Journal Pre-proof

The following article:

Innovative management of hard coal resources in line with rational deposit management

Eugeniusz Jacek SOBCZYK, Michał KOPACZ, Jarosław KULPA, Dominik GALICA, Leszek MALINOWSKI, Piotr OLCZAK, Jacek JAROSZ, Artur DYCZKO, Sylwester KACZMARZEWSKI, Jerzy KICKI and Krzysztof SZAMAŁEK

is accepted, peer reviewed article assigned to issue 4 of volume 69 that is not yet appropriately edited, but is citable using DOI:

https://doi.org/10.7306/gq.1836

This version will undergo additional copyediting, typesetting and review before it is published in its final form.

Innovative management of hard coal resources in line with rational deposit management

Eugeniusz Jacek SOBCZYK[1,*], Michał KOPACZ[1], Jarosław KULPA[1], Dominik GALICA[1], Leszek MALINOWSKI[1], Piotr OLCZAK[1], Jacek JAROSZ[1], Artur DYCZKO[1], Sylwester KACZMARZEWSKI[1], Jerzy KICKI[1] and Krzysztof SZAMAŁEK[2]

[1] Polish Academy of Sciences, Mineral and Energy Economy Research Institute, J. Wybickiego 7A, 31-261 Kraków, Poland; ORCID: 0000-0001-6387-5339 [A.D.], 0000-0002-1729-0046 [D.G.], 0000-0003-2965-1176 [J.J.]. 0000-0002-6076-9626 [S.K.], 0000-0003-3872-7558 [J.K.], 0000-0001-6475-8206 [M.K.], 0000-0003-4590-6853 [J.Ku.], 0000-0002-4002-6702 [L.M.], 0000-0002-4926-0845 [P.O.], 0000-0003-3968-2312 [J.S.]
[2] University of Warsaw, Faculty of Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland; ORCID 0000-0002-7487-5243
*corresponding author jsobczyk@min-pan.krakow.pl

Received: December 5, 2025; accepted: December 19, 2025

Abstract

The European Union, according to the European Green Deal, aims to achieve climate neutrality by 2050. Following this ruling, Poland plans to move to a low-carbon economy, which means progressive closure of Polish hard coal mines. In order to minimize the negative effect of this process on Polish society, we propose a method that supports management of coal deposits by assessing the dynamic resource base, which considers the economic value and cost of coalfields and helps in choosing the most viable exploitation plan. The method uses data extracted from geological and mining structure models to estimate the margin of exploitation of coalfields in multiple variants. The method then adjusts the results by geological and mining conditions including the nuisance factor, and uses it to estimate a variable discount rate and the net present value of each variant. This way, the resource base aligns with the JORC Code, which considers resources as mineable only if this can be done safely and profitably. The method allows for adjusting plans along with changing market conditions. In order to implement this method it is necessary to align Polish mining law with international standards and to deploy advanced digital tools, which may only be achieved by close cooperation between the state, geological administration, mining supervisory institutions and mining companies.

Key words: low-carbon economy, climate neutrality, resource management, mining scheduling.

Introduction

For decades, electricity generation using fossil fuels has contributed to the technological and economic development of many countries. However, for several years now, we have been witnessing a shift away from fossil fuels by a group of the most economically developed countries, due to the ongoing adverse effects of climate change and its impact on society and the natural environment. Climate change is considered the greatest threat to humanity. The Polish geological community is actively conducting research on paleoclimate change and the possibility of using the results of this research to predict the dynamics of global climate change (Szamałek et al., 2025). The key actions proposed by the international community are processes of systematic reduction of carbon dioxide emissions into the atmosphere. The European Union has been a leader in these changes for years, implementing many regulations and instruments to support decarbonization and aiming to achieve climate neutrality by 2050 ; Fit for 55, 2021; The European Green Deal…, 2019; *The European Green Deal Striving*…, 2019)

Following the resolutions and decisions made at the European level, Poland's energy policy is moving towards becoming a low-carbon economy. Decarbonising the Polish economy is a particularly difficult undertaking. The Polish energy mix continues to be dominated by fossil fuels, including hard coal and lignite. Despite an upward trend, renewable energy sources, together with gas sources, only complement the fuel market. Poland's Energy Policy until 2040 (*PEP2040*, 2021) presents a forecast of technological developments for energy generation sources and the primary energy mix.

In addition to EU regulations on CO_2 emission allowance prices, the use of coal in the economy will also be affected by regulations on methane emission reduction (*Regulation (EU) 2024/1787*, 2024). The regulation concerns, among other things, the reduction of methane emissions from active underground hard coal mines, and sets methane emission limits of 5 tonnes of methane per kilotonne of coal extracted by 1 January 2027 and to 3 tonnes of methane per kilotonne of coal extracted by 1 January 2031, which will pose additional challenges in Polish conditions.

The projected increase in electricity demand to over 200 TWh per year will be associated with a gradual decline in the percentage share of coal in the electricity generation mix. In 2024, as much as 34.4% of the 170.2 TWh of electricity produced came from renewable energy sources (Fig. 1).

Hard coal mining is currently the most important supplier of primary fuels to the Polish energy sector. This makes Poland an energy-secure country.

The optimal use of domestic energy resources is the goal of PEP2040, and meeting the current and future demand for fuel and energy in a technically and economically justified manner, while complying with environmental protection requirements, is one of the main elements of the country's energy security. Therefore, all circumstances should be considered so that the possibility of extracting and using hard coal, as provided for in EU regulations, is carried out in a rational manner, with the least environmental damage, stabilizing the energy transition process of the Polish economy and ensuring its energy security.

In this article, we describe an innovative concept for managing hard coal deposit resources based on a dynamic resource base (DBZ) and an economic mining parcel (EPE). It proposes:

- the necessity to move away from traditional, short-term extraction management in favour of rational and sustainable deposit management within the context of the energy transition and decarbonization.
- presenting a methodology based on digital geological modelling, risk assessment, and economic analysis, enabling flexible extraction planning under variable market and geological conditions.
- identifying the benefits of implementing such a system, including increased efficiency of the mining sector, improved energy security for Poland, and mitigation of transition impacts.
- identifying legal and systemic barriers along with proposals for changes necessary to implement a modern resource management model.

The article serves an analytical and project-oriented function, combining scientific foundations with practical recommendations for economic policy and the mining sector.

Innovative management of hard coal resources management

In the era of energy transition and growing uncertainty, modern coal resource management (where coal continues to play the role of an energy market stabilizer) is crucial for national security (Wirth et al., 2025). Hard coal will continue to play a key role in Poland's energy balance in the coming years. Forecasts presented in PEP2040 indicate that domestic hard coal consumption for energy purposes will amount to 22.5 million tonnes in 2030. Some forecasts predict that the demand for hard coal for electricity and heat production will reach 39.6 million tonnes in 2030 and 26.4 million tonnes in 2040 (Tokarski, 2022).

The traditional approach to coal deposit management in Poland is based on the paradigm of short-term efficiency and maximization of current production, often without considering the broader consequences. This is not always consistent with rational deposit management, and mining the most easily accessible and highest quality coal seams leads to the irreversible loss of part of the resources (those with poorer deposit parameters but which can be mined economically), making it difficult or impossible to extract them later. Mining decisions are most often made without a full simulation of the mine's development, resulting in sudden, costly changes in mining strategy and mines being unprepared for deteriorating geological conditions.

Geological, mining, economic and environmental data in individual mines are usually collected separately, which prevents their joint, advanced analysis and does not allow for dynamic simulations that take into account changing market parameters, costs or risks.

Due to its tradition and specific nature, the mining industry is reluctant to implement new management and digitalization technologies. Often, pressure to maintain production volumes makes it difficult to quickly adapt production to changing market demand.

