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Optimizing mining production plan as a trade-off between resources utilization and economic targets in underground coal mines

Introduction

The economic value of deposits and mineral resources scarcity are reflected in the statutory definition of admissible mining activities (Nieć 2018). Within the Polish legal system these regulations are defined in *The Geological and Mining Law* along with executive acts. Their principles can be reduced to the rational management of mineral resources. This rationality means, on the one hand, avoiding wasting unnecessary resources and the need for the economic justification for the extraction of raw materials on the

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other (Sobczyk et al. 2016; Kicki et al. 2019). These rules are reflected, among others, within the crucial planning document called The Deposit Development Project, which presents the management concept, taking technical and economic extraction conditions into account (Rozporządzenie Ministra Środowiska… 2012). Meanwhile, industrial criteria change over time in conjunction with the resource market economic conditions. As market conditions influence mining projects and many other internal project risks are present, this very often means that the amount of industrial resources changes with the ratio between the coal price and its production cost (Szamałek and Wierchowiec 2015). In practice, the need to improve extraction efficiency may result in the selected exploitation of only the most attractive coal seams (i.e. with a thickness of more than 1.5 m; the balance criteria, e.g. for hard coal, indicate that the extraction is justified if seam thickness is greater than 0.6 m) (Rozporządzenie Ministra Środowiska… 2015).

This fact induces the optimization problem of establishing correct relationships between extracted resources quantity and business targets. In the last decades, the Polish state resource policy stressed the need to maximize extracted resource amounts (Sobczyk et al. 2016). Today, in the environment of constantly growing costs and price conditions regulated by the global market processes, attention is paid to the positive economic effect of mining activities (Saługa et al. 2015; Kopacz et al. 2018), which is hard to achieve. In addition, conducting mining activities involves large capital expenditures incurred in the investment phase, which may last even several years without positive cash flows (Saługa 2019). As mentioned by Magda, production output should also reproduce the idea of minimizing unit production cost in order to achieve optimal mine capacity utilization in a mine’s total lifespan (Magda 2014). Having this in mind, effective and dynamic mining production planning is more and more important. The investment process should be preceded by a multi-dimensional, multi-aspect and multi-scenario analysis phase (Del Castillo and Dimitrakopoulos 2019). Additional expenditure at this stage may result in significant effects in the future (Kopacz et al. 2019, 2020; Saługa 2019).

Errors and uncertainties occurring during the process of the deposit exploration are also worth mentioning, as they impact the accuracy of resource base estimation (Carpentier et al. 2016; Hou et al. 2019; Rimélé et al. 2020) and the estimation of mining projects economic effectiveness. All these issues may have a very strong impact on the future of coal mines (Magda 2011).

1. Mine production planning – state of the art

The extraction order is determined by the exploitation and development schedules. As indicated by Hou et al. (Hou et al. 2019) access layout and production scheduling. It is common to optimize each component sequentially, where optimal results from one phase are regarded as the input data for the next phase. Numerous methods have been developed and implemented to achieve the optimal solution for each component. In fact, the interaction between different phases is ignored in the tradition optimization models which only get the suboptimal solution compared to the integrated optimization model. This paper proposes a simultaneous integrated optimization model to optimize the three components at the same time. The model not only optimizes the mining layout to maximize the Net Present Value (NPV, mining production planning is a complex process. The process should be continuous, iterative and multidimensional. In the underground mines, designing and planning mine production in a traditional way is a time-consuming process, which usually means difficulties in achieving an optimal result (Dyczko et al. 2014).

Proper mining production planning means operating in the incomplete knowledge environment. This uncertainty comes from the lack of knowledge about the deposit, its structure, and variability of resources' quality parameters. These are the internal mining project risks and uncertainties. External risk factors come from changes in the mining enterprise business environment (e.g. price fluctuations) combined with the limited flexibility of the extraction process (Ostrowska 2002).

The optimization of a mine production schedule is a comprehensive consideration of various factors, whose purpose is to obtain, in most cases, the maximum NPV (net present value) (Hou et al. 2020). A need for the optimization of the mine production planning process has been raised repeatedly, especially in the periods of economic recession. Scientific publications present different and broad approaches to optimizing mine production plans. Studies on optimization methods used in mining were already carried out in the 1960s (Hou et al. 2019). They usually concerned the methods of canonical network analysis and graph analysis. Networks algorithms were used to design optimal underground mines development (Brzychczy 2007).

Along with IT tools progress, computer-based methods are also utilized in the mining sector to solve many optimization problems. Nhleko and co-authors (Nhleko et al. 2018) stress that optimization methods are used in open pit production scheduling for many years, while they have been developed in underground mines in recent decades. A literature review in that field indicates the concentration of research activity around three areas:

- stope layout, using heuristic algorithms (Sandanayake et al. 2015; Erdogan and Yavuz 2017; Nhleko et al. 2018),
- access and development infrastructure, using heuristic algorithms (Hou et al. 2019; Hou et al. 2020),
- mine production scheduling, using heuristic algorithms and mixed integer programming (Newman and Kuchta 2007; Little et al. 2013; O'Sullivan and Newman 2015).

Examples of mine production planning optimization also concern the following issues:

- machine park selection with the use of data mining techniques, including association rules and classification trees optimal for defined geological and mining conditions (Brzychczy et al. 2018),
- optimal extraction determination, taking mining machines allocation and risk associated with the progress of mining works, using genetic algorithms into account (Brzychczy 2014).

Hou and co-authors (Hou et al. 2019) indicate that traditional optimization methods most often do not take the interactions between individual planning aspects, which are important in searching for globally optimal results into account. Hou, Li and Hu (Hou et al. 2020) put the attention to the fact, that many of the production schedule optimization models do not consider technical constraints related to the deposit access. It is necessary to reach a compromise between design mine structure, deposit body shape and investment expenditures for mine development.

Musingwini (Musingwini 2016) indicates a complex nature of optimized problems in underground mines; many 3D algorithms dealing with mine planning don't guarantee reliability of achieved results. In his opinion, this is one of the main explanations of a lack of advanced optimization algorithms implemented to commercial software for underground mining. The second is academic nature of the most studies on optimizing mine planning. Simultaneously Musingwini signalizes the need of understanding the mining planning optimization processes for the accurate interpretation and utilization of the results in decision making. Researchers emphasize that optimal production schedules based on a mining project should be developed for the purpose of strategy definition (Little et al. 2013; Newman et al. 2016). However, the main problem in mine production design is the uncertainty typical for mining activities.

