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Sustainable management of hard coal resources implemented by identifying risk factors in the mining process

Introduction

Mineral resources constitute the basis for every sector of the world economy. They provide high living standards for contemporary societies, safeguarding meeting the demand for energy, construction materials, they also make up the basis for industry and technological development. Sustainable development is intended to provide the possibility for survival of human civilization in the face of declining resources of non-renewable raw materials

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(especially energy carriers) and increasing anthropogenic pressure, as well as pollution of the natural environment related to it. The implementation of sustainable development imposes the obligation for rational management of natural resources on societies, as well as for providing a raw material base for future generations. Thus, the key element of sustainable development in terms of obtaining and using natural mineral deposits is the rational and economical management of resources.

The implementation of sustainable development of mining and use of mineral resources entails integration of activities in the following three areas (Dubiński 2013):

- technology and economics, providing economic growth, which means achieving long-term sustainability both as regards to planned production volumes, and in meeting the needs of customers, as well as achieving economic efficiency obtained from the sale of the excavated mineral,
- protection of environment, which guarantees the protection of natural resources and the environment, by rational acquisition, which is characterized by savings in depletion of resources. This also means taking measures that minimize the negative impact of the different processes related to the extraction of mineral resources on the various forms of the geological environment and natural environment on the surface,
- social responsibility, which means ensuring safe working conditions, as well as concern for development of local communities in the mining plant environment.

Underground hard coal mining causes numerous ongoing challenges, as well as problems pertaining to strategy and operation. Among the most serious ones, high capital intensity of investment projects in mining as well as dynamically changing conditions in which this sector functions should be listed. The long-term role of the mining sector depends on factors that have their origin both at national and international level.

Mining belongs to sectors of the economy that demonstrate high level of risk, resulting from the occurrence of natural hazards. Mining conditions tend to deteriorate: depletion of resources which have been more readily available in operating mines, increasing excavation depth, which translates into an increase in the temperature in the underground mine workings, extension of transport routes, along which personnel and materials are transported, as well as shortening of effective working time and increase of natural hazards and the content of barren rock in coal seams that are located deeper (Kopacz et al. 2020). The trend of increasing depth of mining makes mine safety a key area for sustainable development of mining, at present and in the future. With proper mitigation of risk, coal bed methane may be considered a resource, thus a source of revenue (Tutak and Brodny 2019; Chećko et al. 2020; Szlązak et al. 2021). Increase of natural hazards, besides reducing mining efficiency, may also lead to development of occupational diseases affecting miners, increasing the incidence of many fatal diseases (Tomášková et al. 2017). It is also worth mentioning that many of those hazards occur also after completion of extraction. The impact of closed mines leads to potentially harmful changes in surface and/or underground water flow, as well as to formation of local depressions, which may have devastating impact upon surface infrastructure (Al Heib et al. 2023).

For analyzing complex risk factors in hard coal mining, for example such as water hazards (Zhao et al. 2023); reduction of dust emissions, reduction of energy consumption (Xu et al. 2023), reducing accidents at work (Hannani et al. 2023), inconvenience caused by mining and geological conditions (Sobczyk and Kopacz 2018), various methods of multi-criteria decision making and neural networks are utilized, among others (Zhang et al. 2022). With regard to popularity and application, both in theory and in practice, the AHP (Analytic Hierarchy Process) method is the most frequently applied multi-criteria method, and is characterized by the greatest diversity of applications (Prusak and Stefanów 2011). This method finds application in various areas of research, among them in: mining (Sobczyk 2008; Bascetin 2009; Sobczyk et al. 2020, 2022), marketing (Wind and Saaty 1980; Davies 2001), power engineering (Pohekar and Ramachandran 2004), medicine (Liberatore and Nydick 2008), environmental engineering (Biedrawa and Sobczyk 2010; Sobczyk et al. 2014), economic science, as well as in the financial sector (Adamus and Łasak 2010). An extension of AHP method is the Fuzzy AHP, which enables selecting the optimal variant, by taking into account not only the assessment of experts, but also their degree of certainty, by using fuzzy numbers to evaluate comparisons in pairs of features within the AHP analysis. Promentilla et al. (Promentilla et al. 2015) applied FAHP for comparing technologies for storing electric energy in renewable energy systems. Siwiec and Pacana (Siwiec 2020), in turn, used this technique for quantitative and qualitative analysis of emission of pollutants from the power and industry sector. The Fuzzy AHP method has been utilized for choosing the right suppliers of goods of proper quality, at a favorable price, in the right time and in proper amounts (Ayhan 2013). Fuzzy AHP and TOPSIS methods have been also used to study the level of socio-economic development of regions (Łuczak and Wysocki 2011).

Polish hard coal mining industry is currently in a difficult situation, in terms of both technologies and economics (Sukiennik et al. 2021). However, it cannot be ignored that the difficult financial situation of Polish mining companies is largely aggravated by their high operating costs. The high cost of coal mining and the volatility of coal prices are two factors determining the efficiency of Polish coal mines (Kopacz et al. 2019). This situation can be corrected by making improvements in planning processes. This would be linked with striving for the most predictable and economically efficient planning of production. In that respect, planning of longwall extraction is necessary, which would take into account the complexity of geological and mining conditions and the economic consequences resulting therefrom (Moore and Friederich 2021; Sobczyk et al. 2022).

Chapter 1. contains an overview of the proposed methodology, by means of providing a digital geological deposit model with extension in the form of selected risk factors, providing selection of factors that influence the cost of mining by means of statistical analysis, as well as developing the indicator of mining risk, RF. Chapter 2. contains the presentation of results, with determination of RF indicator values for specific zones in the test hard coal deposit, and implementation of values of that indicator to discount rate.

1. Materials and methods

The methodology suggested for assessment of the level of risk of underground hard coal exploitation takes into account the influence of all risk factors that result from geological and mining conditions. This methodology is a comprehensive approach to sustainable management of hard coal deposit resources, and it has been verified empirically in the study, using the example of coking coal deposit. Since 2011 the European Commission has been publishing the list of Critical Raw Materials for the EU. Coking coal has been included on that list since 2014 (“Fifth list 2023 of critical raw materials for the EU,” n.d.). The aim for publishing that list is to provide access to raw materials indispensable for digital and green transformation and to reduce the risk connected with supplying them from third countries.

Effective management of deposits should take into account the impact of significant risk factors upon the planning of exploitation. Such risk factors may influence the mining process, taking into account safety, economic efficiency, and rational use of resources. Such an approach to analysis is perceived as a multi-criteria decision problem. In the research process, one of the techniques of Multiple Criteria Decision Analysis (MCDA) has been used, which utilizes the Fuzzy Analytic Hierarchy Process (FAHP). It was hypothesized that the variability of specific geological and mining factors which influence the mining process, safety, or mining effectiveness may be presented as a risk materialized through its influence upon unit cost of production in mining of longwalls. Quantification of this impact may be an argument for correcting the overall risk of the project, in the form of discount rate, vital in the process of assessing its value by means of income methods (CIM Council 2019). For that purpose, the following scheme of procedure was prepared:

- development of digital geological model of deposit (and mining schedule), extended by adding selected risk factors connected with geological and mining conditions;
- identification and selection of factors affecting operating costs, by means of statistical analysis utilizing segmented regression;
- development of mining risk factor, RF, with the use of Fuzzy Analytic Hierarchy Process (FAHP);
- determination of the value of RF for specific zones in test hard coal deposit;
- implementation of values of RF to discount rate, which may be used for making the valuation of a specific mining zone or the entire deposit.