Due to the traditional approach to resource management that is still prevalent in mines, it is necessary to implement innovative hard coal resource management based on advanced digital models. Such innovative management will allow for better planning of extraction, taking into account the changing quality of coal, risks resulting from the geological structure of the deposit (seam), limitations caused by technical requirements, the impact of exploitation on the natural environment. Identification of natural hazards will in turn minimize downtime in exploitation.

A modern, integrated and digital approach to resource management is a pillar of energy security during the transition period and an instrument for supporting the decarbonization of the Polish economy. Innovative resource management should be implemented in all hard coal mines, allowing them to be treated not as isolated production facilities, but as a key, flexible and predictable element of a larger energy system.

This approach will also allow for the development of a long-term and financially stable plan for the decommissioning of mines. The necessary production volume from mines with finite resources can be taken over by other mines with adequate production capacity and resource potential. This advance information can prevent sudden social and economic crises.

There are currently 20 mining plants operating in Poland, extracting thermal and coking coal. Coal mining is considered by many experts to be a highly risky and capital-intensive activity. At the same time, coal mining conditions are deteriorating, the most easily accessible resources in active mines are being depleted, the depth of exploitation is increasing, the temperature in the workings is rising, the transport distances for crews and materials are lengthening, effective working time is decreasing, hazards are increasing, and seams with an ever-increasing content of waste rock are being selected.

The difficult financial situation of Polish mining companies is exacerbated by their high operating costs. Opportunities to improve this situation can be found in streamlining planning processes. This improvement should aim at production planning that is as predictable as possible, while also being economically efficient. In this regard, it seems helpful to plan production in mining longwalls with full awareness of the complexity of geological and mining conditions and the resulting economic consequences.

To this end, it is necessary to create comprehensive standards and tools for the implementation of a modern concept of hard coal deposit resource management in terms of ongoing exploitation and the opening up of new coal deposits. The basis of the concept described in the article is the development of a methodology for estimating the size of recoverable resources in real time, depending on the variable level of production costs and coal prices. The research methodology used includes several key stages:

- methodology for developing a Dynamic Resource Base
- development of a digital model of the deposit;
- development of a mine model with a digital layout of mine workings;
- development of a model of mining nuisance; assessment of the impacts of geological and mining factors on mining constraints;
- development of a methodology for the economic assessment of resources: the concept of the so-called Economic Exploitation Parcel;
- estimation and demonstration of resources according to the international JORC Code standard.

Method of estimating the dynamic resource base

The methodology described below represents an integrated, four-stage research process aimed at developing a dynamic resource base for a hard coal deposit. It constitutes a coherent analytical chain in which a digital geological model of the deposit is a tool ensuring information continuity.

The purpose of the model is to create a three-dimensional representation of the deposit, showing its geometry and spatial variation in mineral quality. In subsequent stages, the geological model is a key source of data for designing mining options and for quantifying the severity of geological and mining conditions and identifying risk factors. The accuracy of the representation of actual geological conditions in the deposit model determines the reliability of the assessment of the economic efficiency of a mining investment project. This entire integrated process is necessary to estimate the resources that are economically viable for exploitation and forms the basis for the classification of resources in accordance with the international JORC Code standard (Szamałek and Wierchowiec, 2015; Sobczyk and Nieć, 2017). This enables the transformation of geological deposit data (Resources) into an economically viable and technically recoverable base of recoverable minerals (Reserves).

Digital deposit model, tunnel development plan and extraction schedule

A digital geological model of a deposit is a spatial representation of a mineral deposit, reflecting its location, geometry and qualitative variability. It serves as an integration platform, combining various geological data (Fig. 2) and interpretations in order to obtain a precise, three-dimensional description of the deposit structure. Such an integrated approach allows for the creation of a coherent picture of the geological structure and planned excavations, while also providing information about potential exploitation risk factors. The digital deposit model is now a standard tool for presenting the results of geological assumptions and planning analyses, and its use is crucial for mining planning systems, supporting decision-making processes at all stages of the mine life cycle (Galica, 2023).

The preliminary step before modelling is to organize and validate geological observations to create a geological database. At this stage, it is crucial to standardize and verify the accuracy of the data collected, including the development of rules defining acceptable values and dictionaries for lithological and stratigraphic divisions (Sosnowski, 2020). The modelling process is preceded by a statistical analysis of the source data, which serves to better understand the deposit and to validate subsequent estimates. This analysis allows the characterisation of geological and mining parameter distributions and the identification of mutual correlations. For example, in the data analysed on coal quality, a strong negative correlation between calorific value and ash content and a significant correlation between apparent density and ash content are commonly observed (Fig. 3). Similar relationships were also observed, for instance, in Polish brown-coal mines (Kozula and Mazurek, 1996).

The construction of a deposit model begins with the development of a structural model, which is the basic geometrical framework representing the structure of the deposit. This model creates a set of surfaces separating individual geological units, determined on the basis of the interpretation of boundaries identified in geological boreholes and observational data from underground workings. In the case of layered deposits, the modelling process additionally involves defining the relationships between units and separating higher-order units, such as strata layers, within which regional trends in the occurrence, thickness and continuity of layers are maintained. With regard to seam deposits, the structural model primarily determines the geometry of the floor and roof of individual seams, which form the basis for further modelling of the quality parameters of the mineral (Golda et al., 2024). It is essential to consider tectonic disturbances, such as faults (Fig. 4), which, through their geometrical parameters, determine the continuity and final shape of the seams. The structural model also reflects sedimentary disturbances, including layer splits, washouts and wedging, which are important factors influencing the variability of the deposit structure.

A numerical model for estimating deposit parameters is created using the structural model. In the case of seam deposits, especially hard coal of small thickness, grid models are commonly used. Block models are preferred for massive deposits or seams with significant thicknesses. Grid models (often classified as 2.5D models) describe seam deposits using the roof and floor surfaces and surfaces describing quality parameters, allowing the geometry and thickness of the seam to be mapped without fully discretising its volume. In contrast, block models (3D) divide the entire deposit space into regular volumetric elements, which allows for detailed mapping of parameter variability within the deposit, but this requires significantly greater computational resources. Grid models are a fully adequate solution for production planning from deposits exploited across the entire thickness of the seam, as the output then covers its entire vertical cross-section, and internal lithological and quality variability has no significant impact on the final, averaged parameters of the mineral (Unver, 2018).

In the methodology adopted, coal thickness (without rock partings) and the thickness of the overburden itself constitute integral, separately modelled structural elements. Quality parameters (e.g., calorific value, ash content) are then interpolated onto the model prepared in this way. The key here is to closely link the sampling interval (e.g., furrow sampling) with the lithological profile of the seam. This allows for an unambiguous definition of whether the sample represents only coal or also includes barren rock partings (those modelled with a thickness usually >5 cm). This aspect is important for the process of averaging samples to the thickness of the modelled layers. Correct estimation of the quality parameters of the run-of-mine (which are the result of the parameters of pure coal and impurities) plays an important role in the further stages of the methodology, requiring strict documentation of the condition of the sample (e.g., air-dry condition, analytical condition) on which the laboratory tests were performed (Table 1).

The mineral quality model is created by interpolating point estimates of deposit quality. Various methods are used to model the spatial distribution of parameters, but geostatistical methods (e.g., point kriging for isoline maps, block kriging for geological or extraction blocks) are preferred (Mucha, 1994; Kokesz, 2003). These are based on the analysis of spatial variability structure using a semivariogram and allow the estimation of parameter values with minimal estimation error and determination of the value of this error in the form of an error map. This gives them a significant advantage over simpler deterministic interpolators, such as the inverse distance method, because deterministic models do not provide a statistical measure of uncertainty (variance) associated with the estimation.