Concluding, still growing interest in various techniques, method and directions for mine production optimization indicates the multitude of undertaken problems and applied research methods. An approach to the individual problem requires specific data input to set up the optimization algorithm and use of advanced numerical methods that require significant computing power and/or complex algorithms. Despite the value of academic research, there are justified concerns about their practical application and wider understanding for mining enterprise management. On the other hand, the results of the simulation method can be implemented to production schedules, helping the mine's staff to better understand mining reality. As we notice, there is still a need to elaborate a simple method that would benefit from the potential of professional digital tools used in mining practice. The value of geological and mining data stored in databases, describing deposit structure and final product quality, in an extensive range of uncertainty and risk, seems to still be underestimated and undervalued in everyday planning and design activity.

This paper is an attempt to elaborate an effective and reliable optimization method that will join the knowledge about the coal deposit, design restriction and mining process limitation with economic targets. The application of the method leads to the selection of the most favorable, under certain conditions, production plan (schedule). The presented method puts together multi-criteria decision algorithms combining geological, mining and economic aspects allowing for the investment risk to be minimized in hard coal mines. Finally it leads to the selection of the optimal exploitation scenario. The elaborated method belongs to strategic mine planning.

2. Digital resource modelling and mine production planning – present state of the art

In modern mining operations, digital solutions support many design processes, such as ventilation (Wallace et al. 2015), rock stability issues (Mayer 2011; Vallejos et al. 2018) or haulage (Bardzinski et al. 2019). Digitized geological data can also be used in an assessment of deposits value (the mutual impact of uncertainty and variability of geological, mining parameters of coal deposits and market prices was analyzed, among others, by Kopacz et al. (Kopacz et al. 2018).

The problem of mine production optimization is widely represented in the literature. Brazil et al. (Brazil et al. 2002, 2009; Brazil and Grossman 2008) used a network model based on weighted Steiner networks theory in order to optimize the cost of accessing orebody and ore transport. Brzychczy and Lipiński (Brzychczy and Wnuk-Lipiński 2013) attempted to optimize the scheduling of available equipment in order to minimize deviations of net output. They also implemented the results into a software module (Brzychczy 2011). 3-dimensional (3D) rock mass models are also widely used in digital mine design, as they serve as a base for locating mine structure and are a source of quality and quantity data for schedules and economic models (Morton 2017; Maritz and Uludag 2019).

Alternative method of mine planning is suggested by Nesbit and co-authors. They propose a numerical method for creating a mine structure design that maximizes NPV of ore mining operation. This method utilizes an evolutionary algorithm that starts by choosing random design parameters and then modifies them, keeping designs achieving higher NPV. Additionally, the algorithm is estimating which of the two methods, top down open-stope mining or bottom-up stopping with backfill, is more profitable for each panel (Nesbitt et al. 2020).

The process of digital transformation of mine production planning in Polish coal mines was induced by the dissemination of digital maps (Tchórzewski and Poniewiera 2012). In the last few years this was furthered by the implementation of numerical models and digital planning and scheduling tools, which increased the coherency of planning environment. A lot of research in the field of digital resources modelling and mine production planning was conducted in Mineral and Energy Economy Research Institute of Polish Academy of Sciences (MEERI PAS). In the Bogdanka coal mine the implementation of such a solution, including strategic and operational perspectives, was integrated with the economic assessment of the resources potential, which allowed for choosing the best production scenario. The range of economic indicators covered asset-based, income and market methods and indicators (Dyczko et al. 2013; Kijanka and Wróbel 2017). Jastrzębska Spółka Węglowa (JSW) recently integrated digital models for its coal deposits with mine production scheduling with respect to optimal quality management and is attempting to extend this implementation with a business perspective.

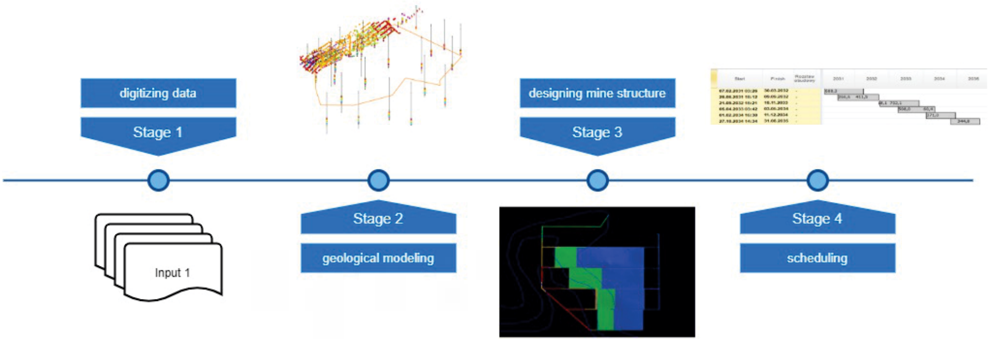


Fig. 1. Stages of creating mining schedule using 3D modelling and design software
Source: own study

Rys. 1. Etapy tworzenia harmonogramu produkcji górniczej z zastosowaniem oprogramowania do modelowania geologicznego oraz projektowania wydobycia

The process of creating a mining schedule suggested by scheduling software ("Deswik") and ("Datamine") providers consists of four main stages.

- Stage 1 – defining and digitizing the available and required geological data,
- Stage 2 – modelling the deposit structure and quality parameters,
- Stage 3 – designing a 3D mine structure model, taking into consideration technical, geological, legal and economic constraints,
- Stage 4 – creating and optimizing a mine schedule in accordance with quantity and quality exploitation targets and available equipment and infrastructure.

3. Source of data and project description

Primary sources of data used for creating the base schedule of the "X" mine were:

- digital deposit model,
- mining, technical and economic parameters.

The deposit model was spread on the area of over 22 km^2 and consisted of 38 singular seams. Two composite seams were additionally modelled among with a carbon roof surface and a ground surface. The model included 10 major and 12 local faults. It was developed by the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, using the available geological data, including:

- 38 surface boreholes and 23 underground boreholes containing detailed descriptions of all lithological layers,
- 33 seam profiles,
- 665 qualitative analyses.

Original model contained 20 quality parameters. For this project authors required:

- 5 coal quality parameters modifying the forecasted price of mined coal – CSR (coke strength after reaction), volatile matter, sulphur content, ash content and calorific value,
- in-seam water, waste content and density for quantitative calculations of available resources and an estimation of mining rate slowdowns caused by the geological conditions.

Due to the lack of the previous exploitation of deposit "X", all quality data came from core samples acquired from the boreholes. Data included in the geological model, which consisted of solids based on a 50 × 50 m grid, was dragged into a task model in which the scheduled tasks were split into 100-meter long sections.