1.1. Digital geological model of deposit and mining schedule

For the purpose of quantifying mining risk, a digital geological model of coking coal deposit has been developed (Figure 1). Structural models describing the physical structure of the deposit were prepared, as well as quality models, which showed the variability of quality parameters of the deposit in space. Input data for modeling specific structural units consisted of information (roof and floor of the layer, lithological description, etc.) obtained from

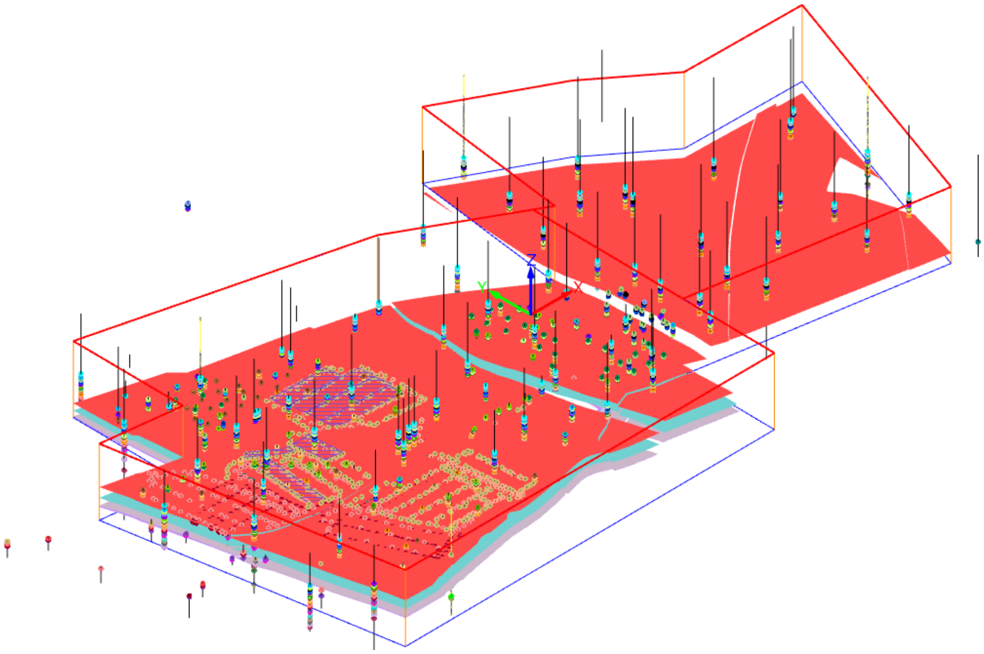

Fig. 1. Location of longwalls analyzed (hatching) against the seam floor (in red), boreholes and logging of workings

Rys. 1. Położenie analizowanych ścian (wylęgowych) względem dna pokładu (na czerwono), otworów wiertniczych i wyrobisk

geological survey boreholes and underground monitoring (boreholes drilled from underground workings and their profiling). The structural grid model also contains information on tectonic disturbances (faults) or sedimentation disturbances (intercalations, wash-outs, and the like).

Models of quality parameters were developed as a result of the estimation of point quality parameters of the deposit, using interpolation methods, as well as on the basis of data from geo-statistical analysis. Input data for the quality models comprised the results of analyses of samples from borehole cores, as well as *in situ* logging of the deposit from underground workings.

On the basis of the digital model of deposit as well as materials and concepts pertaining to planned mining operations, a 3D model of planned excavations in the mining process was prepared, with schedule of mining operations, for the purpose of preparing economic analysis.

In case of mining coal by longwall method, the shape of underground workings depends on numerous parameters: deposit bedding characteristics, tectonics, or natural hazards (Sobczyk and Kopacz 2018). From the digital model of the deposit, the surfaces of the floor and roof of the modeled coal seams were separated, on which previously prepared axes and contours of the designed excavations were then projected. In case of longwalls, the contours were projected to the structural surfaces of the seam, which are decisive for excavation datum and the height of exploitation gate. Development workings (driven in the seam) were prepared on the basis of the position of the seam floor and the assumed cross-section of the workings contour breakout.

1.2. Selection of geological and mining factors which influence the cost of mining, segmented regression method applied

For the purpose of analysis of the influence of risk factors upon unit cost of mining, historical mining data and economic information was analyzed for 81 longwalls mined in the years 2016–2022. For this purpose, longwall mining schedules have been recreated by means of digital tools.

For all longwalls, sets of geological criteria have been prepared (such as natural hazards, seam parameters), as well as mining parameters (such as geometric parameters of longwalls, physical location of longwalls in the mine field) and economic parameters (unit cost of mining). In total, 23 variables have been chosen for initial statistical analysis, from all the factors available in the model.

Due to the incremental nature of changes in some explanatory variables (those concerning natural hazards), and the changing dynamics of the reaction of an dependent variable (unit cost of mining), statistical analysis using segmented regression was chosen. Segmented regression model comprises two different equations, which are combined together, according to the following formula (1):

$$\hat{Y} = \left(b_{01} + b_{11}X_1 + \ldots + b_{k1}X_k\right)\left(Y \le y_{(0)}\right) + \left(b_{02} + b_{12}X_1 + \ldots + b_{k2}X_k\right)\left(Y > y_{(0)}\right) \tag{1}$$

↳ $Y \le y_{(0)}$ – break-even point,
$Y > y_{(0)}$ – logical conditions.

Inequalities $Y \le y_{(0)}$ and $Y > y_{(0)}$ assume the value of 1 if they are true, or the value of 0 if they are false. The application of such a solution allows for a more flexible adjustment of the model to the random nature of some variables. Additionally, the independent variable of “rock-bump hazard” (KZT), due to its random nature (the variable assumes only three different values, (of which the value of 0 is assumed relatively frequently) the decision was made to encode it on nominal scale, attaching two values to it: 0 – no rock-bump hazard, and 1 – occurrence of rock-bump hazard. Non-metric scale coding was also applied to the variable of “longitudinal slope”. Although this variable is measured on a quotient scale, the initial analysis of data and expert knowledge indicate that in the value range between 5 and 15 (longwall inclination angle amounting from 5 to 15 degrees) the productivity of coal face system is the highest. For that variable, the coding applied was as follows:

1 – longwall inclination angle amounting from 5 to 15 degrees, 0 – longwall inclination angle outside that range. To estimate the parameters of the model, quasi-Newton method was used (Dobosz 2004). The estimation procedure was a multi-stage one: in consecutive stages, the least significant variables were rejected and the model was re-estimated, using a new set of remaining variables. Elimination of insignificant variables in the model was performed on the basis of results of the asymptotic t-Student test. Finally, models were selected that showed at least a good matching to the data and had almost all relevant parameters at the significance level of 0.05.

