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Quality management in a 3D geological model – reliability of predicted hard coal quality parameters

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Abstract. This paper presents some of the results of the project undertaken in JSW SA, which aim was to create a three-dimensional model of the deposits that make up the company and schedule company's production. The assessment of the quantity of coals without analysis of qualitative data, i.e. physicochemical parameters, coking parameters, and optical petrographic analysis is not suitable for obtaining commercial contractors. To obtain information on the quality of the coal seam, the geological service of the mine takes coal samples. In the stratigraphic model and quality model, dedicated interpolators are used for interpolation and extrapolation. In the seam quality model, the most optimized interpolators are Inverse and Height. Modelled parameters such as volatile parts content and random vitrinite reflectivity were analysed in detail. The Height interpolator looks for both a random and a linear dependency. It extracts random changes locally while searching for linear dependencies and extrapolates them to a deposit area that does not have qualitative data. There is a risk of extrapolating a given value to infinity. Nevertheless, the amount of data and the area modelled allows you to close its scope at an acceptable level. A separate POLYGON interpolator based on mxl express surfaces was created to map coal type range. It uses interpolated quality parameters at a given location, generating a range of a particular type of coal. Setting the trend of variability makes it possible to predict higher coal types in deeper, unrecognized batches of deposits according to documented variability in parameters.

1 Introduction

The purpose of launching the 3D deposit modelling and production scheduling project at JSW S.A. was to create a 3D model of the deposits included in the company. The modelling initially covered industrial deposits, where production was planned until 2030 [1]. The result, and the main goal of the project, was to create a powerful database of the reserves and quality parameters of coals within, which was in practice at the fingertips of geological

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services. The data was used to automatically make long-term mining schedules with the prospect of exploiting seams with the most optimal parameters [2]. Data from the deposit model and production planning systems can also form the basis for evaluating the economic efficiency of a mining investment project [3, 4] and be used in other departments of the mine, such as the design and simulation of the ventilation network [5].

The "Knurów" deposit owned by Jastrzębska Spółka Węglowa is located within the administrative boundaries of the cities of Gliwice and Knurów, as well as the municipalities of Czerwionka-Leszczyny and Gierałtowice. The area of the documented deposit is about 39.5 km^2. The deposit, which is in the Upper Carboniferous (Namur and Westfal) layers, is developed from the coal seams of the Orzesze strata (seams of group 300, Westfal B), the Ruda strata (seams of group 400, Westfal A), the Anticline layers (seams of group 500, Namur B-C) and the Poręba strata (seams of group 600, Namur A). The entire deposit is layered with packets of sedimentary rocks such as claystone, siltstone, sandstone, and conglomerate [6]. The deposit is characterized by intensive fold and fault tectonics, which is related to the proximity of two large dislocation zones of regional significance. These are the Orlowsko-Boguszowickie overthrust and the Michałkowicko-Rybnickie overthrust, which run along the western edges of the mining area [7].

Of the main fault zones, four should be mentioned that have the greatest influence on the morphological formation of the deposit. These are: the Gierałtowice fault zone with a width of about 300 meters with a total amplitude of throws of 40 meters, the central fault zone with throw ranging from 12 to 22 meters, the Beksz fault zone with throw ranging between 25 and 40 meters, and the Ornontowice fault zone with a vertical extent of up to 18 meters. In addition, there are several smaller faults located throughout the deposit. Heading south from the northern border with the "Sośnica" mine, the deposit is intersected by a fold zone called the "Knurów anticline", consisting of two anticlines and two synclines, which continues in the "Szczygłowice" and "Dębieńsko" deposits. The northern part of the deposit excluded from mining is dominated by a series of overthrusts and tectonic scales [6], while the south part of the "Knurów anticline" has the character of a monocline sinking to the SE at an average angle of 15º. The thickness of the seams exploited and planned for further exploitation is between 1.50 m and over 6 m. The deposit has been recognized and documented to the level of 1050 m. The dominant types of coal according to PN-82/G-97002 are types 34.2 gas-coking and 35.1 ortho-coking [8]. The coals are characterized by very good quality parameters enabling their use both in the power and coking industries [9].