Mine "X" is located in the south-western part of the Upper Silesian Coal Basin. The deposit consists of 14 seams of commercially mineable coal. Those seams are 0.6 to 3 meters thick and contain mostly coking coal of good quality. At present, the deposit is being horizontally accessed. Drilling development works are ongoing at the level 1,110. So far,

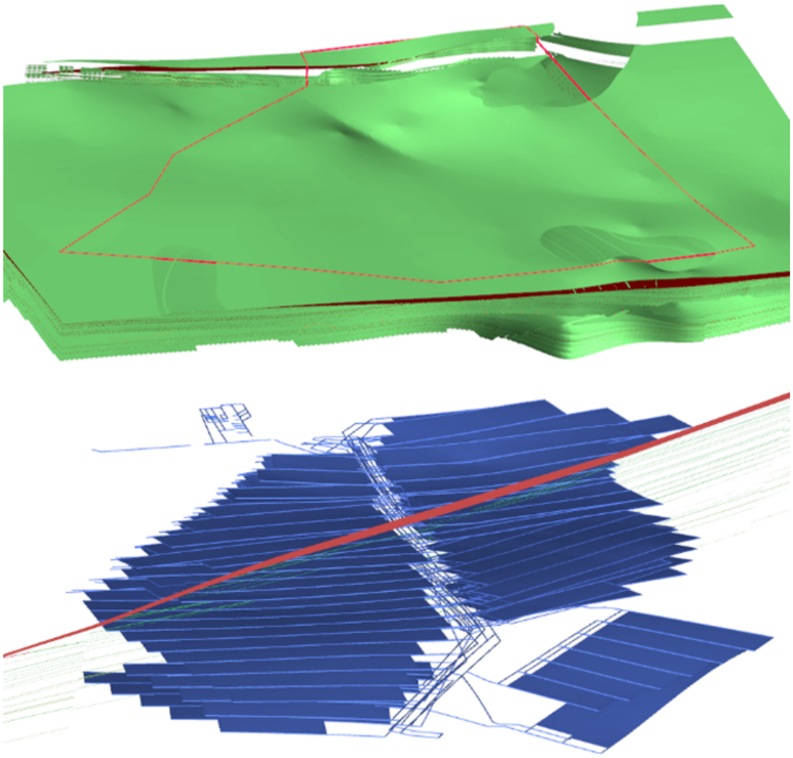


Fig. 2. Seams location and mine structure in the deposit "X"
Source: own study

Rys. 2. Sposób zalegania pokładów i struktura wyrobisk w złożu „X" the mine vertical infrastructure consists of 1 main shaft. Drilling an additional material shaft with a ventilation function in the future is planned (the related expenditure has been included in the economic model). Currently, the mine "X" is connected by the underground infrastructure with a processing plant located in the neighboring mine, where coal enrichment will be carried out. "X" mine is planned to reach its full capacity at 2028.

4. Research objectives, methodology and scope of work

Some aspects of choosing the optimal mining schedule have already been mentioned and discussed in previous chapters. However, these methods cannot be used universally without evaluation, as mining techniques differ depending on the deposit geology, expected natural hazards, local mining conditions and compliance with mining law. In addition, due to the complexity of mining projects as well as the uncertainty of available data, which is particularly sparse in early stages of mine planning, researchers lean to operate on models with a high level of abstraction.

Research objectives

We have formulated two research objectives.

The basic research objective was to elaborate a method for selecting the best of many possible mining scenarios taking the set of different geological, mining and economic criteria into account. In particular, we aimed to develop a method of finding exploitation schedule bringing the best economic results with respect to the process planning requirements and design constraints of the existing mine infrastructure. The developed method meets a number of requirements:

- generated mining scenarios are technically and legally feasible,
- the method considers all of the feasible scenarios that can be generated using a given mine design,
- scenarios follow given production targets and the capacity of the planned and existing infrastructure,
- the final result is a list of mining scenarios ranked by selected economic criteria.

The method belongs to the family optimization methods where the numbers of geological, mining, technical and economic factors with their constraints define the conceptual model with the target function being maximized. Our maximized parameters represent economic objectives, as described in detail below.

The second research objective was to compare the mining scenarios with an actual one, called – Base Case, that was chosen by the management of the mine "X" to be implemented in the future. For this purpose, we reproduced the Base Case in our economic assessment model. Finally we were able to express the value of the elaborated method and its reliability as the range of output scenarios and to point out the best one. Many of the selected scenarios appeared to be better than the Base Case.

The optimization problem was quite sophisticated having the computational capability to calculate thousands of scenarios and need to reduce the number of them to only a few – the best ones in mind.

Research process

The method proposed by authors consists of four stages, each driven by a number of criteria. Figure 3 presents the idea of the elaborated methodology with respect to the number of scenarios considered at each stage in the experiment. It is worth mentioning that the number of scenarios analyzed is being significantly reduced (from millions to a few) after implementing the next selection criteria. The research process consists of four stages:

- mine planning and design – technical perspective,
- assessing the resources economic potential – the first group of selection criteria,
- meeting mine's technical targets and restrictions – the second group of selection criteria,
- extended, dynamic economic assessment of the selected scenarios – the third group of selection criteria.

Detailed, operational workflow of the research process is shown in Figure 4.

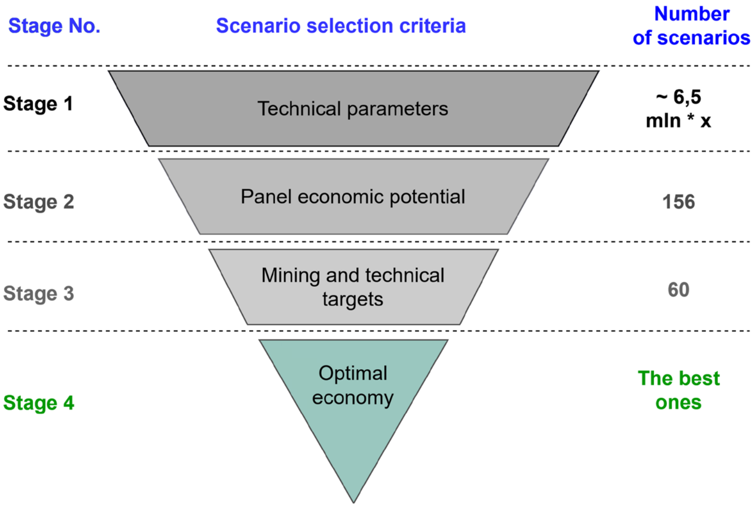


Fig. 3. Idea of the elaborated methodology ("x" is a number of scenarios generated from 1 set of mining zones)
Source: own study

Rys. 3. Idea opracowanej metodologii
(„x" to liczba scenariuszy wygenerowanych z 1 zestawu grup partia-pokład)