The result of the deposit modelling stage is an integrated numerical model (mesh or block), containing the spatial distribution of estimated geological and quality parameters. It forms the basis for resource estimation and for the design and scheduling of exploitation plans (Cichowlas and Malinowski, 2024). Crucially, a model based on geostatistical methods also includes quantified uncertainty (e.g., in the form of estimation variance) for key parameters. This information contributes directly to the subsequent stages of the methodology, enabling the development and evaluation of various deposit development options.

The finished geological model forms the basis for the development and evaluation of deposit development options. At this stage, considering the technical and economic assumptions adopted (e.g. minimum exploitable thickness, technology used, production targets), access and preparatory works as well as the geometry of the mine workings are designed. The digital model of the deposit significantly facilitates variant analysis, allowing for a quick analysis of many possible ways of developing the deposit or for the optimisation of the mining excavation design in relation to the geological conditions identified, e.g., in order to avoid zones of tectonic disturbance or maximise extraction from areas with the desired quality parameters (Kopacz et al., 2020).

The developed deposit development variant is then subjected to the process of scheduling of mining and production. Scheduling must take into account production targets and constraints resulting from geological and mining conditions as well as the availability of production resources (e.g., mining departments or mining machines; Kulpa et al., 2024).

The result of this process is a digital production schedule, which dynamically forecasts the quantity and quality of the mineral mined , as well as the amount of mining work performed, for specific periods (e.g., monthly or annually). Such a detailed schedule provides the necessary technical information that is crucial for assessing the geological and mining conditions of exploitation. This data is also necessary to generate revenue and cost streams, which form the basis for assessing economic efficiency.

Impact of geological and mining nuisance on extraction process

The second stage of the methodology involves constructing models of the impact of adverse geological and mining conditions on the exploitation process. This is a necessary step because the geological model itself, and the mining excavation design and schedule developed on its basis, describe the development plan, but they do not quantify the risks or difficulties of its implementation for individual exploitation parcels. These difficulties are a key risk factor that directly affects operating costs and, consequently, the profitability of the project. In order to objectively assess the nuisance of the geological and mining conditions of the exploitation process, the methodology uses the mathematical multi-criteria decision-making method AHP (Analytic Hierarchy Process) and multidimensional comparative analysis (Fig. 5). The use of the AHP method in hard coal mining has been extensively described in publications by Sobczyk (2008; Sobczyk et al., 2022).

The relative importance (weights) of individual criteria in the AHP hierarchy is determined on the basis of structured expert assessments. Specialists with in-depth knowledge of geology, mining and economics (scientists, engineers and management staff) play a key role in this process. The pair comparison method is used, whereby experts compare each criterion with every other criterion at the same level of the hierarchy in terms of their impact on the next criterion above in the hierarchy. These assessments are quantified using Saaty's fundamental nine-point scale, which allows subjective but structured assessments to be mathematically converted into a consistent vector of priorities (relative weights) for each element of the model (Saaty, 2001). To ensure the reliability of the results, a consistency ratio is calculated, which allows the logical consistency of the comparisons made by the experts to be verified.

The final result of stage 2 is the definition, based on the models developed, of synthetic indicators of exploitation nuisance. This indicator quantifies the level of exploitation risk in individual exploitation parcels. It is not an aim in itself, but constitutes a key input parameter for Stage 3, i.e. the economic assessment of resources. In accordance with the methodology, the calculated indicators will be taken into account when estimating the required discount rate in the discounted cash flow analysis, which allows for a realistic link between the quantified geological and mining risk and the financial assessment of the project.

Economic assessment of resource base

Economic verification of resources involves conducting a profitability analysis for each coalfield to determine whether it meets the criteria for an economic exploitation field (EPE). An EPE is understood to be a section of a deposit, separated by geological disturbances, safety pillars or legal borders, which can be extracted in an economically viable manner (Kopacz et al., 2020; Malinowski et al., 2025). In relation to hard coal mining, an EPE is a set of mining faces drawn within a coalfield (plot), assessed individually in terms of their technological and economic potential. Using dedicated mining design tools (software), an optimised layout of longwall workings is simulated, changing their geometrical parameters in order to comply with mining design principles and to cover the largest possible area of the parcel and the resources available therein, while minimising the costs necessary for its extraction.

The discounted cash flow method was used to carry out this assessment, and the net present value (NPV) was adopted as the basic decision criterion (the criterion NPV = 0 was recognized as a sufficient condition for determining the economic efficiency of the reserves base in the our method; we don't need to compare the level of internal rate of return do the value of discount rate for the decision-making process). The status of an EPE is granted to plots for which the calculated and risk-adjusted NPV is positive (NPV >0), which means that their extraction will be profitable in a model scenario.

To determine the EPE, it is necessary to use a previously developed digital geological model. The multitude of decision-making factors and the complex geometry of the deposits make it difficult to directly express the objective function for an effective parcel. Obtaining data from the model enables the estimation the parameters of the mining parcel to be automated, and thus allows checking of mining variants in a manner close to the heuristics of a full review. For the purposes of optimising the placement of individual faces, a dedicated tool has been developed that works on the deposit data structure in Deswik software. In this process, hundreds of layouts of individual faces in a given parcel are generated, and the best variants are selected. NPV as a criterion cannot be used at this stage, as layouts do not yet have an assigned a date of mining, and NPV requires a time parameter to be calculated. Instead, as an intermediate criterion, we propose the unit net margin of the coal mined within the variant..

Determining the EPE requires the construction of a dedicated economic efficiency assessment model which considers all relevant internal and external conditions affecting the operating margin and total cash flows over the life of the parcel.

The unit net margin was determined using the following formula:

$$M_e = \frac{W_s - K_e}{M_s}$$

where:
M_e – unit net margin of the variant [PLN/tonnes]
W_s – product sales revenue [PLN],
K_e – exploitation cost in the variant [PLN],
M_s – extracted resource mass [tonnes].

The value of the raw material is determined as the product of the weight of the extracted raw material and its price, which is equal to its stock market price adjusted by the quality parameter variability of the mineral contained in the deposit (this information comes from a digital model of the deposit quality) (Grudziński, 2009).

The extraction (exploitation) costs in this method are the sum of three groups of costs aggregated from 20 processes separated in the process-based approach to exploitation costs (Kopacz, 2015):

- Direct exploitation costs – these include variable costs directly attributable to a given longwall, determined as the product of the number of days of mining and the exploitation costs converted into working days:
- The costs of development excavations, which are the product of the length of the development tunnels in the plot and their unit excavation costs, depending on the purpose of the excavations. This group includes only excavations carried out directly for the needs of a single plot.
- Plant maintenance cost mark-up, determined as the ratio of the annual plant maintenance costs to the number of days needed to extract the parcel, divided by the average number of longwall faces planned to be mined in parallel at the plant. The method of determining the mark-up is given in the formula:

$$NK_z = K_z \frac{\sum_1^n \frac{w_{śn}}{p_n}}{365 * n_r}$$

where:
NK_z – mining plant maintenance cost mark-up on exploitation plot, PLN,
K_z – yearly costs of mining plant operating cost, excluding costs of group I and II, PLN/year,
$w_{śn}$ – longwall *n* length, in m,
p_n – average longwall extraction advance in, m/d,
n_r – number of longwalls extracted in parallel according to the mining schedule, -.
Another element of this process is considering the contamination of the excavated material with waste rock, which directly affects both revenue (through the quality of the commercial product) and cost (transport, processing, storage of waste rock). This methodology takes into account both contamination resulting from waste rock partings identified in the geological model and off-deposit additions, mainly from roof overburden and development and works.
The idea of determining resources in a parcel within the EPE concept is shown in Figure 6.

Once the parameters for individual parcels have been determined, it is possible to draw up a complete mining schedule, which allows for the use of the net present value (NPV) indicator, which takes into account the loss of value of money over time.