2 Methodology

A key role in the recognition of the geological structure in recent years has been played by PIG-PIB (Polish Geological Institute National). According to the current Geological and Mining Law (Journal of Laws of 2019, item 868) it is PIG-PIB that is responsible for recognizing the deep geological structure of the country, as well as for parametric modelling of shallow geological structures in Poland. PIG-PIB's position is unequivocal – 3D geological modelling, coordination and interpretation of generated 3D models should become a statutory task of the Geological Survey [10].

In the underground mining of coal-bearing formations, both deep geological mapping and assessment of natural hazards and those caused by coal mining play a significant role [11 – 13]. Recently, digital mapping and subsurface data management techniques, related to GIS techniques, have been applied in the Polish coal mining industry [14, 15]. However, fully three-dimensional geological modelling, which is based on numerical methods, is still used sporadically in industrial practice, in contrast to oil and gas exploration and exploitation – it is already common practice in these areas [16].

The main task of geological cartography, as well as modelling, is to present as faithfully as possible a picture of the geological structure of a given study area. In the next stage, cartographic modelling through the inclusion of numerical models of deposits enables rational management of natural resources in accordance with the guidelines of the current Geological and Mining Law. In addition, for an operating mining plant, the ability to effectively manage the data in the geological model as well as the numerical model provides the basis for the efficient use of the resources of a mineral deposit (e.g., coal), optimizing mining costs, as well as predicting output [10, 17].

2.1 Model research

The broad term modelling research refers primarily to experimental research on a given object determining its suitability for a purpose defined for it. Modelling is an integral part of many scientific disciplines [18], in this case it should be understood as the use of science for industrial achievements. In the context of the 3D deposit model, the term *geological* modelling studies should be used. In addition to the tests verifying the execution of the model and its suitability for the processes related to production scheduling and the operation of the mining plant, a review or preliminary verification of the degree of geological reconnaissance of the deposit is carried out [19, 20]. This allows the introduction of necessary modifications for the correct geometrization of the deposit [21, 22]. Therefore, putting the geological model in the context of the experimental model as a system of assumptions and relations between objects is correct [23, 24].

The main inconvenience in modelling is too little borehole data. In some plots, there is the possibility of supporting the model with roadway profiling algorithmically converted to virtual geological boreholes [25]. However, it is necessary to remember, that the number of boreholes does not depend on the creator of the 3D model but on the investor recognizing the deposit. In some cases, the generated bottom surface location may be of too high uncertainty. As information grows in result of better reconnaissance of the deposit, the model can be updated on an ongoing basis [26, 27].

In the case of the “Knurów” deposit, the main fault zones in the poorly recognized parts, the courses of minor accessory faults, the formation of the Knurów anticline, and the variability of the relationship between adjacent seams in terms of cleavage and twinning were analysed in detail.

2.2 Deposit quality model

Assessing the value of a resource without analysing qualitative data, i.e. physicochemical parameters, coking parameters, and optical petrographic analysis, is unfounded for winning commercial contractors. Today’s climate policy and increasingly strict demand criteria for coking coal with specific parameters force the company to determine the specifications of the raw material *in situ* before it is brought to the surface.

In order to obtain information on the quality of the deposit, the geological service of the mine conducts ongoing sampling in accordance with internal regulations and with the guidelines of the Polish standard PN-G/04501:1998 [28]. Furrow samples are taken from corridor excavations, mainly from preparatory works, and core samples are taken from boreholes. To optimally identify the quality in each parcel of land, the sampling grid should be properly laid out so that the quality information obtained represents the most accurate distribution of quality parameters in space (Fig. 1).

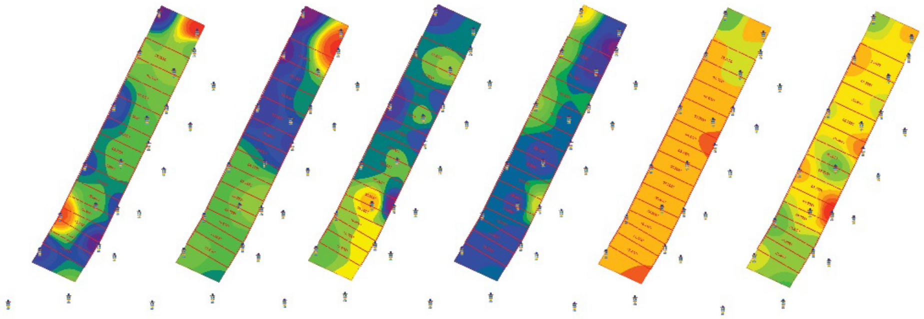


Fig. 1. A set of quality parameter maps for an example longwall parcel with marked sampling locations.