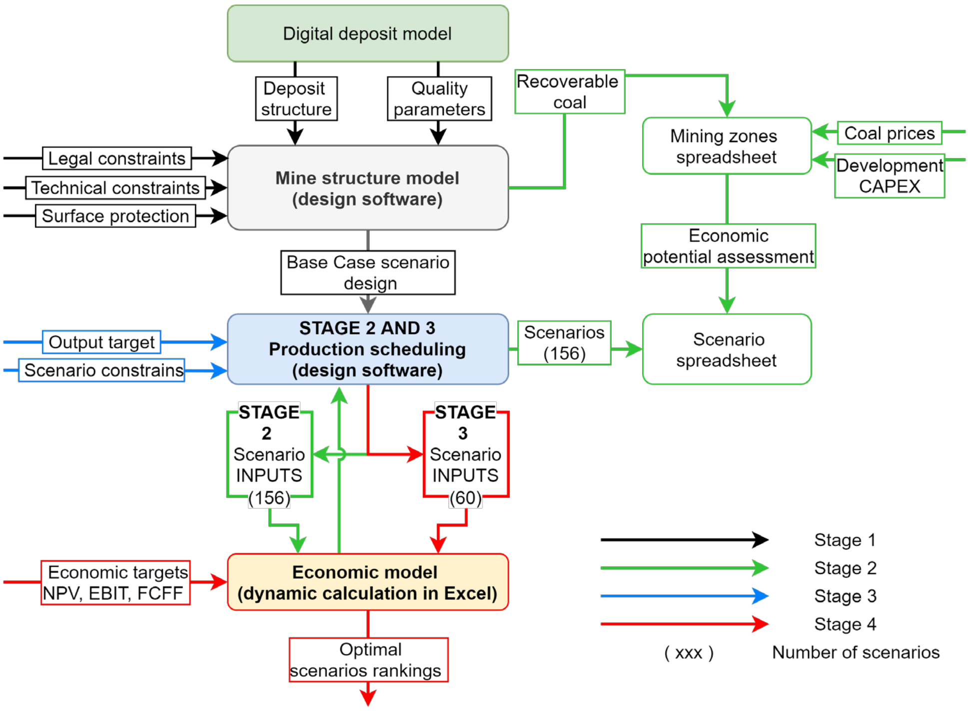


Fig. 4. Workflow model of the research process
Source: own study

Rys. 4. Model przepływu pracy w metodzie badawczej

STAGE 1: Mine planning and design

At the first stage mine structure was designed. Although Nesbit et al. (Nesbitt et al. 2020) suggest to use the algorithm to optimize this stage in ore mining, this method cannot be directly applied to coal mining in Poland (the mining operation is the longwall method restricted both by local law and natural hazards such as flooding, high methane content, tremors, and coal self-combustion properties). Therefore we suggest that at this stage production design should cover all recoverable resources following balance criteria (Rozporządzenie Ministra Środowiska… 2015), and be focused on allowing for safe and legally admissible exploitation, while minimizing the total cost of mine structure. The mine structure is for further needs divided into mining zones, by which we consider sets of longwalls located in one seam, included in one ventilation loop, that can be removed from the schedule or modified without interfering in continuity of ventilation structure of the rest of the mine.

In the analyzed mine, at this stage, the mine structure consisted of 26 distinct mining zones, from 2 to 13 longwalls each. It creates circa 6.5 million combinations of possible scenarios (from each of these combinations multiple scenarios can be generated). In the experiment we decided that the deposit can be mined by 1 to 6 longwall sets at any given time, which could potentially result in circa 32 million scenarios.

STAGE 2: Assessing the resource economic potential

In the second stage, for each mining zone, resources economic potential W_z was calculated with use of the formula:

$$W_z = RR \cdot \left(P_i - a\right) - l \cdot K_j \tag{1}$$

where: *RR* is recoverable coal available for extraction in the mining zone adopted from the Deswik software, P_i is a coal price in the year *i* ($i \in (1;120)$), estimated using yearly price forecasts of reference coal index (described with the range of quality parameters), *l* is the total length of the roadways required for safe extraction of the mining zone, excluding roadways required for mining in multiple zones (produced by the Deswik), K_j is the average cost of drilling of 1 meter of the roadway (calculated at the average for different types of mine workings, based on enterprise data) and is price deflator – dynamic vector of coal quality parameters calculated as the difference between the referential coal quality parameters and quality of coal in the mining area in the year *i*.

The idea of coal price calculating is presented with use of the set of the equations (2 and 3):

$$P_i = P_{ref} - a_i \tag{2}$$

$$a_i = SUM\ of \left\{ \begin{array}{c} \text{for:} \\ Min \le CSR_i, S_i, V_i, A_i \le Max \\ \ldots \\ \text{and for:} \\ CSR_i;\ if\ CSR_j \ge CSR_{\max} than \left(CSR_{\max} - CSR_j\right) \cdot 0.8 \\ S_i;\ if\ S_j \ge S_{\max} than \left(S_{\max} - S_j\right) \cdot 10 \\ V_i;\ if\ V_j \le V_{\max} than \left(V_{\max} - V_j\right);\ \ if\ V_j \ge V_{\min} than \left(V_j - V_{\min}\right) \\ A_i;\ if\ A_j \le A_{\max} than \left(A_{\max} - A_j\right);\ \ if\ A_j \ge A_{\min} than \left(A_j - A_{\min}\right) \end{array} \right\} \tag{3}$$

↳ P_i – a coal price in the year *i* ($i \in (1;120)$),
P_{ref} – the market price of coal in the year *i*,
CSR – coke strength after reaction,
S – sulphur content,
V – volatile matter,
A – ash content, all given at the as-received base,
Min, *Max* – the barrier values where the surplus and deductions are being calculated.

Mining zones were then sorted by the W_z parameter. Scenarios generated in this stage were created by removing the rising number of mining zones with the lowest economic potential. On this basis, in our reference project, 26 combinations of mining zones resulting in 156 scenarios were generated.

STAGE 3: Meeting mine's technical targets and restrictions

At this stage scenarios were removed from the further analyses if they either couldn't reach the mining yearly output target or if their total output value could not outweigh the sum of the capital expenditures required for mine infrastructure and equipment.

$$\text{for: } Min \le Q(L_i), Q(T_i),\ Q(H_i), Q(Z_i) \le Max \tag{4}$$

and

$$Min\left(Max\left(L_i, T_i, H_i, Z_i\right)\right) = k \rightarrow \frac{RB}{k} \rightarrow T \tag{5}$$

↳ $Q(L_i)$, $Q(T_i)$, $Q(H_i)$, $Q(Z_i)$ is the resultant production limited respectively by longwall raw coal output (L), transportation (T), production shaft (H) and processing plant (Z) capabilities. RB denotes resource base divided by yearly production output k.