The revenue stream is determined on the basis of the exploitation schedule developed, which defines the volume of production and the quality of coal over time, which, in conjunction with the forecast prices, allows for the estimation of financial inflows. At the same time, the cost stream, including capital expenditure (CAPEX) and operating costs (OPEX), is estimated on the basis of the deposit development variant developed at the same stage.

In investment projects, the starting point for economic assessment is the reference discount rate, most often determined using the Weighted Average Cost of Capital (WACC) method for the entire deposit. An important element of the proposed methodology is the differentiation of this assessment and the departure from the use of a single, average discount rate for all parts of the deposit and the entire project period. For this purpose, a nuisance index is used, calculated for each plot in Stage 2, which refers to a value reflecting the average risk of the deposit. The relative risk difference calculated in this way is used to adjust the base premium for specific project risk. As a result, a parcel with a higher nuisance index than the reference value receives a correspondingly higher discount rate, which proportionally reduces its NPV. At the elementary level, this adjustment applies to each individual working face that is part of a given parcel, and the risk of the parcel becomes a derivative of the risk of the individual longwalls.

The collection of all EPE parcels identified in this way forms the quantitative basis for the Dynamic Resource Base (DBZ). This concept is based on the assumption that the DBZ is determined within the limits of safe and profitable exploitation carried out at an acceptable level of risk for a given investment project. The DBZ concept thus assumes that the amount of resources in a deposit is dynamic – it remains dependent on variable internal and external market conditions affecting both operating costs and revenues from the sale of raw materials. It is therefore linked to the theoretical foundations of dynamic resource theory and rational mineral deposit management (Szamałek, 2011).

The use of a digital exploitation model makes it possible to test many variants of the order in which individual parcels are extracted and to search for the variant with the highest total NPV. However, many variants of the order must be excluded for safety reasons or in order to avoid destroying the deposit by undercutting.

The methodology allows for sensitivity analysis to be carried out, e.g. depending on changes in market coal prices, which demonstrates the dynamic nature of the approach. This allows for production planning in coalfields with full awareness of the complexity of geological and mining conditions and the resulting economic consequences, and, as a result, for the development of mine development plans based on the economic value of the deposits.

Resource classification in accordance with the JORC Code

The next and final stage of the methodology involves the possibility of reporting resources in accordance with the international JORC Code standard. This standard distinguishes between two categories of solid mineral concentrations: *Resources* (comparable to Polish industrial resources) and *Reserves* (recoverable resources that can be related to operational resources or even commercial coal volume) (Sobczyk and Nieć, 2017).

The classification of the *Resources* category is based on the degree of geological recognition and certainty of estimation, which result from the geological model and the characteristics of the source data on which it is based (Fig. 7).

The transition from the *Resources* category to the *Reserves* category requires the application of so-called Modifying Factors. These include technical, economic, legal, environmental and social aspects that demonstrate that extraction is feasible and profitable (Sobczyk and Nieć, 2017). In the methodology proposed, Stage 2 and Stage 3 constitute a quantitative and objective determination of these factors. Identifying a parcel as an Economic Exploitation Parcel (EPE), i.e. an area with a positive risk-adjusted NPV, represents the required proof of the economic viability of extraction.

The final stage is a synthesis of the entire methodology, enabling the precise conversion of *Resources* into *Reserves*. The conversion process follows the following principle: part of the measured geological resources (*Measured*) that obtained EPE status in Stage 3 are classified as *Proved Reserves*. Similarly, part of the indicated geological resources that met the EPE criteria are classified as *Probable Reserves*. Resources with the lowest degree of recognition, belonging to the inferred category, are not converted into recoverable resources (Sobczyk and Nieć, 2017). In this way, the final summary of recoverable resources – comprising the sum of proven and probable resources – constitutes a quantitative representation of the DBZ, developed in accordance with international standards.

Legal and organizational aspects of introducing the innovative resource management model

The implementation of an innovative model for managing hard coal deposits based on the concept of a DBZ and EPE requires not only the development of advanced analytical tools and assessment methodologies, but also the creation of an appropriate legal framework and system infrastructure. The current institutional and legal conditions in Poland, although providing the basis for mining activities, do not fully take into account the needs of modern, dynamic resource management in the context of energy transition and international reporting standards. The section below identifies key legal and systemic barriers and formulates proposals for legislative and organizational changes necessary for the effective implementation of the model proposed.

Institutional and legal conditions of DBZ and EPE implementation

The current legal framework governing mineral resource management in Poland is based primarily on the provisions of the Geological and Mining Law (*Ustawa z dnia 9 czerwca 2011 r. - Prawo geologiczne i górnicze*, 2011). This Act defines the basic categories of resources (geological resources, balance resources, industrial resources) and sets out the rules for their documentation, recording and reporting. However, despite many years of operation, this system shows significant discrepancies with international resource classification standards, in particular the JORC Code, which is becoming the *de facto* global benchmark for investors and financial institutions.

The main legal barrier is the lack of clear definitions and procedures for documenting geological resources in the Resources/Reserves system in the Polish system that are consistent with the JORC Code. The Polish classification is based mainly on the geological degree of deposit recognition (A, B, C1, C2), while the JORC Code requires a wide range of modifying factors (technical, economic, legal, environmental and social) to be taken into account. In the case of exploitable reserves, some of these factors are already reflected in the deposit development plan (PZZ) and the mining plant operation plan, but they do not directly create a formal equivalent of the Reserves category as defined in the JORC Code. The concept of DBZ and EPE, which integrates geological and technical-economic assessment, points to the need to clarify the rules for reporting resources and reserves in Poland and to introduce mechanisms for their dynamic updating.

Another important institutional factor is the structure of supervision over the management of mineral deposits. This supervision is exercised by geological administration bodies (subordinate to the Minister of Climate and Environment) and mining supervision bodies. The Minister of Energy, responsible for the state's raw materials and energy policy and the rational management of strategic mineral resources, and the Chief Geologist of the Country play a key role. On the mining supervision side, the State Mining Office and regional mining authorities are of fundamental importance. The division of competences between these institutions, including the separation of responsibilities between the Ministry of Energy, the geological administration and mining supervision, does not always favour a comprehensive, integrated approach to resource management at the operational level of the mine. Geological documentation of deposits, which forms the basis for determining resources (and is a tool for implementing the state's raw materials policy), is prepared by licensed geologists acting on behalf of entrepreneurs or other authorised entities, and then approved by the competent geological administration authorities. On the other hand, mining operation plans, which specify the actual method of exploitation, are subject to approval by the mining supervision authorities. The lack of mechanisms for continuous, formal coordination between these processes –

with the participation of the Ministry of Energy as the entity responsible for the consistency of raw materials policy – hinders the implementation of the DBZ concept, which requires dynamic synchronization of geological information with operational planning and economic assessment.

The current reporting requirements for resources and production, based on static annual resource balances, reflect the information provided by companies in accordance with current regulations. The limitations stem primarily from the current form of the regulations, in particular those concerning the deposit development plan (PZZ), which do not provide for mechanisms for systematic, dynamic updating of economically viable resources for extraction. This structure of the system hinders full transparency in resource management and flexible production decisions adapted to changing market and technical conditions.

The implementation of the DBZ and EPE models therefore requires a change in the regulatory paradigm – a shift from static, bureaucratic reporting of resource volumes according to fixed geological categories to dynamic, continuous resource management that takes into account their economic viability and operational risk. This requires not only updating the law, but also changing the organizational culture in the institutions supervising the mining sector and in the mining companies themselves.

Need for update of law in the context of the JORC Code and digital deposit modelling

The harmonization of the Polish system for classifying and documenting mineral resources with the JORC Code standard is a key element enabling the implementation of the DBZ and EPE concepts. The JORC Code standard, developed by the Joint Ore Reserves Committee, is recognized as one of the leading international codes for reporting mineral resources. Adopting this standard in Polish geological and mining law (even as an option for parallel use alongside the current Polish classification system) would bring a number of benefits, including increased transparency and credibility of resource information for investors, easier access to international capital markets, and the promotion of rational deposit management (Moore and Friederich, 2021).