After rejecting statistically insignificant explanatory variables in the model describing the variable "unit cost of mining", in a further model, the following variables were taken into account: thickness, reserves, panel length, length of longwall, depth, the absolute methane content (CH4), rock burst hazard (KZT), tectonic and sedimentation disturbances (KZU), spontaneous combustion of coal (KZS). In this case, the estimated break-even point in this segmented regression had the value of 80.5965. The results of model estimation are provided in Table 1. The direction of influence in case of explanatory variables is as follows: thickness (–), reserves (–), panel length (–), length of longwall (–) reduce unit costs, whereas the variables of: depth (+), CH4 (+), KZT (+), KZU (+), KZS (+) increase those costs.

The following variables: thickness (–), reserves (–), panel length (–),length of longwall (–), depth (+), exert more intense influence upon the dependent variable in case of higher levels of unit costs positioned above the break-even point than in case of lower values of unit costs (below the break-even point). For example, increase of coal seam thickness by one unit results in reduction of unit costs by the average of 14.9151 units, if costs exceed 80.5965, whereas for unit costs below that value, the increase of coal seam thickness by one unit implies reduction of unit costs by the average of 1.7616 units, ceteris paribus. The strongest negative influence upon unit costs below the break-even point comes from spontaneous combustion hazard: increase of that hazard by 0.1 results in cost increase by the average of 21.3712, ceteris paribus. Then, in case when unit costs are above the break-even point, the most significant increase of unit costs results from rock-bump hazard: the presence of such hazards increases the unit cost by the average of 31.8599 units, ceteris paribus.

The results of estimation by means of segmented regression model indicate that 85.67% of unit costs variability is explained by the variability of 9 model-building variables ($R^2 = 85.67\%$). Therefore, in a further analysis to estimate the impact of risk on efficiency of mining in specific zones of the deposit, the following factors have been taken into account:

- Thickness;
- Reserves;
- Panel length;
- Length of longwall;
- Depth;
- Indicators describing different types of natural hazards: CH4, KZS, KZT, and KZU.

In addition, the factor "distance from the nearest hoisting shaft" was taken into account, which influences the effective working time in the longwall face.

Table 1. Results of estimation with the use of segmented regression model, describing the dependence of unit costs on geological and mining conditions in coal seams

Tabela 1. Wyniki estymacji z wykorzystaniem segmentowego modelu regresji opisującego zależność kosztów jednostkowych od warunków geologiczno-górniczych pokładów węgla

Independent variable	Parameter assessment	Standard error	*t*	*p*
B0 constant	34.3787	14.3360	2.3981	0.0197
1. Thickness (–)	–1.7616	0.5511	–3.1964	0.0023
2. Reserves (–)	–0.0011	0.0005	–2.3140	0.0242
3. Panel length (–)	–0.0383	0.0092	–4.1611	0.0001
4. Length of longwall (–)	–0.0850	0.0107	–7.9532	0.0000
5. Depth (+)	0.0185	0.0081	2.2688	0.0270
6. CH4 (+)	0.3323	0.1076	3.0886	0.0031
7. KZT (+)	16.6732	5.3568	3.1125	0.0029
8. KZU (+)	10.6508	3.5650	2.9876	0.0041
9. KZS (+)	21.3712	6.7343	3.1735	0.0024
B0 constant	283.8618	85.5774	3.3170	0.0016
1. Thickness (–)	–14.9151	4.7474	–3.1418	0.0026
2. Reserves (–)	–0.0297	0.0051	–5.8472	0.0000
3. Panel length (–)	–0.0425	0.1128	–0.3766	0.7079
4. Length of longwall (–)	–0.1427	0.0664	–2.1482	0.0359
5. Depth (+)	0.0935	0.0247	3.7785	0.0004
6. CH4 (+)	0.0989	0.0517	1.9128	0.0607
7. KZT (+)	31.8599	9.8727	3.2271	0.0021
8. KZU (+)	4.4218	1.3941	3.1717	0.0024
9. KZS (+)	19.8399	5.9743	3.3209	0.0016
R^2	85.67%			

All these factors characterizing the parameters of the longwalls are estimated on the basis of geological model of deposit, additionally that model has been extended by adding five risk factors resulting from natural hazards. The first of them is the absolute methane content "CH4", a continuous parameter interpolated on the basis of quarterly indications of total methane content (including ventilation methane content and methane drainage). Further four parameters are discrete variables, where a numeric value is attached to a given mining zone, taken from the suggested range.

To describe the risk of coal extraction associated with the occurrence of tectonic disturbances (faults), as well as foldings, or thinning of the seam, a factor pertaining to tectonic and sedimentation disturbances, "KZU", has been proposed, on the basis of historical data concerning mining from specific areas (including those panels that are located above and below the panel analyzed):

- A_t – absence of faults or minor faults (explored zones),
- B_t – faults found, with technologically permissible fault throw level, from the point of view of,
- C_t – faults with large throw, causing limitation of face advance, and unexplored zones (high level of uncertainty).

Another parameter which extends the deposit model by adding risk parameters is the "KZS", that is spontaneous combustion of coal. The currently valid method of classification of coal from the perspective of spontaneous combustion properties of coal has been described in Polish Norm PN-93/G-04558(*PN-93/G-04558. Węgiel kamienny. Oznaczenie wskaźników samozapalności [Hard coal, determination of spontaneous combustion of coal]*, n.d.). On its basis, two indicators are determined: Sz^a – response time, and A – activation energy, on the basis of which a given coal is included in one of five groups due to its spontaneous combustion properties (Słowik 2008).

The fourth quality parameter was "KZT", rock burst hazard. In underground hard coal mines, two levels of rock burst hazard are determined in the rock mass prone to rock bumps, otherwise rock burst hazard is not determined.

Hazard of gas and rock outbursts, "KZR" is one of the most dangerous natural hazards occurring in underground mining. The risk of outbursts increases with increasing depth of mining. Polish regulations contain two categories of hazards: prone to methane and rock outbursts (SWMS) and threatened by methane and rock outbursts (ZWMS).

1.3. Development of mining risk factor (RF) with the use of Fuzzy Analytic Hierarchy Process (FAHP)

The way of developing the mining risk factor (RF) consists of generating a synthetic feature of the Fuzzy Analytic Hierarchy Process (FAHP). FAHP uses expert opinions to determine weighing factors which determine the importance of features and, at the same time, allow to eliminate the features being least important in the linear ordering of objects (Chang 1996). The weights of features are determined on the basis of fuzzy opinions of experts, the so-called soft opinions.

The following stages of the procedure are distinguished:

Stage 1. Modeling the problem in the form of a hierarchical structure of a multi-criteria evaluation task of evaluating objects.

Hierarchical structure of multi-criteria object evaluation is created by decomposing the problem into constituent elements: the main evaluation criterion (in the case of this analysis:

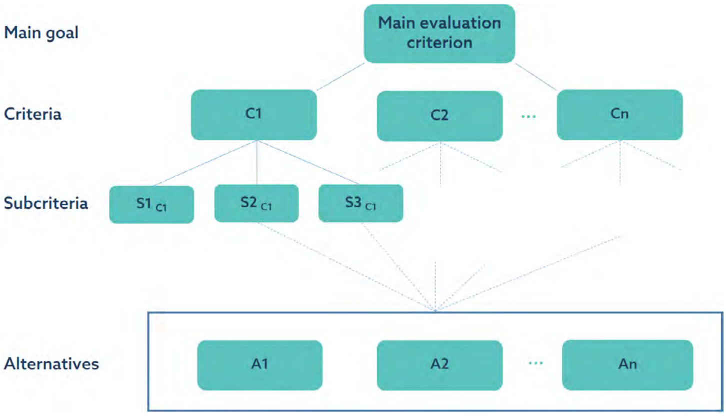

Fig. 2. Scheme of hierarchical structure (own study)

Rys. 2. Schemat struktury hierarchicznej (opracowanie własne)

the level of risk of increase in unit operating costs in deposit zones), minor criteria (groups of risk factors), sub-criteria, and assessed objects (Figure 2). The main evaluation criterion, minor criteria, and sub-criteria that describe the studied objects are mutually connected.

