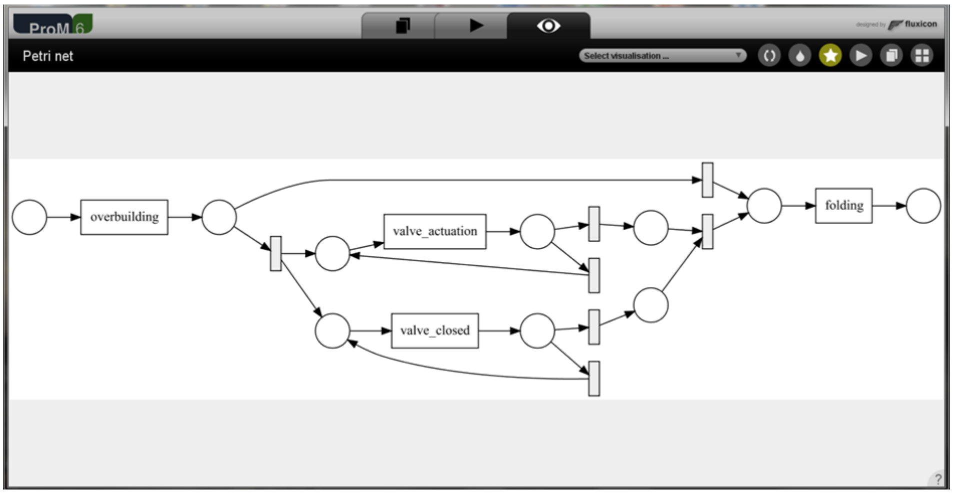

Fig. 5. Discovered Petri net
Source: Author's elaboration with ProM software.

Created model is rather simple and is characterised by very high replay fitness (97%). Petri net gives the general view of the process realisation. More detailed information about process performance could be obtained by analysis with *Replay a Log on Petri Net for Performance/Conformance Analysis* option (Fig. 6).

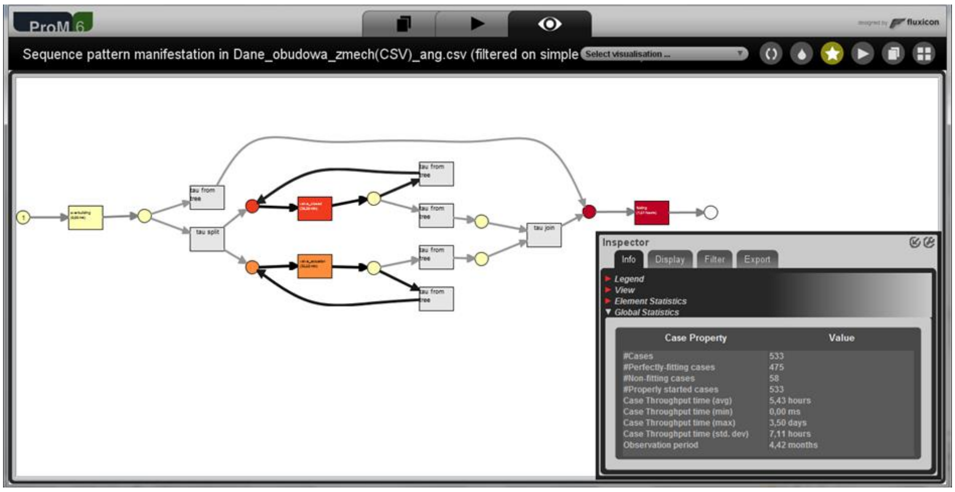

Fig. 6. Process performance analysis on the Petri net
Source: Author's elaboration with ProM software.

In performance analysis, statistics of individual events and whole process are provided. Regarding the analyzed roof support cycles, the average value of duration of the roof cycle is 5,38 hours with standard deviation of the single cycle equaling 7,01 hours. Relation of standard deviation to average value indicates a high variability of the process. The maximum duration of the roof cycle is 3,5 days which is related with non-working days (Easter holidays).

Deeper analysis of the roof support operation brings the following observations: average value of sojourn time for valve_actuation event is 56,57 minutes with standard deviation

1,66 hours and for valve_closed event – 59,30 minutes with standard deviation 1,74 hour. Folding event is characterized by average value of sojourn time equaling 1,55 hours with deviation of 3,12 hours. All relations between standard deviation and average values of sojourn time denote that analyzed process has non-stationary character.

In case of roof support cycle, its performance depends directly on characteristics of rock mass lying above longwall face. Presented roof operation process models can be base for further analysis, which should be extended with geological data and data mining techniques.

Conclusions

Identification and analysis of processes are necessary actions for process management and risk management in organization. The basic element for process analysis is valuable model reflecting process' real performance.

In underground mining for process modelling and analysis purposes, various collections of data could be used. As example in this paper, analysis of roof support operation process, based on data from monitoring system, is presented. The study has included creation of the process model and its analysis (based on event logs) with use of process mining techniques.

Performed analyses enabled gaining of new knowledge about roof support operation process, which cannot be obtained with popular analytic techniques, as time-series analysis or linear regression.

Models based on events recorded in monitoring systems can support management of the mining process and its risks in the underground mine enabling real process performance analysis.

Knowledge of event log-based process model may be also used in comparison between formal process model (formulated e.g. in ISO documentation) and "as-is" model, in order to identify the deviations (in plus or in minus) in process performance. The same model can be used for deeper analysis of bottlenecks or analysis of other process perspectives (e.g. organizational).

In case of presented roof operation process, provided model could be base for further analysis, e.g. investigation of dependency between process performance and geological and mining conditions of its realisation.

In a mining company, process management is very challenging action due to specific conditions of mining processes realisation, especially concerning underground mining.

To manage risk in the mining enterprise, firstly, the processes should be identified and analysed. Our research concerns a mining process in underground coal mine and equipment operation in longwall faces. In the paper we present analysis of roof support operation based on data from monitoring system with process mining techniques. Process mining is a relatively young research discipline which brings together capability of several known disciplines e.g.: data mining, machine learning, modelling and analysis of processes. Process mining techniques can provide managers with new insights into the processes realized in an enterprise, influencing the quality of decision-making in process management and the risk management of those processes.

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