The yearly output target, maximum of the production, was determined by the bottleneck of each of the individual elements of the production process including vertical and horizontal transport, ventilation and the processing plant capabilities. Very often the limitation can be the output of the longwall faces but in other cases production may be reduced by shaft transportation or ventilation limitations. In our method, we took all the mentioned restrictions of production process in the "X" mine into account (output scenarios should meet all the technical restrictions due to mine nominal production capability). The upper limit of a project's lifespan was calculated as a function of selected resources base and yearly production output.

STAGE 4: Extended, dynamic economic assessment of the selected scenarios

In this phase scenarios were implemented into a mining scheduling software. Then sets of data from generated schedules were put into the economic model. The range of inputs, on the yearly base, covered:

- Run-Of-Mine – *ROM*,
- coking coal and steam coal output – Q,
- average value of selected coal quality parameters (described in the stage 2),
- length of mine roadways to be mined,
- number of road headers and longwall complexes working each year,
- number of road headers and longwall complexes that need to be bought or replaced each year.

To assess the economic value of selected scenarios, we also have to calculate:

- capital expenditures (CE) – CAPEX,
- assets amortization and depreciation (Am) and residual value (W),
- revenues (R) – function of the coal output and coal price (P),
- cash coal production cost (Cc) with respect to the level of waste rock amount (coal impurities), consist of a fixed and variable part,
- taxes (T),
- output economic measures such as:
  - EBITDA (EBIT),
  - NOPAT,
  - FCFF,
  - NPV,

where EBITDA and EBIT are measures of scenario profitability, NOPAT is the net operating profit after taxes and FCFF denotes the free cash flow. NPV (net present value) represents the sum of discounted cash flows (FCFF) with respect to discount rate established at 7.7%.

Calculation of the profits and cash flows was performed using the following equations:

- EBITDA = $R - Cc$,
- EBIT = EBITDA – Am,
- NOPAT = EBIT – T,
- FCF = NOPAT + $Am - CE + W$.

As the same economic model was used to assess all the scenarios with a different lifespan amounting to a maximum of 120 years, some dynamic formulations were used especially for establishing the value of capital expenditures (CE) and operating costs (Cc).

Total value of CE was the sum of subtotal CAPEX for:

- mine development,
- longwall complex and equipment,
- headings complex and equipment,
- mine basic infrastructure
- sustaining CAPEX,
- other CAPEX.

The cost of mine development was a product of the length of the seam's roadways and average price of 1 meter of tunnel. Expenditures for longwall and headings complexes followed the production scale and drilling advancement. The value of basic infrastructure was a sum of the cost of vertical development by shafts and other mine infrastructure supporting the longwall operation. Total sustaining capex in a given scenario was calculated as a product of coal output and unit sustaining capex. Other capital outlies covered the expenditures for other mine infrastructure such as transportation and haulage, ventilation and dewatering systems.

Revenues were calculated as a function of coal output and its price based of premium hard coking coal index (LV PHCC) with long term price of 150 USD/Mg.

For the approximation of coal operating cash costs (variable part) we used the quadratic function (5) elaborated by Kopacz for underground coal mines (Kopacz 2017). Formula 5 requires a calculation of the coal yield EY_w denoted here simply by the equation (4): $EY_w = Q/ROM$. Formula 4 reflects the idea that the cost of coal production should be, in general, higher for the exploitation with growing amount of waste rocks, and this relation is not linear.

$$Cc = 383 \cdot EY_w^2 - 843 \cdot EY_w + 787 \tag{6}$$

The fixed part of the operating costs was an expert judgement based on real data form the ‘‘X’’ mine.

In this stage, the remaining 60 scenarios were ranked using two economic criteria. This allowed to choose the best available mining plan (schedule), which maximizes the value of the entire project.

5. The key assessment

Table 1 covers the values of input variables used in an assessment model. Production parameters, such as the average longwall and roadway mining rate, longwall equipment, seam thickness, section area of roadways were estimated using values characteristic for Polish mines. The costs of equipment, infrastructure, workforce and other operating expenses were estimated on the real values from the “X” mine. The long term forecast of the coal market price is our own research.

6. Results and conclusions

Table 2 contains a ranking of the scenarios grouped according to the decreasing NPV. The highest NPV values were achieved in the scenarios marked with symbols 22E, 21E and 19E, the value of which exceeded PLN 720 million. The baseline scenario, on the other hand, was only ranked as 51 of 60 in total. It can also be seen that in the best scenarios NPV is nearly 50% higher, with lower total investment expenditures. If this criterion needs to be put into focus, the best scenario seems to be 19E, in which:

- amount of recovered coal (Q) is lower by nearly 9 million Mg,
- scenario lifespan is 4 years shorter,
- total capex is smaller by nearly PLN 360 million,
- **NPV is higher by PLN 238 million.**

Table 1. Description and values of the key input parameters in assessment model

Tabela 1. Opis i wartości kluczowych parametrów wejściowych modelu

Name/tape of selected criteria	Symbol	Unit measure	Boundary criteria		Expected value
			Minimum	Maximum	
Mining area location depth	MA	m	–	1000	800
Deposit seam thickness	St	m	0.6	5	2
Recoverable coal amount form mining zone	RR	Mg [millions]	0	–	5.0
Length of roadways required for extraction from the mining zones	l	km	0	30	10
Cost of drilling by roadway type	Kj	PLN [thousands]	3.0	15.0	5.0
Longwall raw coal output	L	Mg/y [thousands]	–	6.0	4.9
Transportation limits	T	Mg/y [thousands]	–	6.5	4.9
Production shaft capability	H	Mg/y [thousands]	–	6.0	4.9
Processing plant capability	Z	Mg/y [thousands]	–	6.7	4.9
Run of Mine	ROM	Mg [millions]	126	165	164
Total coal output	Q	Mg [millions]	63	81	80
Long term coal price	P	USD	130	150	150
Coke strength after reaction	CSR	%	45	60	53
Volatile matter	V	%	24	31	28
Sulphur content	S	%	0.1	0.9	0.5
Ash content	A	%	5.2	9.0	6.0
Headings advancement	–	m [thousands]	304	406	405
Capex for mine basic infrastructure	–	PLN [millions]	–	–	1 162
Capex for mine development	–	PLN/m [thousands]	–	–	18
Capex for longwall complex and equipment	–	PLN/complex [millions]	–	–	90
Capex for road headers and equipment	–	PLN/complex [millions]	–	–	10
Total sustaining Capex	–	PLN/Mg	–	–	9.3
Other capex		PLN/Mg	–	–	10
Fix operating cost		PLN [millions]	15 700	20 100	20 100
Variable unit cost		PLN/Mg	–	–	162
Tax rate	T	%	–	–	19
Discount rate	d	%	–	–	7.7

Source: own study.