Stage 2. Determination of the validity of criteria and characteristics by assigning weighting factors to them, which factors have been obtained from Fuzzy Analytic Hierarchy Process (FAHP).

Weighting factor vectors can be obtained according to the following procedure:

(1) Comparison of characteristics in pairs, within the evaluation criterion. Comparisons are made in pairs, as regards the importance of the characteristics in relation to the specific minor criterion, utilizing the nine-point Saaty scale for that purpose (Table 2), expressed by means of triangular fuzzy numbers. The results of the comparisons are presented in the form of fuzzy matrix comparisons made in pairs $\tilde{A}$.

The weights of criteria are determined by experts by means of pairwise comparisons, in which subjective evaluations are used to describe the intensity of one criterion in relation to another one. Evaluations are made in the form of triangular fuzzy numbers, the span between which implies ambiguity or lack of certainty of the given evaluation.

The pairwise comparison matrix is illustrated by the equation 2, where $\tilde{d}_{ij}^{k}$ indicates the preference of the k-th expert concerning the i-th criterion in relation to the j-th criterion, using triangular fuzzy numbers, e.g. $\tilde{d}_{12}^{1} = (2, 3, 4)$.

$$\tilde{A}^k = \begin{bmatrix} (1,1,1) & \tilde{d}_{12}^k & \dots & \tilde{d}_{1n}^k \\ \tilde{d}_{21}^k & (1,1,1) & \dots & \tilde{d}_{2n}^k \\ \dots & \dots & \dots & \dots \\ \tilde{d}_{n1}^k & \tilde{d}_{n2}^k & \dots & (1,1,1) \end{bmatrix} \tag{2}$$

Table 2. A fuzzy nine-point preference scale between two comparable elements

Tabela 2. Rozmyta dziewięciopunktowa skala preferencji pomiędzy dwoma porównywalnymi elementami

Description of the fuzzy nine-point preference scale	Classical Saaty scale	Fuzzy scale based on triangular fuzzy numbers	Inverse values from fuzzy scale
Equal importance	1	(1, 1, 1)	(1, 1, 1)
Weak or moderate advantage	3	(1, 3, 5)	(1/5, 1/3, 1)
Strong (big) advantage	5	(3, 5, 7)	(1/7, 1/5, 1/3)
Very strong or decisive advantage	7	(5, 7, 9)	(1/9, 1/7, 1/5)
Extreme advantage	9	(7, 9, 9)	(1/9, 1/9, 1/7)
For compromise comparisons between the above values	2 4 6 8	(1, 2, 4) (2, 4, 6) (4, 6, 8) (6, 8, 9)	(1/4, 1/2, 1) (1/6, 1/4, 1/2) (1/8, 1/6, 1/4) (1/9, 1/8, 1/6)

Source: own study based on (Saaty 1987).

where:

$$\tilde{d}_{ij}^{k} = (l_{ij}, m_{ij}, u_{ij}) \quad \text{and} \quad \tilde{d}_{ij}^{k} = \tilde{d}_{ij}^{k-1} = \left(1/u_{ij}, 1/m_{ij}, 1/l_{ij}\right), \quad (i, j = 1, 2, \ldots, n)$$

When criteria are evaluated by several experts (K), valuation preferences are averaged and calculated according to the equation 3.

$$\tilde{d}_{ij} = \frac{\sum_{k=1}^{K} \tilde{d}_{ij}^{k}}{K} \tag{3}$$

(2) Calculation of the geometric mean of the fuzzy comparative values of each criterion, according to the equation 4 (Buckley 1985).

$$\tilde{r}_i = \prod_{j=1}^{n} \tilde{d}_{ij}^{\,1/n}, \quad i = 1, 2, \ldots, n \tag{4}$$

(3) Fuzzy weights of each criterion are calculated according to the equation 5, in line with the following procedure:

- calculation of the sum of the geometric mean of fuzzy comparative values, $\tilde{r}_i$,
- calculation of summing vector power (–1) and increasing ordering of the triangular fuzzy number,

- calculation of fuzzy weight for individual criteria ($\tilde{w}_i$), multiplying each value of $\tilde{r}_i$ by reverse summing vector (–1).

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \otimes \tilde{r}_2 \otimes \ldots \otimes \tilde{r}_n)^{-1} \tag{5}$$

(4) Conversion of fuzzy weights of individual criteria ($\tilde{w}_i$) into final weights by means of equation 6 (Chou and Chang 2008),

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \tag{6}$$

(5) Normalization of weight of the individual criteria, according to the equation 7.

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{7}$$

The obtained weights of the criteria making up the hierarchical model of the assessment pertaining to the level of risk concerning increase of unit costs of mining in deposit zones have been used to construct the mining risk factor, *RF*. This factor is the sum of the product of weights of individual criteria with normalized values of these criteria in analyzed zones of deposit (equation 8).

$$RF = \sum_{i=1}^{n} N_i \cdot z_i \tag{8}$$

↳ RF – value of mining risk factor, *RF*,
i – number of statistical characteristic,
n – amount of statistical characteristics,
N_i – weight of ith statistical characteristic,
z_i – value of normalized characteristic.

The structure of hierarchical model for assessing the risk of increase of mining unit costs in deposit zones is presented in Figure 3. Criteria used for the model are those highlighted in the first part of this paper, determined by means of segmented regression.

The hierarchical model is made up of 4 levels. The first one comprises the main objective of the task – assessment of the level of risk of increase of unit mining costs in parts of deposit. The model's second level is represented by 3 main groups of risk factors, which contain:

1. Mining factors,
2. Geological factors,
3. Natural hazards.

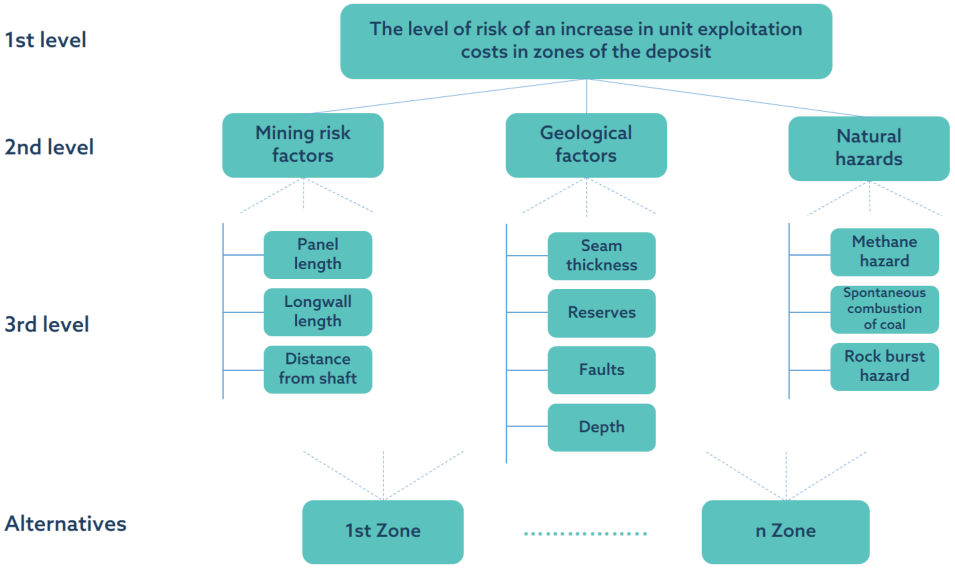

Fig. 3. Model for risk assessment concerning increase of unit costs of mining in deposit zones

Rys. 3. Model oceny ryzyka wzrostu jednostkowych kosztów eksploatacji w strefach złożowych

On the third level of the hierarchical model, partial criteria were introduced, which are a specific extension of criteria grouped at level two.