The deposit quality model as well as the 3D geological model was made in the Datamine MineScape software, using the corresponding module. The collected qualitative information was assigned to the corresponding deposit statements in geological boreholes and tabulated. Each modelled seam has a set of qualitative data, which, after appropriate interpolation, is used to make a quality map visualizing the distribution of the selected parameter. The qualitative information is also recorded spatially, described by *X*, *Y* and *Z* coordinates of a virtual seam solid, which is used for scheduling purposes in the Deswik software (Fig. 2).

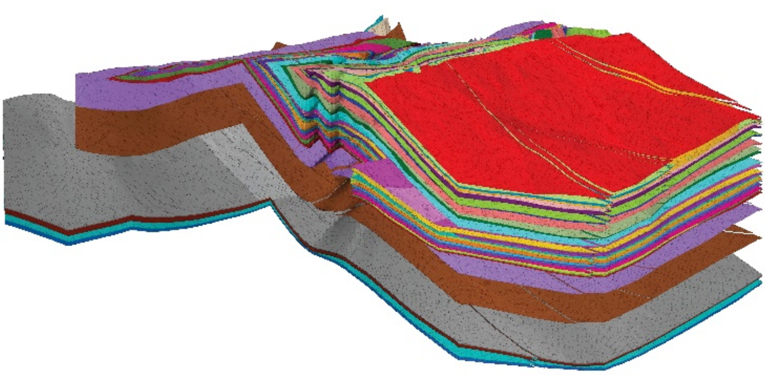


Fig. 2. Generated set of seam solids used by Deswik software for scheduling using tunnel projections.

2.3 Categories of deposit recognition

Both the Geological Documentation of the deposit and the Deposit Development Project are based on the categories of exploration based on the Decree of the Minister of Environment of December 22, 2011 on the geological documentation of the deposit [29]. They are separated by, among other things, possessed qualitative data of the mineral:

- cat. C2 – "the quality of the mineral is recognized on the basis of systematic sampling over the full range of possible uses of the mineral";
- cat. C1 – "the degree of recognition of the deposit is sufficient to develop a project for the development of the deposit, including a detailed determination of the form, structure, tectonics of the deposit and the quality of the mineral in the deposit";
- cat. B – "it requires determining the form and structure of the deposit, the correlation of layers, the basic features of tectonics in an unambiguous manner, the quality and

technological properties of the mineral should be confirmed by the results of tests on a semi-technical or industrial scale".

Within the boundaries of the deposit designated by the concession, there are regions not affected in any way by corridor or borehole mining works or located outside the concession area. In the second case, the depth of exploration of the deposit should also be considered (Fig. 3). In the case of forecasting the quality parameters in longwall plots for the regions in question, it is necessary to interpolate the available data, or in the absence of such data, instead extrapolate. In the case of an anisotropic deposit with a high coefficient of variation, this should be done with great care.