In the long term, it would be desirable to introduce the category of "reserves according to international standards" into the Geological and Mining Law, documented in accordance with the JORC Code or equivalent standards. However, amending the law is a complex process and unlikely in the short term. Therefore, it is particularly important to be able to adapt the implementing provisions under the authority of the Chief Geologist of the Country – in particular the rules for preparing geological documentation and deposit development plans (PZZ) – so as to enable the gradual implementation of solutions in line with the JORC Code philosophy without the need for immediate amendment of the Act itself.

A key element of this category would be the concept of the EPE, which constitutes the basic unit for assessing mining profitability. The resources contained within parcels that meet the EPE criteria (positive NPV with risks taken into account) would form the basis for reporting extractable resources (Reserves) and would be subject to ongoing updates as technical, economic and market conditions evolve.

Need for integration of geological and mining data

Effective implementation of the Dynamic Resource Base concept requires close integration of geological data – characterizing the structure and quality of the deposit—with mining data that describe the course and parameters of actual extraction. In current practice in Polish hard coal mines, these datasets are typically collected and managed in separate IT systems, which makes their combined analysis and use for dynamic production planning and resource management more difficult.

Geological data, including drilling results, geophysical logs, coal quality tests, and interpretations of deposit structure, form the basis for building digital geological models. These data are usually stored in specialized geological databases or deposit-modelling software systems (e.g., MineScape, Surpac, Micromine, Deswik, Leapfrog). On the other hand, mining data related to the progress of mining operations, the location of workings, the advance of longwall faces, the volume and quality of output, and operational parameters (productivity, downtime, costs) – are recorded in IT systems used for production management, operational planning, and mining reporting. Additionally, important information on mining conditions, such as the occurrence of natural hazards (methane, rockburst, water hazards), is documented in hazard-monitoring systems and in databases maintained by mine operations departments.

The integration of geological and mining data is a necessary condition for realizing the Dynamic Resource Base concept, as it enables the transformation of static geological documentation into dynamic tools for production and resource management that respond in real time to changing operational and market conditions.

Role of digital models in resource management

Effective implementation of the DBZ and EPE concepts is not possible without the support of advanced information systems that integrate geological, mining, economic and environmental data and enable complex analyses and simulations. These systems must meet a range of functional and technical requirements in order to effectively support decision-making processes at various levels of mine management, from operational planning to strategic investment decisions.

The foundation of an information system supporting resource management under the DBZ concept is advanced geological-modelling and mine-planning software. Such systems (e.g., MineScape, Deswik, Surpac, Vulcan, Micromine) enable the construction of three-dimensional deposit models, the design of mine workings, scheduling of mining operations, and estimation of production volume and quality. A key requirement is that this software supports methodologies consistent with international resource-classification standards (JORC Code), including the ability to define and quantify modifying factors and to automatically generate reports compliant with these standards.

Equally important is the implementation of systems for the economic assessment of mining projects, enabling financial analyses using discounted cash flow methods at the level of individual extraction parcels. These systems must be tightly integrated with geological models and production schedules so that they can automatically generate forecasts of revenues (based on estimated output volume and quality and projected coal prices) and costs (CAPEX and OPEX calculated from the technical parameters of mine workings and assumed unit operating costs). A key functionality is the ability to differentiate the discount rate depending on the risk level of individual parcels, estimated on the basis of indicators describing the severity of geological and mining conditions.

Role of government administration in implementing the new model

Effective implementation of an innovative resource management model based on the DBZ and EPE concepts requires active involvement of the state administration at several levels: legislative, supervisory, educational, and in the form of financial and organizational support. The energy transition currently facing the Polish hard coal mining sector makes this role particularly important, as decisions made in the coming years will have a crucial impact on the country's energy security, the socio-economic situation of mining regions, and the ability to use coal deposit resources rationally during the transition period.

The DBZ concept, thanks to its dynamic nature and consideration of a broad spectrum of modifying factors, provides a tool enabling rational and responsible management of the transition process, ensuring that decisions regarding the continued operation or closure of individual mines are based on reliable economic and geological analyses rather than on short-term political calculations or social pressures.

Conclusions

An innovative concept for managing hard coal deposits is based on the integration of advanced digital models, risk assessment, and economic analyses. This approach enables a shift from short-term extraction maximization toward sustainable, profitable and rational deposit management.

The concept proposed responds to contemporary challenges related to economic decarbonization, price volatility and supply uncertainty in raw materials markets, as well as deteriorating mining conditions. In the context of the energy transition, EU regulations, and the declining share of coal in the national energy mix, traditional methods of managing hard coal deposits are proving insufficient.

The innovative concept of hard coal resource management assumes that the Dynamic Resource Base (DBZ) is defined within the boundaries of safe and profitable extraction carried out at an acceptable level of investment risk. The DBZ concept therefore demonstrates that the quantity of recoverable resources in a deposit is dynamic and depends on both internal and external – market-driven – factors that affect operating costs and revenue from coal sales. A key element of this concept is the idea of the Economic Extraction Parcel (EPE), defined as a separate part of the deposit that can be mined in an economically viable manner, i.e., while maintaining a positive operating margin.

The concepts of the DBZ and the EPE address the challenges of the energy transition by enabling flexible, profitable, and safe production planning under variable market and geological conditions. Their implementation may significantly contribute to increasing the efficiency of the mining sector, improving Poland's energy security, and mitigating the socio-economic impacts of the transition.

The core of the proposed methodology is a four-stage research process consisting of:

1. Construction of a digital geological model of the deposit, enabling precise estimation of the quantitative and qualitative parameters of coal.
2. Assessment of the nuisance of geological-mining conditions, using the AHP to quantify operational risk.
3. Economic verification of resources, through discounted cash flow analysis and the delineation of EPEs.
4. Resource classification according to the JORC Code, enabling the transition from Resources to extractable Reserves.

The concept developed allows for the dynamic adaptation of production plans to changing coal prices, operating costs, geological conditions and environmental requirements.

Implementation of the innovative resource-management concept proposed, across all hard coal mines, would make it possible to:

1. Rationally manage the deposit – thanks to precise modelling and economic assessment, irreversible resource losses can be avoided and extraction can be planned to maximize economic value at an acceptable level of risk.
2. Support the energy transition – the DBZ enables long-term and financially stable mine-closure planning, minimizing sudden socio-economic disruptions and supporting the just transition of mining regions.

3. Increase efficiency and energy security – implementing the DBZ and EPE concepts allows for the optimization of national coal resource utilization, which is crucial for the stability of the energy system during the transition period.

To apply the innovative resource-management concept to the hard coal sector, pilot DBZ projects must be implemented in selected mines, followed—after demonstrating the method's effectiveness—by the adoption of the concept across all steam-coal mines. To achieve this, the following actions are required:

1. Legal and systemic changes: Effective implementation requires aligning Polish geological and mining law with international standards (JORC Code), introducing mechanisms for dynamic resource updates, and integrating geological, mining and economic data into a unified information system.
2. Digitalization and institutional cooperation: Deployment of advanced digital tools (e.g., Deswik, MineScape). The implementation of a modern resource-management model requires close cooperation between state administration, mining supervisory authorities, and mining enterprises.

Acknowledgements. The publication was carried out as part of the GOSPOSTRATEG.IX-0016/22 project entitled "Dynamic management of demand, production, resource management and logistics of distribution of hard coal in an economy implementing a decarbonization energy mix". The project is financed by the National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju, NCBR).

The Authors have no conflicts of interest to declare.