In the group of mining risk factors, the following 3 partial criteria were distinguished:

1. Panel length, (m),
2. Longwall length, (m),
3. Distance from the hoisting shaft, (m).

In the group of geological factors, 4 specific criteria were allocated:

1. Seam thickness, (m),
2. Reserves, thousand, (Mg),
3. Tectonic disturbances, (factor),
4. Coal seam depth, (m).

In the category of natural hazards, the following were introduced specifically:

1. Methane hazard, (m^3/min),
2. Spontaneous combustion of coal, (group),
3. Rock burst hazards, (degrees).

1.4. Implementation of risk factor (*RF*) as project risk adjustment

So far, attention has been focused on determining the risk factors, *RF*, for specific zones of the deposit analyzed in coal mine X. However, these are not the values which may be considered directly in the valuation of individual zones of the deposit or entire deposits. The issue is that they correspond to the project own risk and do not correlate with the commonly known approaches to valuation of investment projects in mining and risk assessment. In that area, the use of weighted average cost of capital (WACC) dominates (Torries 1998), or – alternatively – the utilization of risk adjusted discount rate (RADR) (Saługa 2009), constituting the basis for selecting proper discount rate (risk measure) in income-approach methods based on cash flow projection. Utilization of both approaches is pretty subjective and limited; it requires adaptation to the specificity of deposits assessed, while these activities do not have a clearly defined methodology of proceeding. Also, appropriate mentioning of reference projects is missing, as well as parameterized values of particular decision variables. The use of WACC or RADR also requires their adaptation to the specificity of the project and may reduce the credibility of both approaches in estimating total risk measures of the evaluated deposit.

The aim of this part of the study is to develop an original approach to the assessment of own risk for hard coal deposits (or their parts) included in WACC concept. When determining the adjusted own risk assessment of a project, the hypothesis that was based upon was that the variability of individual geological and mining factors can be expressed in an aggregated manner, in the form of variability of project risk, *Rp,* using the risk factor, *RF*. In the concept of weighted average cost of capital (WACC), project risk is understood as a component of cost of own capital (*KKW*). Such an adjustment of WACC has been proposed, where by its means it would be possible to properly reflect the specificity and variability of individual geological and mining parameters in the process of assessing the economic efficiency of hard coal deposits.

At the basis of the concept of adaptation of WACC there is the assumption that, with some generalization, both components of WACC may be combined, namely the cost of own capital (*KKW*) and cost of outside capital (*KKO*), by arranging and simplifying the components of the formula for WACC to meet the needs of further analyses. For this purpose, the following research procedure was used:

1. Cost of own capital often happens (turns out) to be calculated on the basis of the model of CAMP:

$$\beta(r_m - r_f) + r_f \tag{9}$$

where

$$r_m - r_f \tag{10}$$

is the project risk premium, and

$$Rp(r_m - r_f)$$

corresponds to *Rp* (%).

2. Cost of outside capital is understood as the sum of the risk-free rate r_f, adjusted to the duration of the project and the bank's margin M, which can be expressed by the formula:

$$KKO = r_f(\text{WIBOR,O}) + M \tag{11}$$

The bank's margin is the value of the benefit, including the bank's project risk assessment Rp and the project environment. The bank's margin will thus be monetized by the bank as profit W (%). We have:

$$KKO = O + M \tag{12}$$

and

$$M = Rp + W \tag{13}$$

3. r_f has been described by the following dependence:

$$r_f \cong \begin{cases} \text{WIBOR fort} & t < 1 \\ O & t > 1 \end{cases} \tag{14}$$

where r_f is the market equivalent of undiversified risk (environment) that can be expressed for projects up to one year of duration, e.g. WIBOR rate (%), or, in case of medium- and long-term projects – by interest rate for State Treasury bonds with an appropriate maturity date of O (%).

We therefore have, in general form:

$$\text{WACC} \cong KKW + KKO = \left(\beta(Rp) + r_f\right) + (r_f + Rp + W) \tag{15}$$

and, after taking into account the share of own and outside capital $\frac{V_e}{V_e + V_d}$ or $\frac{V_d}{V_e + V_d}$ as: A and accordingly: $(1 - A)$, as well as income tax (T) we obtain:

$$\text{WACC} \cong \frac{V_e}{V_e + V_d} \cdot \left(\beta(Rp) + r_f\right) + \frac{V_d}{V_e + V_d} \cdot (r_f + Rp + W) \cdot (1 - T) \tag{16}$$

Simplifying on both sides towards Rp, WACC may be shown as:

$$\text{WACC} = Rp \cdot (A \cdot \beta + 1 - A) + W \cdot (1 - A) + r_f \tag{17}$$

however, in the proposed calculations leading to the determination of free cash flows, interest on loans, as monetary value of financial costs, which are subject to income tax *T* in the part (1 – *T*) is deductible.

Weighted cost of capital WACC, determined by formula 17, is useful for calculating the cost of capital individually for each zone and for the entire deposit (mine), via making appropriate corrections of *Rp*. Relative difference of the factor *RF*, is determined for each zone in accordance with the formula:

$$\delta_i = \frac{RF_i - RFc}{RF_c} \tag{18}$$

Values of factor δ_i determined in this way constituted the basis for calculating *KKW* equivalent to global WACC, for specific zones.

2. Results

For quantification of the importance of the different criteria in relation to the objective, which has been to assess the level of risk that unit costs of mining zones of hard coal deposits, expert assessments were obtained, presented in pairwise comparison matrices. In this case, the opinions of experts in the field of geology, mining, and valuation of investment projects were used.

Table 3 contains the results of calculations of priority vector for level 2 criteria. Respective weights (W_{L2}) for the three groups factors amount to: 0.129 in case of mining factors, 0.255 in case of geological factors, and 0.617 for natural hazards.

Table 4 contains the results of calculations of priority vector for partial mining criteria. Respective weights (W_{LM}) amount to: 0.396 in case of panel length, 0.127 in case of longwall length, and 0.477 in case of distance from shaft.

Table 5 contains the results of calculations of priority vector for partial geological criteria. Respective weights (W_{LG}) amount to: 0.135 in case of seam thickness, 0.148 in case of reserves, 0.262 in case of tectonics, and 0.454 in case of seam depth.