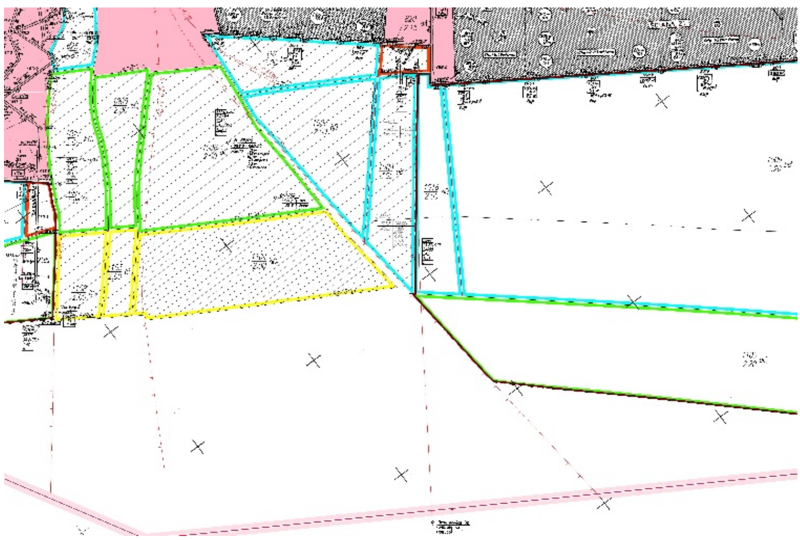
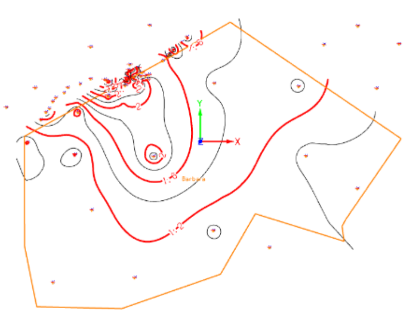


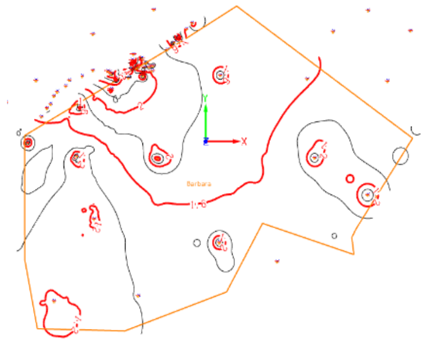
Fig. 3. Excerpt from the map from the Geological Documentation of the deposit with marked parcels of the corresponding category of recognition and the area outside the scope of the concession.

2.4 Tool selection – interpolators

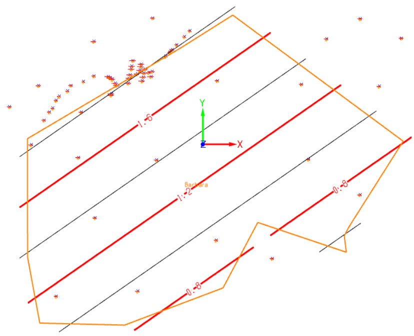
The stratigraphic model and the MineScape quality model use dedicated interpolators for interpolation and extrapolation. Here are four main ones, which differ in their purpose and how they calculate data:



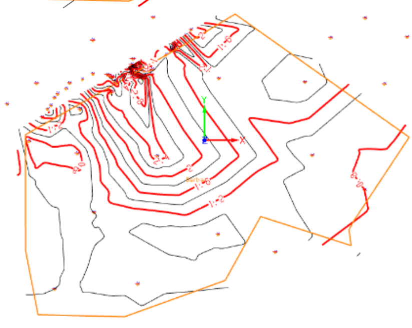
FEM – The basic interpolator used according to the recommendations of the manufacturer of Minescape software for modeling the surface, trend of layer deposition and thickness. This interpolator has a tendency of over-interpretation when the data are highly variable. It is not used in modeling qualitative parameters.



INVERSE – Interpolator used most often in the deposit quality model. It uses the method of the square of the inverse of the distance. Used for random distribution of quality parameters.



INVERSE – Interpolator subject to local trends. It searches for linear relations, but its use is not always safe.



PLANAR – This interpolator is the most predictable is for this type of data. Its downside is the rather granularity of the isolines, which is partially remedied by the use of smoothing when generating the grid model. This interpolator also performs disastrously with extrapolation.

In the deposit quality model, the most optimal interpolators are Inverse and Height. In the following, their use will be described for modelling interdependent parameters affecting, in part, the determination of technological coal type using the Polish standard [30]. Parameters such as dry and ash-free volatile content V^{daf} [%] and random vitrinite reflectivity R_0 [%] were analysed in detail.