Table 2. Result of the assessment – scenarios rank by NPV

Tabela 2. Wynik oceny – ranking scenariuszy według wartości NPV

No	Scenario name	NPV [MPLN]	Lifespan (T)	Coal production (Q) [MMg]	Capital expenditures (CE) [MPLN]	Diff. (NPV, %)	Diff. (NPV) [MPLN]	Diff. (T)	Diff. (Q) [MMg]	Diff. (CE) [MPLN]
1	1-22 E	727	2061	77.2	6,178	49	240	–1	–3.8	–362
2	1-21 E	724	2060	75.9	6,081	49	238	–2	–5.1	–458
3	1-19 E	724	2058	72.0	6,179	49	238	–4	–9.0	–361
4	1-19 D	719	2058	72.0	5,971	48	232	–4	–9.0	–569
5	1-19 F	713	2058	72.0	5,844	47	227	–4	–9.0	–695
6	1-22 D	712	2061	77.2	6,077	46	226	–1	–3.8	–463
7	1-18 E	701	2057	69.8	5,804	44	215	–5	–11.2	–736
8	1-19 C	697	2058	72.0	5,816	43	211	–4	–9.0	–723
9	1-20 E	694	2059	74.2	6,115	43	208	–3	–6.7	–424
10	1-21 D	689	2060	75.9	6,632	42	203	–2	–5.1	93
11	1-25 E	688	2062	80.4	6,267	41	202	0	–0.5	–272
12	1-21 F	687	2060	75.9	6,099	41	201	–2	–5.1	–441
13	1-18 F	686	2057	69.8	5,623	41	199	–5	–11.2	–917
14	1-20 D	680	2059	74.2	5,848	40	193	–3	–6.7	–691
15	1-16 F	674	2055	65.4	5,763	39	188	–7	–15.6	–777
…	…	…	…	…	…	…	…	…	…	…
49	1-26 F	494	2062	81.0	6,669	2	7	0	0.0	129
50	1-17 B	491	2064	67.6	5,740	1	5	2	–13.3	–799
51	Base Case	486	2062	81.0	6,540	0	0	0	0.0	0
52	1-26 C	485	2063	81.0	6,377	0	–2	1	0.0	–163
…	…	…	…	…	…	…	…	…	…	…
60	1-26 B	(31)	2074	81.0	6,371	–106	–517	12	0.0	–169

Source: own study.

Table 3. Result of the assessment – scenarios rank by EBIT

Tabela 3. Wynik oceny – ranking scenariuszy według wartości EBIT

No	Scenario name	EBIT [MPLN]	Lifespan (T)	Coal production (Q) [MMg]	Capital expenditures (CE) [MPLN]	Diff. (EBIT, %)	Diff. (EBIT) [MPLN]	Diff. (T)	Diff. (Q) [MMg]	Diff. (CE) [MPLN]
1	1-25 F	11,959	2062	80.4	6,459	2	247	0	–0.5	–81
2	1-25 D	11,954	2062	80.4	6,351	2	242	0	–0.5	–189
3	1-25 E	11,946	2062	80.4	6,267	2	234	0	–0.5	–272
4	1-25 C	11,926	2062	80.4	6,277	2	214	0	–0.5	–263
5	1-24 F	11,849	2061	79.6	6,477	1	137	1	–1.4	–63
6	1-24 D	11,819	2061	79.6	6,254	1	107	1	–1.4	–286
7	1-24 E	11,801	2061	79.6	6,282	1	89	1	–1.4	–258
8	1-26 F	11,729	2062	81.0	6,669	0	17	0	0.0	129
9	1-24 C	11,727	2062	79.6	6,282	0	15	0	–1.4	–258
10	1-26 E	11,727	2062	81.0	6,395	0	15	0	0.0	–144
11	Base Case	11,712	2062	81.0	6,540	0	0	0	0.0	0
12	1-26 C	11,647	2063	81.0	6,377	–1	–65	–1	0.0	–163
13	1-23 F	11,516	2061	78.6	6,563	–2	–196	1	–2.4	23
14	1-23 D	11,480	2061	78.6	6,368	–2	–232	1	–2.4	–172
15	1-23 E	11,478	2061	78.6	6,884	–2	–234	1	–2.4	345
16	1-23 C	11,470	2061	78.6	6,149	–2	–242	1	–2.4	–391
17	1-22 F	11,465	2060	77.2	6,167	–2	–247	2	–3.8	–373
18	1-22 E	11,388	2061	77.2	6,178	–3	–325	1	–3.8	–362
19	1-22 D	11,354	2061	77.2	6,077	–3	–359	1	–3.8	–463
…	…	…	…	…	…	…	…	…	…	…
60	1-15 D	9,240	2055	63.4	5,473	–21	–2,472	7	–17.6	–1,066

Source: own study.

Table 3 contains the ranking of scenarios according to the EBIT. It can be seen that the 10 scenarios are better scored. However, the percentage differences between EBIT (in relation to EBIT of Base Case) are very small – less than 2%. For the maximization of EBIT scenario 25E should be chosen, in which:

- the volume of extracted resources (Q) and the lifetime (T) are comparable,
- Capex is lower by nearly PLN 272 million,
- **the cumulative EBIT is higher by PLN 234 million.**

Table 4 contains the ranking of the scenarios according to the cumulative net cash flow (FCFF). 10 scenarios achieve higher values than the Base Case scenario. However, the percentage differences (to reference scenario) are small – less than 4%. If one wishes to maximize FCFF, they may choose a scenario 25E, in which:

- the volume of extracted resources (Q) and the lifetime (T) are comparable,
- Capex is lower by nearly PLN 272 million,
- **the cumulative FCFF is higher by PLN 304 million.**

A graphic illustration of the achieved results is presented in the Figure 5. Green buttons represent extracted zones in seams from 1 to 14. In the Base Case scenario exploitation is conducted by maximum 5 longwall systems in comparison to scenarios where NPV and EBIT/FCFF are maximized with the use of 6 and more longwall complex simultaneously.