Table 3. Fuzzy pairwise comparative assessment matrix and its calculated priority vector for criteria of level 2

Tabela 3. Rozmyta macierz ocen porównawczych parami i jej wyliczony wektor priorytetów dla kryteriów poziomu 2

Group of criteria	Mining	Geological	Natural hazards	W_{L2}
Mining	(1, 1, 1)	(1, 1/2, 1/4)	(1/3, 1/5, 1/7)	**0.129**
Geological	(4, 2, 1)	(1, 1, 1)	(1, 1/3, 1/5)	**0.255**
Natural hazards	(7, 5, 3)	(5, 3, 1)	(1, 1, 1)	**0.617**
				C.I. = 0.011

Table 6. contains the results of calculations of priority vector for partial criteria pertaining to natural hazards. Respective weights (W_{LH}) amount to: 0.550 in case of methane hazard, 0.153 in case of spontaneous combustion hazard, and 0.296 in case of rock-bump hazard.

Table 4. Fuzzy pairwise comparative assessment matrix and its calculated priority vector for mining criteria of level 2

Tabela 4. Rozmyta macierz oceny porównawczej parami i jej obliczony wektor priorytetów dla kryteriów górniczych poziomu 2

Group of criteria	Panel length	Longwall length	Distance from shaft	W_{LM}
Panel length	(1, 1, 1)	(1, 3, 5)	(1, 1, 1)	**0.396**
Longwall length	(1/5, 1/3, 1)	(1, 1, 1)	(1/3, 1/5, 1/7)	**0.127**
Distance from shaft	(1, 1, 1)	(7, 5, 3)	(1, 1, 1)	**0.477**
				C.I. = 0.018

Table 5. Fuzzy pairwise comparative assessment matrix and its calculated priority vector for geological criteria of level 2

Tabela 5. Rozmyta macierz oceny porównawczej parami i jej wyliczony wektor priorytetów dla kryteriów geologicznych poziomu 2

Group of criteria	Seam thickness	Reserves	Tectonics	Depth	W_{LG}
Seam thickness	(1, 1, 1)	(1, 1, 1)	(1, 1/2, 1/4)	(1/2, 1/4, 1/6)	**0.135**
Reserves	(1, 1, 1)	(1, 1, 1)	(1, 1/2, 1/4)	(1, 1/3, 1/5)	**0.148**
Tectonics	(4, 2, 1)	(4, 2, 1)	(1, 1, 1)	(1, 1/2, 1/4)	**0.262**
Depth	(6, 4, 2)	(5, 3, 1)	(4, 2, 1)	(1, 1, 1)	**0.454**
					C.I. = 0.023

Table 6. Fuzzy pairwise comparative assessment matrix and its calculated priority vector for criteria related to natural hazards, level 2

Tabela 6. Rozmyta macierz oceny porównawczej parami i jej wyliczony wektor priorytetów dla kryteriów związanych z zagrożeniami naturalnymi, poziom 2

Group of criteria	Methane content (CH4)	Spontaneous combustion (KZS)	Rock bumps (KZT)	W_{LH}
Methane content (CH4)	(1, 1, 1)	(1, 3, 5)	(1, 2, 4)	**0.550**
Spontaneous combustion (KZS)	(1/5, 1/3, 1)	(1, 1, 1)	(1, 1/3, 1/5)	**0.153**
Rock bumps (KZT)	(1/4, 1/2, 1)	(5, 3, 1)	(1, 1, 1)	**0.296**
				C.I. = 0.088

Another step is the calculation of risk factor, *RF*. *RF* is the sum of the products of respective weights of the valuation levels with related criteria for respective zones of deposit (equation 4).

Risk factors used for the development of the factor, had such orders of magnitude which required harmonization and introduction of comparability through standardization. Quotient transformation was applied (Sokołowski 1982):

For stimulants:

$$z_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \tag{19}$$

For destimulants:

$$z_{ij} = \frac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \tag{20}$$

↳ t – number of deposit zone,
j – number of statistical characteristic (criterion),
x_{ij} – value of the j-th characteristic, in i-th zone of deposit,
$\min\{x_{ij}\}$ – minimum value (lower reference point),
$\max\{x_{ij}\}$ – maximum value (upper reference point),
z_{ij} – transformed values.

Values of risk factor, *RF* obtained by means of Fuzzy Analytic Hierarchy Process FAHP were calculated for eight zones of hard coal deposit. This factor is made up of ten risk factors, arranged in three groups: factors concerning mining, geological factors, and natural hazards. The values of individual risk factors in the analyzed zones of the deposit are shown in Table 7. Normalized results for each factor are provided in Table 8.

The average value of *RF* for the entire deposit amounts to 0.29, in case of four analyzed zones (*B*, *N*, *S*, and *W*) the *RF* values are lower, whereas the remaining ones (*C*, *K*, *PN*, and *PW*) have markedly higher values of risk factor than the average for the deposit (Figure 4).

The highest level of risk factor, *RF*, amounting to 0.64 belongs to zone *PN*. The value of *RF* assessed for zone *K* is nearly equally high (0.55). Those values indicate the priority attached to methane (CH4) in the assessment of risk, which makes those zones most disadvantageous ones. In case of zone *PN* such a high value of *RF* results also from very small thickness of the seam, short panel length, as well as a very long distance from the hoisting shaft.

Table 7. Values of each criterion in respective zones of the deposit

Tabela 7. Wartości poszczególnych kryteriów w poszczególnych strefach złoża

Zone	No. of longwalls	Mining factors			Geological factors				Natural hazards		
		Panel length*	Longwall length*	Distance from shaft*	Seam thickness*	Reserves total	KZU*	Depth*	CH_4*	KZS*	KZT*
B	9	900	244	1,122	2.80	8,684	0.75	855	11.48	0.12	0.17
C	7	942	186	1,435	3.20	6,112	0.75	1,065	10.57	0.13	0.00
K	8	1,112	206	2,226	2.15	7,401	0.50	989	15.96	0.16	0.75
N	21	727	213	1,723	2.45	13,043	0.57	905	9.27	0.08	0.00
PN	3	760	236	4,438	1.35	1,476	0.75	947	30.60	0.07	0.00
PW	5	793	271	3,696	1.86	3,762	0.75	1,062	10.22	0.07	0.00
S	7	984	224	1,937	1.85	5,408	0.70	855	14.99	0.07	0.00
W	12	903	255	2,455	1.67	9,411	0.25	969	9.22	0.07	0.00
Deposit AVG	72	890	227	2,016	2.29	55,297	0.58	944	11.84	0.10	0.13

* Averaged data for zone in accordance with reserves in respective longwalls.
Source: own study.

The lowest level of risk, with $RF = 0.17$, has been obtained in zone *W*. This low value of risk factor results mainly from low methane (CH4) content, and minimum constraints resulting from tectonics.