3 Results

3.1 Establishing the trend of the rate of carbonization

The content of volatile parts in hard coal decreases with the rate of carbonization, i.e. the degree of maturity of organic matter. This is caused, among other things, by the loss of oxygen and the release of hydrogen in the process of vitrinite formation [31]. Vitrinite itself, on the other hand, measurably increases reflectivity due to changes in coal internal structure. Both parameters together show a linear relationship (Fig. 4).

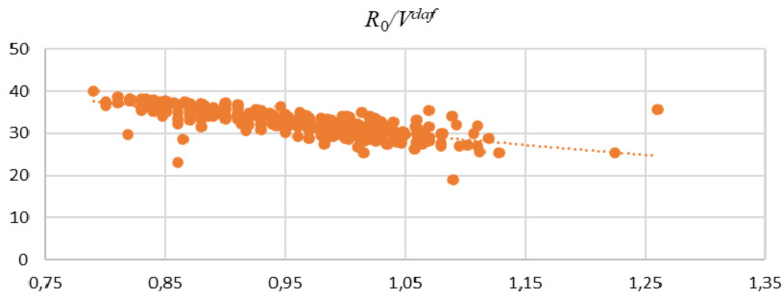


Fig. 4. Graph of the relationship between the content of volatile parts and the random reflectivity of vitrinite based on the correlation of more than 300 coal samples from the "Knurów" deposit.

Three main factors influence the maturity of coal: time, temperature, and pressure. In the case of the deposit under consideration, the metamorphism of organic matter was most influenced by uplift and folding during the Permian period. Due to regional tectonic changes, the deposit has a fold-monoclinal character with the uplift of layers to the SE, while on the NW side it is developed in the form of a fold zone with two anticlines and two synclines called the "Knurów anticline" [6]. Documentation of the parameters under consideration showed their linear variation with the depth of the deposit, which is also reflected in the other quality parameters. Due to the documentation of the deposit up to the level of 1050 m, the geological service of the mine does not have data from outside the concession area. To be able to forecast the above parameters taking into account their variability with the azimuth of sinking, it is necessary to select an individual interpolator with a modified anisotropy parameter to change the direction of the trend from axial to directed according to sinking. For this purpose, a Height interpolator in the 3rd power degree was used to make the calculated parameters as likely as possible. If the Inverse interpolator was used for the other parameters, the distribution of V^{daf} and R_0 would be very random, often changing in undesirable ways at deeper levels. (Fig. 5).

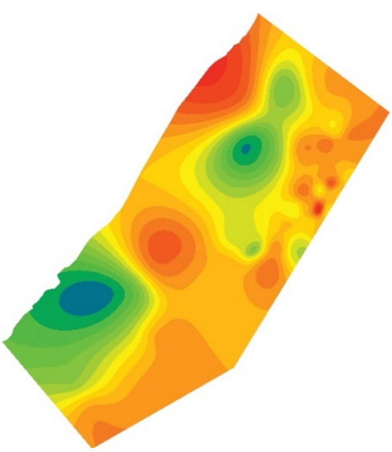


Fig. 5. Map of the range of volatile content using random interpolation. The higher the V^{daf} values, the closer the colour to red. There is no apparent trend.

The Height interpolator searches for both random and linear dependence. It locally separates random changes while searching for linear dependencies and extrapolates them to the area of the deposit without qualitative data (Fig. 6). There is a risk of extrapolating a

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given value de facto to infinity. Nevertheless, the amount of data and the area covered by the modelling allows to close the range of data to an acceptable level. This applies to industrial seams with sufficiently numerous samplings, because in the case of a small number of analyses it is safest to model each seam individually with the Inverse interpolator.

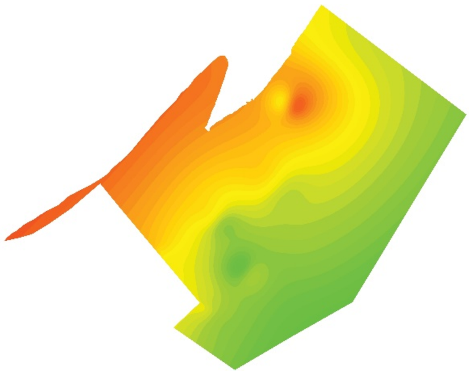

Fig. 6. Map of the range of volatile content using linear interpolation. The higher the V^{daf} values, the closer the color to red. A clear trend of decreasing V^{daf} values with depth toward the SE.