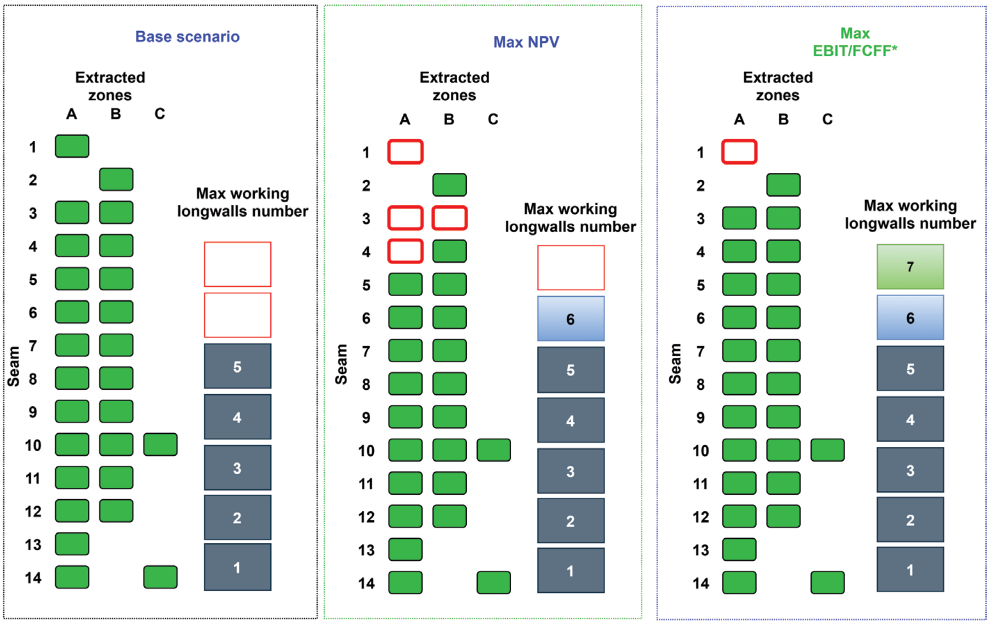


Fig. 5. Graphics illustration of the achieved results
Source: own study

Rys. 5. Graficzna ilustracja osiągniętych wyników

Table 4. Result of the assessment – scenarios rank by FCFF

Tabela 4. Wynik oceny – ranking scenariuszy według wartości FCFF

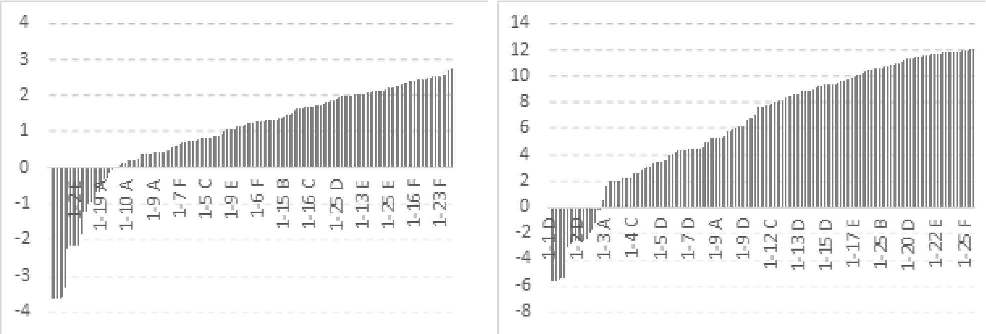
No	Scenario name	FCFF [MPLN]	Lifespan (T)	Coal production (Q) [MMg]	Capital expenditures (CE) [MPLN]	Diff. (FCFF, %)	Diff. (FCFF) [MPLN]	Diff. (T)	Diff. (Q) [MMg]	Diff. (CE) [MPLN]
1	1-25 E	8,752	2062	80.4	6,267	4	304	0	–0.5	–272
2	1-25 C	8,721	2062	80.4	6,277	3	273	0	–0.5	–263
3	1-25 D	8,706	2062	80.4	6,351	3	258	0	–0.5	–189
4	1-24 D	8,654	2061	79.6	6,254	2	206	1	–1.4	–286
5	1-25 F	8,649	2062	80.4	6,459	2	202	0	–0.5	–81
6	1-24 E	8,624	2061	79.6	6,282	2	176	1	–1.4	–258
7	1-24 C	8,551	2062	79.6	6,282	1	104	0	–1.4	–258
8	1-26 E	8,550	2062	81.0	6,395	1	102	0	0.0	–144
9	1-24 F	8,547	2061	79.6	6,477	1	100	1	–1.4	–63
10	1-26 C	8,478	2063	81.0	6,377	0	30	–1	0.0	–163
11	Base Case	8,448	2062	81.0	6,540	0	0	0	0.0	0
12	1-23 C	8,419	2061	78.6	6,149	0	–28	1	–2.4	–391
13	1-26 F	8,389	2062	81.0	6,669	–1	–59	0	0.0	129
14	1-22 C	8,376	2061	77.2	5,961	–1	–72	1	–3.8	–579
15	1-22 F	8,356	2060	77.2	6,167	–1	–91	2	–3.8	–373
16	1-21 C	8,335	2060	75.9	5,847	–1	–112	2	–5.1	–692
17	1-22 D	8,317	2061	77.2	6,077	–2	–131	1	–3.8	–463
…	…	…	…	…	…	…	…	…	…	…
60	1-18 D	6,064	2057	69.8	7,991	–28	–2,383	5	–11.2	1,451

Source: own study.

Red 'empty' buttons represent the difference between the analyzed scenarios and economic targets. As it was mentioned, to achieve the maximum NPV there is a need to exploit only selected zones and mining areas. To maximize EBIT and FCFF one needs to continue the mining process until the resource base is nearly depleted.

To better explain the impact of Stage 3 optimization process, Figure 6 presents NPV and FCFF plots of achieved economic results in Stage 2 and Stage 3, respectively. By analyzing the left graph, one can notice that the NPV of the best scenarios exceeded the level of PLN 2.5 billion, while the worst of them generated negative NPV of nearly PLN 3.8 billion. The worst-case scenarios also generated negative cumulative FCFF of about 6 PLN billion, while the value of the total cash flows of the best scenarios reached PLN 12 billion. The differentiation of the obtained effects is therefore very large.

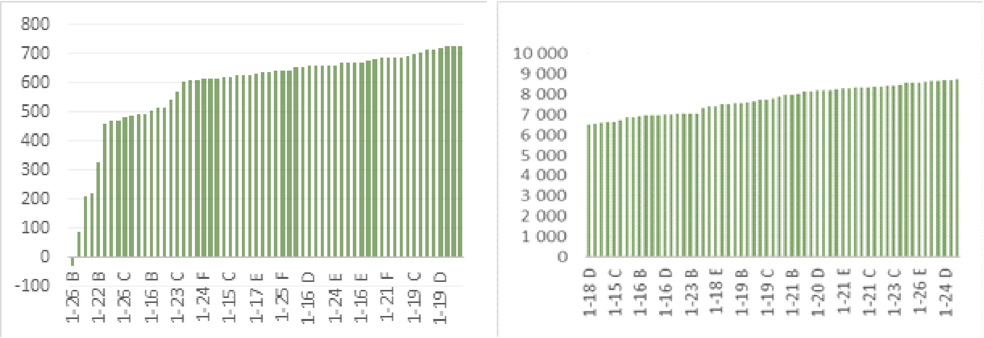
After implementing the optimization criteria in stage 3, the variability of the economic results was significantly reduced (Figure 7). The NPV of the worst scenarios was slightly



a) b)

Fig. 6. Results of the modelling process in Stage 2
a) NPV [billion PLN], b) FCFF [billion PLN]
Source: own study

Rys. 6. Wyniki procesu modelowania w etapie 2
a) NPV [miliardy PLN], b) FCFF [miliardy PLN]



a) b)

Fig.7. Results of the modelling process in Stage 3
a) NPV [million PLN], b) FCFF [million PLN]
ource: own study.