The following assumptions were made for specific components, to present the numerical result of the work done: WACC = 10%: $A = 0.5$; $\beta = 1.2$; $r_f = 5\%$; $W = 2\%$. On such a basis, the base value of Rp was estimated at 3.64% (equation 19 with one unknown, solved in Excel using the goalseeking formula). Substituting the project risk *Rp* thus determined to formula 17 allowed to determine the corresponding values of KKW amounting to 4%, and KKO amounting to 6%. On the other hand, values of Rp_i for specific zones were determined using the formula (21):

$$Rp_i = Rp_i(1 + \delta_i) \tag{21}$$

Substitution of all variables, with newly estimated values of Rp_i to formula 17 (for WACC), though, allowed to determine the adjusted values of the weighted cost of capital for

Table 8. Normalized results for each criterion and the overall result for zone of deposit

Tabela 8. Znormalizowane wyniki dla poszczególnych kryteriów oraz wynik ogólny dla strefy złoża

Zone	Mining factors			Geological factors				Natural hazards			**Risk Factor RF**
	Panel length	Longwall length	Distance from shaft	Seam thickness	Reserves	KZU	Depth	CH_4	KZS	KZT	
Weights P1	*0.129*			*0.255*				*0.617*			
Weights P2	*0.40*	*0.13*	*0.48*	*0.14*	*0.15*	*0.26*	*0.45*	*0.55*	*0.15*	*0.30*	
Weight W_{GL}	*0.05*	*0.02*	*0.06*	*0.03*	*0.04*	*0.07*	*0.12*	*0.34*	*0.09*	*0.18*	
B	0.11	0.10	0.56	0.08	0.08	0.13	0.10	0.09	0.13	0.16	**0.23**
C	0.10	0.13	0.71	0.07	0.11	0.13	0.12	0.09	0.15	0.00	**0.33**
K	0.09	0.12	1.10	0.11	0.08	0.09	0.12	0.13	0.18	0.72	**0.55**
N	0.13	0.12	0.85	0.09	0.14	0.10	0.11	0.07	0.10	0.00	**0.20**
PN	0.13	0.11	2.20	0.17	0.18	0.13	0.11	0.25	0.08	0.00	**0.64**
PW	0.12	0.09	1.83	0.12	0.10	0.13	0.12	0.08	0.08	0.00	**0.33**
S	0.10	0.11	0.96	0.12	0.10	0.12	0.10	0.12	0.08	0.00	**0.23**
W	0.11	0.10	1.22	0.14	0.11	0.04	0.11	0.07	0.08	0.00	**0.17**
Deposit AVG	0.11	0.11	1.00	0.10	0.10	0.10	0.11	0.10	0.11	0.12	**0.29**

Source: own study.

Table 9. Assessed values of Rp_i for specific zones and the entire mine

Tabela 9. Oszacowane wartości Rp_i dla poszczególnych stref i całej kopalni

Zone	*RF* Risk Factor	δ Relative difference for *RF* (%)	**Rp_i (%)**	$WACC_i$ (%)
B	0.23	–18.1	2.98	9.28
C	0.33	16.5	4.24	10.66
K	0.55	92.3	6.99	13.69
N	0.20	–28.8	2.59	8.85
PN	0.64	125.6	8.20	15.02
PW	0.33	15.3	4.19	10.61
S	0.23	–19.0	2.95	9.24
W	0.17	–41.5	2.13	8.34
Mine	**$RF_c = 0.29$**		**3.64**	**$WACC_c = 10\%$**

Source: own study.

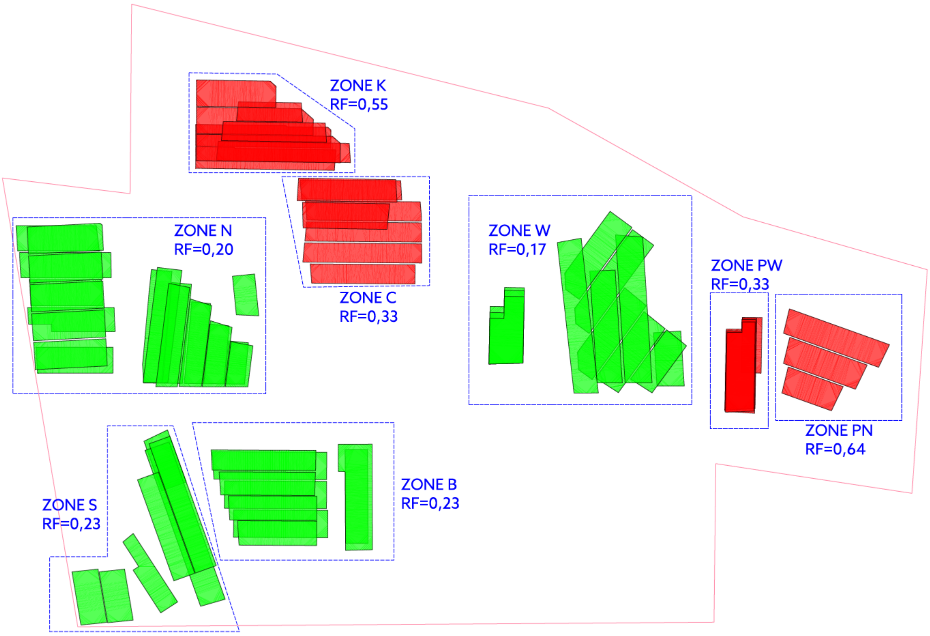

Fig. 4. Values of risk factor, RF in the analyzed zones of the deposit
(in green: zones with RF below the average for the entire deposit,
in red: zones with RF above the average for the entire deposit)

Rys. 4. Wartości współczynnika ryzyka RF w analizowanych strefach złoża
(kolor zielony: strefy o RF poniżej średniej dla całego złoża,
kolor czerwony: strefy o RF powyżej średniej dla całego złoża)

individual zones and for the whole mine. The values of Rp and WACC for specific zones and the entire mine are presented in Table 9.

When analyzing Table 9, one can notice that the values of Rp_i differ significantly, which influences the differences in the value of $\mathrm{WACC_i}$. Zones with the highest RF (zone *PN*) have Rp_i amounting to some 8% and over 15% in case of WACC. The lowest Rp_i was calculated for zone *W* (Rp_i = 2.13%. for *RF* = 0.17). The corresponding value of WACC is 8.34%. Therefore, this correctly reflects the risk assessment on the basis of *RF* indicator calculated in the previous studies. For the assumptions made, taking into account the attached formulae, averaged values of *Rp* and $\mathrm{WACC_c}$ can also be estimated for the entire mine, weighing the values of individual variables for *Rp* and $\mathrm{WACC_c}$ with the (coal) resources in a given zone (Table 7). Taking into account the weights made it possible to estimate the own risk value of the analyzed mine *Rpc,* which amounted to 3.64%, and $\mathrm{WACC_c}$ amounting to 10.00%.

Conclusions

Fuzzy Analytic Hierarchy Process (FAHP) has been used to develop the risk factor, *RF*. Nine risk factors were used, they were selected on the basis of statistical analysis using segmented regression, additionally the distance from nearest hoisting shaft was taken into account, which influences the effective working time for longwall mining. The values of RF were used to assess the risk when estimating the economic efficiency of panel mining, with the use of discounted cash flow method. This is an important forecasting "barometer" for mining, it is also the basis for a rational management of deposits. The *RF* indicator shows, on the one hand, the scale of hazards and threats and, on the other hand, the impact on the assessment of the economic effects of the mining plant operation. Zones with higher values of *RF* generate higher operating costs of mining. It is highly probable that they will be economically inefficient. The assessment of mining risk with use of *RF* indicator can be used as an element of decisions-making concerning the sequence and time of mining of specific zones. Selective management of longwall mining, taking into account the level of risk, provides opportunities for optimizing the cost of mining.