3.2 Determination of the coal type range

Visualization of coal type is not available in MineScape. The technological type of coal classification used in Poland [30] is not used anywhere else in the world. The coal type index itself is determined from the relationship of volatile content V^{daf}, dilatation b, free swelling index SI, and sinterability according to prof. Roga RI. A separate Polygon interpolator based on mxl* expression surfaces was created to map the range of a given type. It uses the interpolated quality parameters at a given location to generate the range of a particular coal type. The interpolator used and the V^{daf} parameter modelled accordingly are not insignificant. Determination of the variation trend makes it possible to forecast higher coal types in deeper, yet unrecognized parts of the deposit (Fig. 7). This is crucial for quality forecasts for the purpose of obtaining commercial contracts for a specific, narrowly targeted type of raw material.

Fig. 7. Coal type coverage maps for the same seam using Inverse interpolator (left) and Height interpolator (right).

* MineScape Expression Language

Random interpolation in this example, in the case of a small number of samples or when samples are significantly distant from the designed longwall parcel, carries over the found parameter value, which is not necessarily desirable. Despite the findings of type 35.1 and 35.2A coals in the southern part, V^{daf} values are not extrapolated according to depth. Instead, data from other parts of the seam determining type 34.2 have a big impact. By using linear interpolation with trend anisotropy, the geologist is given the opportunity to model a coal seam with the right technological type as predicted at the right depth level.

4 Discussion

The accuracy of deposit recognition is affected by the quantity and quality of data. Knowledge of the geological structure and distribution of qualitative parameters of the modelled deposit guides the execution of the project to a strictly defined form. If the modelled deposit does not have a rich resource of geological and qualitative information due to poor reconnaissance or lack of options to make measurements, verifying the documenter's geological interpretation is possible thanks to the use of the 3D model together with the deposit quality model. The use of the program's algorithms for transferring the trend of layer deposition and the variation of quality parameters makes it possible to reproduce with high probability the correct geological structure of the deposit with all its properties. However, one cannot rely solely on the interpretation of geological information done by the algorithms controlling the used software. Both input and output information must be controlled and validated by a geologist at each stage of processing.

To correctly model a deposit in terms of quality, knowledge of the dependence of parameters on geological conditions and the interdependence between them is required. A frequent topic addressed in the world literature is the influence of petrographic composition on coal quality. This applies to both coking [32] and basic parameters. The discernment of petrography [33] in individual fragments of a deposit makes it possible to model sedimentary basins that define a given coal facies [34] characterized by specific physical and chemical parameters. The above considerations provide a tightly focused view of the geologist's role in managing and forecasting the quality of commercial coal. For the most accurate spatial recognition of coal quality, it is necessary to trace its genesis.

5 Conclusions

The article elucidates the trend of carbonization rate in hard coal, highlighting its dependence on factors like time, temperature, and pressure. It notes a decrease in volatile content with increased carbonization, indicating the maturity of organic matter. This relationship is further influenced by regional tectonic changes, leading to linear variations in parameters such as reflectivity with the depth of the deposit. Such insights underscore the intricate interplay between geological processes and coal formation, emphasizing the need for a nuanced understanding of these factors in predicting coal quality.

Furthermore, the text discusses the methodology for determining coal types, particularly in the context of Poland's unique classification system. Techniques like the Polygon interpolator is employed to map the range of specific coal types based on quality parameters. This becomes pivotal for forecasting higher coal types in deeper sections of the deposit, essential for securing commercial contracts. The discussion underscores the significance of accurate coal type classification in optimizing resource utilization and meeting market demands.

It is necessary to emphasize the indispensable role of geologists in managing and forecasting coal quality. Geologists are tasked with validating both input and output data throughout the modeling process, ensuring the reliability of interpretations. Understanding the complex interdependencies between geological conditions and coal quality is paramount for accurate modeling. This necessitates a meticulous approach to data analysis and the discernment of petrography to capture the intricacies of coal facies. Ultimately, the text underscores the critical role of geologists in navigating the complexities of coal exploration and resource management.

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