Rys. 7. Wyniki procesu modelowania w etapie 3
a) NPV [miliony PLN], b) FCFF [miliony PLN]

lower than 0, and the best ones exceeded PLN 720 million (with the same values of the inputs). Similarly, the value of total cash flows ranged from PLN 2.7 billion to PLN 8.7 billion in the best scenario.

In conclusion, the developed methodology (elaborated model), through a number of applied criteria, divided into 4 stages, enabled the selection of scenarios that maximize the economic efficiency of the "X" mine. In the given example economic effectiveness was measured by three different economic criteria representing different evaluation perspectives. The NPV that takes the time value of money into account, seems to represent the interests of the project stakeholders in the most appropriate way, aimed at maximizing the financial effects in the short term. Other criteria such as EBITDA and EBIT – measures of scenario profitability, may, in turn, better reflect the interests of the owner of geological assets, interested in a stable resources depletion.

We mentioned in the introduction that NPV is recommended as a decisive criterion to assess the amount of the recoverable coal reserves, its economic potential and business attractiveness, but it seems to be the most complicated. The established research process allowed for cooperation between the digital model of the "X" deposit, production scheduling tools and the developed dynamic economic model resulted in establishing several potentially better scenarios than the base case, recommended for implementation in the "X" mine. It can be clearly seen based on scenario ranking followed by descending NPV. Finally, we were able to construct nearly 50 production schedules with ultimately lower capital expenditures and a shorter period of production. Therefore, the developed method is of practical use and can successfully be applied to many other examples of hard coal deposits where mining is carried out with use of the longwall system. To make mining operation profitable it often requires the use of only the most attractive coal reserves located in thick seams with high quality parameters with respect to reasonable capital investment. Selective mining operation may ultimately conflict with the, very popular in last years, idea of rational deposit depletion, which assumes the maximization of resources use.

The elaborated multi-criteria optimization method can support mine's management in the decision making process when approaching the new deposit development. It links geological and mining deposit parameters with coal quality and with market conditions, identifying the most common and distinctive risks in an assessment model.

It is worth mentioning that there is an additional flexibility and economic potential not included in the developed method, resulting from the optimization the structure of the mine development. Works in this field would be continued.

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OPTIMIZING MINING PRODUCTION PLAN AS A TRADE-OFF BETWEEN RESOURCES UTILIZATION AND ECONOMIC TARGETS IN UNDERGROUND COAL MINES

Keywords

resource utilization, underground coal mining, mine production planning,
optimization, digital model, economic effectiveness

Abstract

The paper presents multi-criteria optimization method allowing for selection of the best production scenarios in underground coal mines. We discuss here the dilemma between strategies maximizing economic targets and rational resources depletion. Elaborated method combines different geological and mining parameters, structure of the deposit, mine's infrastructure constrains with economic criteria such as the net present value (NPV), earnings before deducting interest and taxes (EBIT) and the free cash flows to firm (FCFF). It refers to strategic production planning. Due to implementation of advanced IT software in underground coal mines (digital model, automated production scheduling) we were able to identify millions of scenarios finally reduced to a few – the best ones. The method was developed and tested using data from mine operation "X" (a real project – an example of a coking coal mine located in Poland). The reliability of the method was approved; we were able to identify multiple production scenarios better than the one chosen for implementation in the "X" mine. The final product of the method were rankings of scenarios grouped according to economic decision criteria. The best scenarios reached NPV nearly 50% higher than the Base Case, which held only 52. position out of 60. According to EBIT and FCFF criteria, 10 scenarios achieved results higher than the Base Case, but the percentage differences were very small, below 2 and 4%, respectively. The developed method is of practical importance and can be successfully applied to many other coal projects.

OPTYMALIZACJA PLANOWANIA PRODUKCJI GÓRNICZEJ JAKO KOMPROMIS POMIĘDZY WYKORZYSTANIEM BAZY ZASOBOWEJ A MAKSYMALIZACJĄ EFEKTÓW EKONOMICZNYCH KOPALŃ WĘGLA KAMIENNEGO

Słowa kluczowe

Wykorzystanie zasobów surowców mineralnych, podziemne górnictwo węgla kamiennego,
planowanie produkcji górniczej, optymalizacja, cyfrowy model złoża, efektywność ekonomiczna

Streszczenie

W artykule zaprezentowano wielokryterialną metodę optymalizacji produkcji górniczej, prowadzącą do wyboru najlepszych harmonogramów wydobycia w podziemnych kopalniach węgla kamiennego. Przeprowadzono także dyskusję nad dylematem pomiędzy wyborem strategii maksymalizujących efekty ekonomiczne a racjonalną gospodarką zasobami. Opracowana metoda łączy różne parametry geologiczne i górnicze, budowę złoża, ograniczenia infrastruktury kopalni, z kryteriami ekonomicznym takimi jak NPV, EBIT i FCFF. Tym samym wpisuje się w obszar planowania strategicznego. W związku z wdrożeniem zaawansowanych narzędzi IT w podziemnym górnictwie węglowym (cyfrowy model złoża, zautomatyzowane harmonogramowanie produkcji górniczej) możliwe było zidentyfikowanie milionów scenariuszy, ograniczonych w efekcie końcowym do kilku najlepszych. Metoda została zaprojektowana i przetestowana z wykorzystaniem danych dotyczących projektu górniczego „X" (projekt rzeczywisty – przykład kopalni węgla koksowego zlokalizowanej w Polsce). Jej zastosowanie umożliwiło identyfikację wielu scenariuszy produkcji lepszych od wariantu wybranego do wdrożenia w tej kopalni. Tym samym potwierdzono jej skuteczność. Produkt finalny metody stanowią rankingi scenariuszy zgrupowanych według różnych kryteriów oceny efektywności ekonomicznej. Najlepsze scenariusze osiągnęły wartości NPV blisko 50% wyższe od scenariusza bazowego, który spośród 60 zajął dopiero 52. miejsce. Według kryteriów EBIT i FCFF, 10 scenariuszy osiągnęło wyniki lepsze niż scenariusz bazowy, ale różnice w ujęciu procentowym były jednak bardzo niewielkie, odpowiednio poniżej 2 i 4%. Opracowana metoda ma przede wszystkim praktyczne znaczenie i może być z powodzeniem stosowana w wielu przypadkach projektów węglowych.