REFERENCES

Cichowlas, A., Malinowski, L., 2024. Monitoring the share of barren rock in extracted run-of-mine using digital deposit model and mine structural model – case study. E3S Web of Conferences, **526**, 01006. https://doi.org/10.1051/e3sconf/202452601006

COM, 2021. 550 Final, Dokument 52021DC0550, European Commission (2021). https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX:52021DC0550

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Empty. 'Fit for 55': Delivering the EU's 2030 Climate Target on the way to climate neutrality. (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0550

European Electricity Review, 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics

Fit for 55, Council of the European Union, (2021). https://www.consilium.europa.eu/pl/policies/fit-for-55/#what

Galica, D., 2023. Cyfrowy model geologiczny złoża jako narzędzie wspomagania decyzji w działalności kopalni węgla kamiennego (in Polish). https://min-pan.krakow.pl/dzialalnosc-naukowa/wp-content/uploads/sites/7/2021/10/Cyfrowy-model-geoligiczny-z%C5%82o%C5%BCa-jako-narz%C4%99dzie-wspomagania-decyzji-w-dzia%C5%82alno%C5%9Bci-kopalni-w%C4%99gla-kamiennego.pdf

Golda, K., Paszek, L., Kulpa, J., 2024. Geological and technological viewpoint on 3D Deposit Model – examples of use in Pniówek Coal Mine. E3S Web of Conferences, **526**, 01007. https://doi.org/10.1051/e3sconf/202452601007

Grudziński, Z., 2009. Propozycje struktur cenowych dla węgla kamiennego energetycznego i węgla brunatnego (in Polish). Polityka Energetyczna, **12**: 159–171.

Kokesz, Z., 2003. Difficulties and limitations in geostatistical modelling of mineral deposits variabilities and resources/reserves estimation by kriging (in Polish with English summary). Gospodarka Surowcami Mineralnymi, **19** (1): 35–55.

Kopacz, M., 2015. The impact assessment of quality parameters of coal and waste rock on the value of mining investment projects – hard coal deposits (in Polish with English summary). Gospodarka Surowcami Mineralnymi, **31** (4): 161-188.

Kopacz, M., Malinowski, L., Kaczmarzewski, S., Kamiński, P., 2020a. Optimizing mining production plan as a trade-off between resources utilization and economic targets in underground coal mines. Gospodarka Surowcami Mineralnymi, **36** (4): 49–74. https://doi.org/10.24425/gsm.2020.133948

Kozula, R., Mazurek S., 1996. Wstępna ocena stopnia rozpoznania podstawowych parametrów złożowych konińskich złóż węgli brunatnych w blokach geologicznych metodą krigingu (in Polish). Górnictwo Odkrywkowe, **38** (3): 78-85.

Kulpa, J., Jekiełek, M., Malinowski, L., 2024. Challenges and effectiveness of IT tools used in mining for forecasting production parameters. E3S Web of Conferences, **567**, 01014. https://doi.org/10.1051/e3sconf/202456701014

Malinowski, L., Kopacz, M., Sobczyk, J., Kulpa, J., Galica, D., Olczak, P., Jarosz, J., Dyczko, A., Kaczmarzewski, S., Kicki, J., 2025. Method for estimating the size of mineable resource base in the concept of an effective exploitation parcel (EPE). Gospodarka Surowcami Mineralnymi, **41**: 167–195. https://doi.org/10.24425/gsm.2025.155343

Moore, T.A., Friederich, M.C., 2021. Defining Uncertainty: Comparing Resource/Reserve Classification Systems for Coal and Coal Seam Gas. Energies, **14**, 6245. https://doi.org/10.3390/en14196245

Mucha, J., 1994. Metody geostatystyczne w dokumentowaniu złóż. Katedra Geologii Kopalnianej AGH, Kraków.

PEP2040 - Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. W sprawie polityki energetycznej państwa do 2040 r. https://isap.sejm.gov.pl/isap.nsf/download.xsp/WMP20210000264/O/M20210264.pdf

Regulation (EU) 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32024R1787

Saaty, T.L., 2001. The Analytic Network Process, fundamentals of decision making and priority theory (Second edition). RWS Publications.

Sobczyk, E.J., 2008. Analytic Hierarchy Process (AHP) and Multivariate Statistical Analysis (MSA) in Evaluating Mining Difficulties in Coal Mines. In: 21st World Mining Congress–New Challenges and Visions for Mining, Kraków. Taylor & Francis Group, A Balkema Book, London, 329–345. https://scholar.google.com/scholar?cluster=8563319847786458062&hl=en&oi=scholarr

Sobczyk, E.J., Galica, D., Kopacz, M., Sobczyk, W., 2022. Selecting the optimal exploitation option using a digital deposit model and the AHP. Resources Policy, **78**, 102952. https://doi.org/10.1016/j.resourpol.2022.102952

Sobczyk, E.J., Nieć, M., 2017. Praktyczne zastosowanie zasad kodeksu JORC na przykładzie polskich złóż węgla kamiennego. Górnictwo Odkrywkowe, **58** (4): 61-67. http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-211e3781-9423-430f-8068-21f084b8d290

Sosnowski, P., 2020. A New Look at the Geological Structure of the Knurów Hard Coal Deposit in Light of Model Tests. New Trends in Production Engineering, **3**: 186–196. https://doi.org/10.2478/ntpe-2020-0015

Szamałek, K., 2011. Rational mineral deposit management in the light of mineral resources theory. Gospodarka Surowcami Mineralnymi, **27** (4): 5–15.

Szamałek, K., Wołkowicz, S., Marks, L., 2025. Lessons from the past: A guide for the future. Przegląd Geologiczny, **XXX**: XXX-XXX.

Szamałek, K., Wierchowiec, J., 2015. The meaning and role of the bankable feasibility study (BFS) as a basis for JORC mining projects' feasibility assessment and profitability evaluation (in Polish with English summary). Gospodarka Surowcami Mineralnymi, **31** (3): 25-44. https://doi.org/10.1515/gospo-2015-25

The European Green Deal, European Commission, 2019. https://www.europarl.europa.eu/topics/pl/article/20200618STO81513/zielony-lad-klucz-do-neutralnej-klimatycznie-i-zrownowazonej-ue

The European Green Deal Striving to be the first climate-neutral continent, 2019. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Tokarski, S., 2022. Transformacja energetyczna—Zapotrzebowanie na źródła energii pierwotnej w perspektywie 2040 r. Co się zmieni po wybuchu wojny na Ukrainie? Nowa Energia, nr 2. http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-be6fe004-c347-4112-921e-eb17d9fad97b

Unver, B., 2018. Fundamentals of 3D modelling and resource estimation in coal mining. Journal of Mining and Environment, **9**: 623-639. https://doi.org/10.22044/jme.2018.6848.1515

Ustawa z dnia 9 czerwca 2011 r. - Prawo geologiczne i górnicze. (2011). https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20111630981

Wirth, H., Kudełko, J., Dyczko, A., 2025. Process approach in the organization and management of mining enterprises. Geological Quarterly, **69**, 54.