We believe that a significant accomplishment of this paper is the determination and quantification of the RF indicator, as well as the concept of its inclusion in the structure of WACC as a consolidated measure of project risk. Such an approach can be taken into account in the process of estimating the risk of mining projects, while the calculated value of WACC may be treated as risk-adapted discount rate, used to update future cash flows generated by the project.

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SUSTAINABLE MANAGEMENT OF HARD COAL RESOURCES IMPLEMENTED BY IDENTIFYING RISK FACTORS IN THE MINING PROCESS

Keywords

mineral resources, sustainable development of mining, digital deposit model, FAHP, risk factor

Abstract

Dealing with risk and addressing risk consequences constitute indispensable and specific elements of every business activity. The aim of this paper has been to assess the level of risk connected with the process of exploitation of hard coal deposits used for the production of coke in Poland, that is why a methodology has been developed which takes into account the impact of significant risk factors resulting from both geological and mining conditions upon unit cost of coal mining. This methodology constitutes a comprehensive approach to sustainable management of hard coal resources. The key source of information pertaining to exploitation risk factors is the digital geological model of hard coal deposit which has been developed. It comprises a structural model as well as a quality model of the basic quality parameters of coal. Structural models and coal quality models have been developed on the basis of litho-stratigraphic profiles from geological exploratory boreholes and underground observations (boreholes drilled from underground workings and their profiling). The structural grid model also contains information on tectonic disturbances (faults) or sedimentation disturbances (intercalations, wash-outs, and the like). The digital model was used as the basis for devising time schedules of development and preparatory works, as well as coal extraction proper.

Historical results of mining and economic data from 81 longwalls mined in the years 2016–2022 have been used for the purpose of analysis of the impact of risk factors on unit operating costs. The analysis comprised a total of 23 criteria which influence the costs of mining. From that group, 10 risk factors have been selected by means of statistical analysis using segmented regression, these factors have been utilized to make an assessment of the forecast concerning risk factor level for zones of the deposit meant for mining until the year 2035. The risk factors taken into account were those which are due to natural hazards, geological structure of the deposit (coal seam) and technical limitations. Risk factor (RF) indicator has been developed, for its construction the Fuzzy Analytic Hierarchy Process (FAHP) has been used. The value of RF, which expresses the aggregated form of variability concerning individual factors pertaining to geology and mining, has been used to determine the adjusted own risk assessment when estimating the economic efficiency of the coking coal deposit for 8 exploitation zones with the use of discounted cash flow method. The assessed average value of RF for the entire deposit amounted to 0.29. The lowest level of RF was noted in case of zone W ($RF = 0.17$), whereas the highest value of risk occurs in zone PN ($RF = 0.64$). The values of RF were used to calculate the rate of discount as consolidated measure of own risk, when assessing investment projects in mining. For zone W with the lowest risk of mining the discount rate amounts to 8.34%, whereas in case of zone PN which has the highest risk level, it amounts to 15.02%. Assessing the level of mining risk provides the possibility to optimize the cost of mining, and may be utilized for making decisions concerning the sequence and time of mining from particular zones of the deposit.

ZRÓWNOWAŻONE ZARZĄDZANIE ZASOBAMI WĘGLA KAMIENNEGO REALIZOWANE POPRZEZ IDENTYFIKACJĘ CZYNNIKÓW RYZYKA W PROCESIE WYDOBYWCZYM

Słowa kluczowe

zrównoważone górnictwo, cyfrowy model złoża, zasoby surowców, FAHP, wskaźnik ryzyka

Streszczenie

Radzenie sobie z ryzykiem z jego konsekwencjami to nieodzowny i specyficzny element każdego działania biznesowego. Celem artykułu była ocena poziomu ryzyka związanego z procesem eksploatacji złóż węgla kamiennego wykorzystywanych do produkcji koksu w Polsce, dlatego opracowano metodykę uwzględniającą wpływ istotnych czynników ryzyka wynikających zarówno z warunków geologicznych, jak i górniczych, na koszt jednostkowy wydobycia węgla. Metodologia ta stanowi kompleksowe podejście do zrównoważonego zarządzania zasobami węgla kamiennego. Kluczowym źródłem informacji o czynnikach ryzyka eksploatacyjnego jest opracowany cyfrowy model geologiczny złoża węgla kamiennego. Zawiera model strukturalny oraz model jakościowy podstawowych parametrów jakościowych węgla. Modele strukturalne i modele jakości węgla opracowano na podstawie profili litostratygraficznych z odwiertów badań geologicznych i obserwacji podziemnych (otwory wiertnicze z wyrobisk podziemnych i ich profilowanie). Model siatki strukturalnej zawiera również informacje o zaburzeniach tektonicznych (uskokach) lub zaburzeniach sedymentacji (interkalacje, wymywania itp.). Model cyfrowy posłużył jako podstawa do opracowania harmonogramów prac rozwojowych, przygotowawczych i samego wydobycia węgla.

Do analizy wpływu czynników ryzyka na jednostkowe koszty operacyjne wykorzystano historyczne wyniki badań górniczych i dane ekonomiczne z 81 ścian eksploatowanych w latach 2016–2022. W analizie wzięto pod uwagę łącznie 23 kryteria wpływające na koszty wydobycia. Z tej grupy wyłoniono 10 czynników ryzyka w drodze analizy statystycznej metodą regresji segmentowej, na podstawie których dokonano oceny prognozy poziomu czynników ryzyka dla stref złoża przeznaczonych do eksploatacji do roku 2035. Wzięto pod uwagę czynniki ryzyka, które wynikają z zagrożeń naturalnych, budowy geologicznej złoża (pokład węgla) oraz ograniczeń technicznych. Opracowano wskaźnik czynnika ryzyka (*RF*), do jego budowy wykorzystano proces *Fuzzy Analytic Hierarchy Process* (FAHP). Wartość współczynnika RF, wyrażająca zagregowaną postać zmienności poszczególnych czynników geologiczno-górniczych, posłużyła do wyznaczenia skorygowanej własnej oceny ryzyka przy szacowaniu efektywności ekonomicznej złoża węgla koksującego dla 8 stref eksploatacyjnych przy zastosowaniu zdyskontowanych metoda przepływu środków pieniężnych. Oszacowana średnia wartość *RF* dla całego złoża wyniosła 0,29. Najniższy poziom *RF* odnotowano w strefie *W* (*RF* = 0,17), natomiast największa wartość ryzyka występuje w strefie *PN* (*RF* = 0,64). Wartości *RF* posłużyły do obliczenia stopy dyskonta jako skonsolidowanej miary ryzyka własnego przy ocenie projektów inwestycyjnych w górnictwie. Dla strefy *W* o najniższym ryzyku eksploatacyjnym stopa dyskontowa wynosi 8,34%, natomiast dla strefy *PN* o najwyższym poziomie ryzyka wynosi 15,02%. Ocena poziomu ryzyka eksploatacyjnego daje możliwość optymalizacji kosztów wydobycia i może być wykorzystana do podejmowania decyzji dotyczących kolejności i czasu eksploatacji poszczególnych stref złoża.