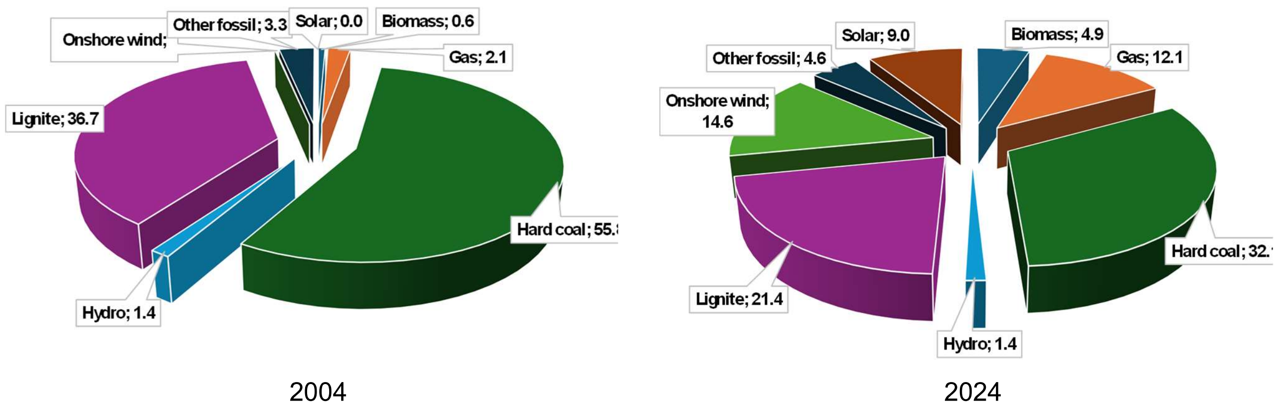

Fig. 1. Structure of energy sources in Poland in 2002 and 2024 (*European Electricity Review*, 2025)

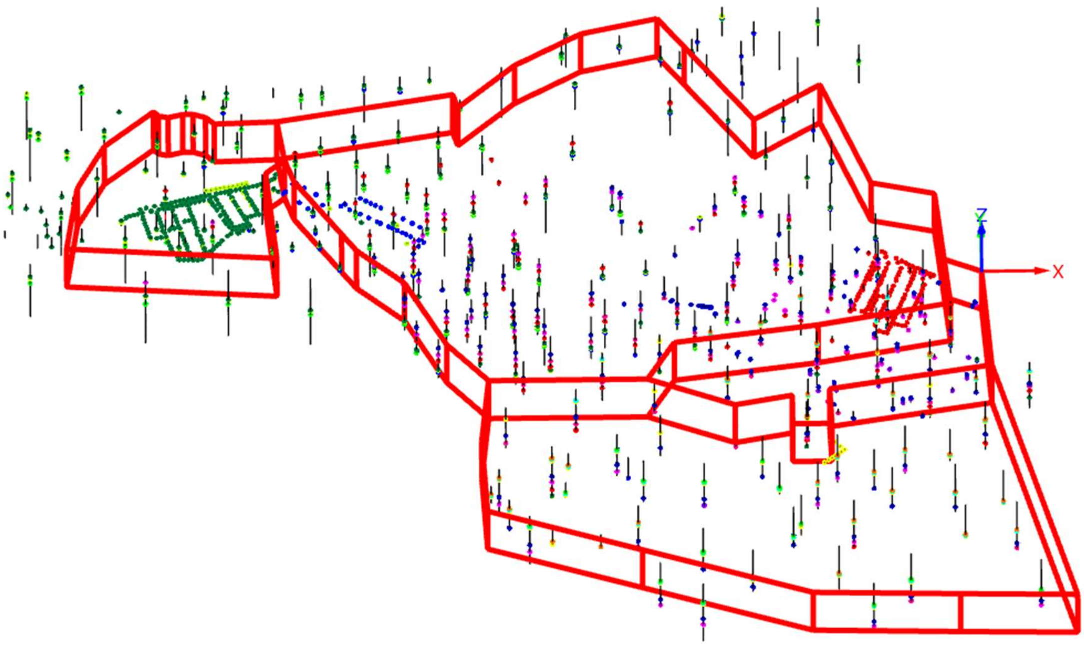

Fig. 2. Visualization of surface boreholes, underground boreholes and geological profiles used for modelling the deposits of one of Polish hard coal mine (screenshot from Datamine Minescape software)

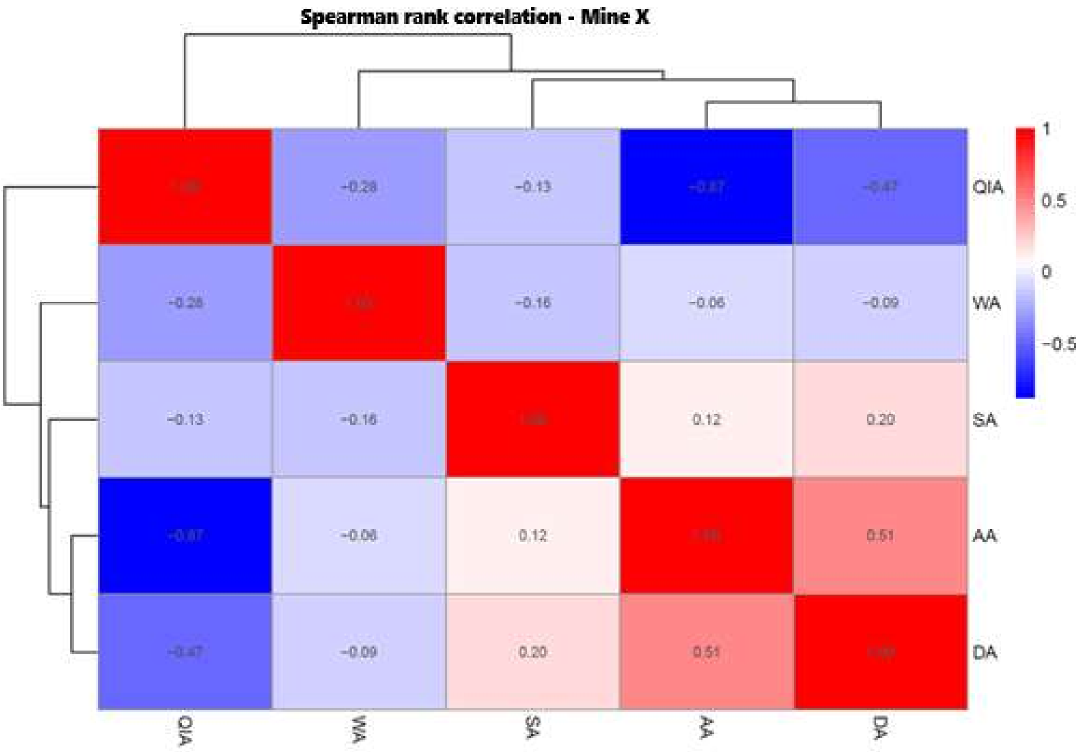

Fig. 3. Shapiro-Wilk test results and Spearman rank correlation coefficient for hard coal quality parameter data from one Polish mine

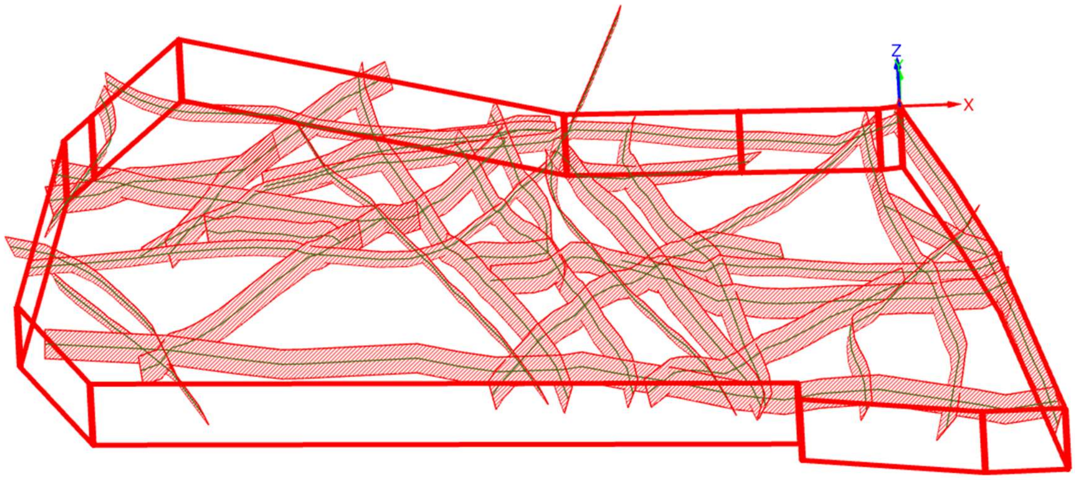

Fig. 4. Fault planes taken into account in a deposit model of one Polish mine

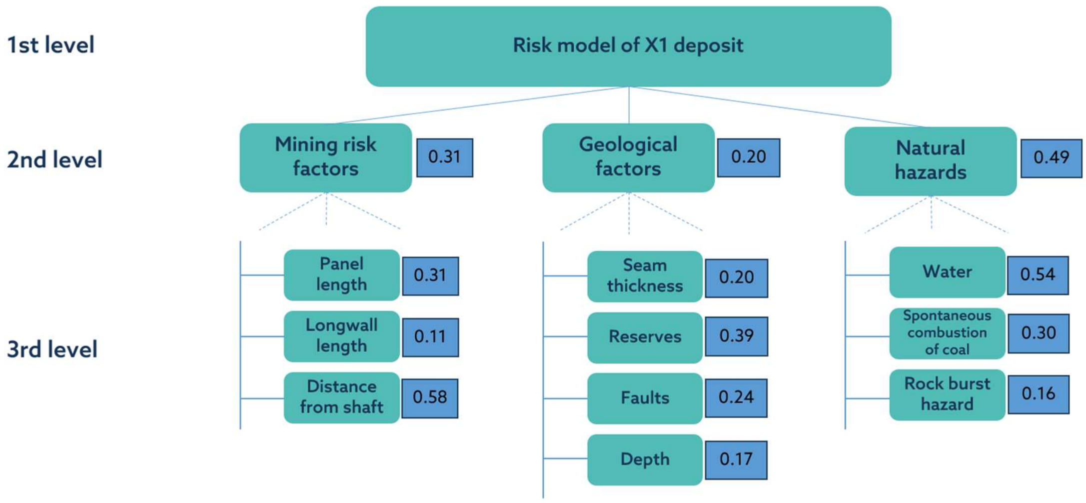

Fig. 5. Risk assessment model of increase of unit exploitation costs in longwalls

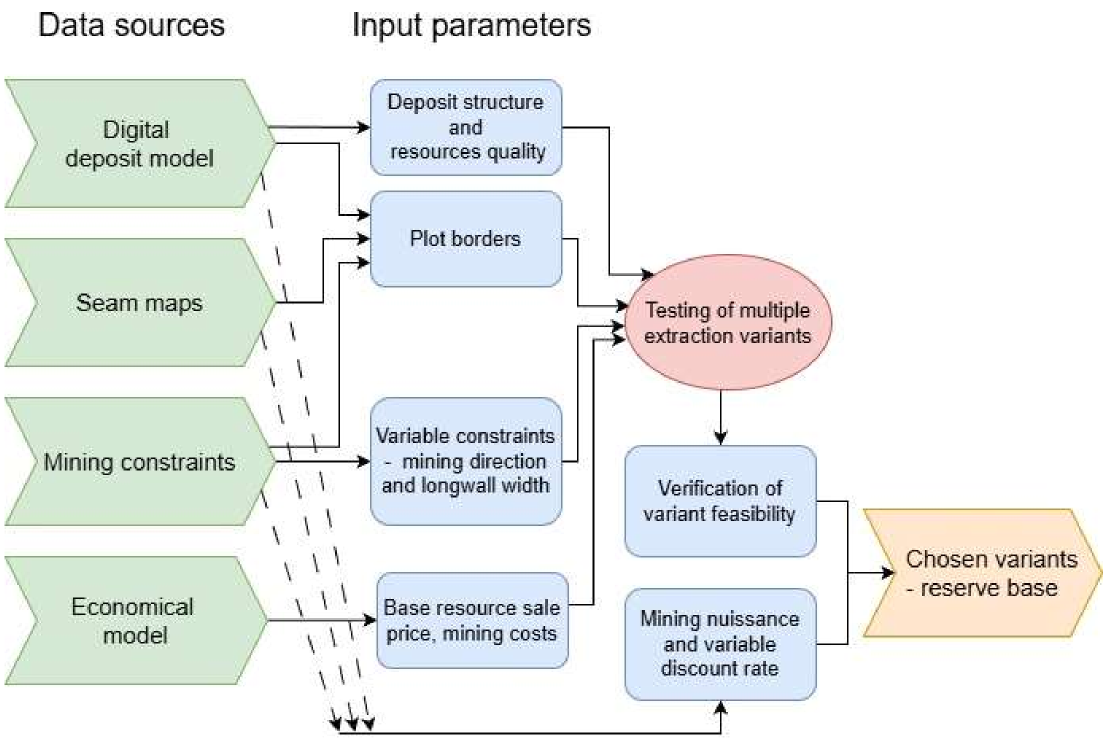

Fig. 6. Process of choosing an extraction variant for EPE

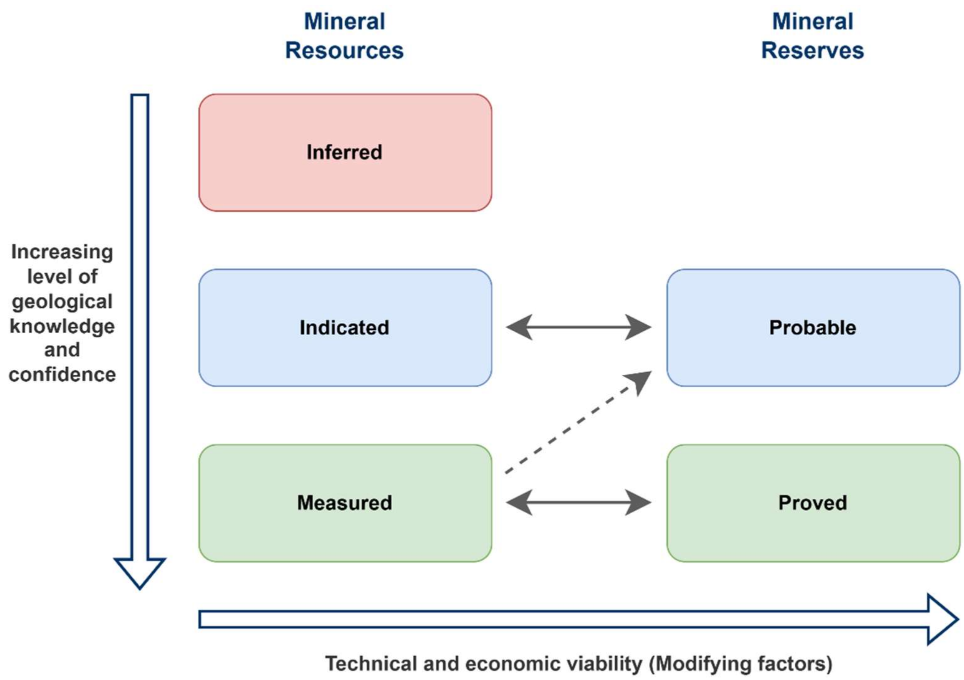

Fig. 7. Diagram of classification of solid mineral deposits according to JORC Code

Table 1. Modelled quality parameters of the deposit and their sample conditions in one Polish hard coal mine

No.	Mineral quality parameter	Symbol in the deposit model	Unit	Sample condition
1	Ash content	aa	%	AD - Air Dried
2	Specific density	da	g/cm^3	AD - Air Dried
3	Apparent density	dr	g/cm^3	AR - As Received
4	Calorific value	qia	kJ/kg	AD - Air Dried
5	Total sulphur content	sa	%	DB - Dry Basis
6	Volatile matter	vf	%	DAF - Dry Ash Free
7	Analytical moisture content	wa	%	AD - Air Dried
8	Surface moisture content	wx	%	DB - Dry Basis