monitoring systems [4]. This data encompasses rock properties, mine geometry, stress conditions, and previous roof fall incidents, forming a robust foundation for further analysis.

In hard coal mines, one of the main sources of waste rock in the excavated material is roof fall [5]. It increases the contamination of the ore with waste rock, which in turn increases the operating costs of the mine [6]. The exploitation of thinner and thinner seams, the application of plough technology, the increasing speed of progress in coal excavation – all these factors significantly affect the purity of coal seam mining. The LW "Bogdanka" S.A. has undergone significant changes in coal mining technology over the last several years, as industrial exploitation of thin seams below 1.5 m began [7].

In thin shearer longwalls, there is a tendency, both natural and forced by the geometric dimensions of the longwall equipment, to increase the height of the longwall, which is most often realised through ripping of the floor and the roof of the seam. This leads to a deterioration in the quality of the excavated material [8]. Bearing this in mind, and in order to ensure rational and effective utilisation of the coal reserves located in seams of low thickness, LW "Bogdanka" S.A. has commenced coal mining with the use of the ploughing technique [7 – 9].

The change in mining technology has meant that coal yield from longwalls has become strongly dependent on factors affecting the occurrence of waste rock in the excavated material [2, 10]. This has led to the search for methods to predict the susceptibility of roof rock to falling, to determine its magnitude, and to help optimize the mining process, particularly in terms of determining the methods of roof steering [11, 12].

Advanced statistical methods and machine learning algorithms analyze the collected data to identify patterns and correlations between different variables that contribute to roof falls. These analyses are crucial for understanding the complex interactions within the underground environment. Numerical modeling techniques, such as finite element analysis (FEA) and discrete element modeling (DEM), simulate the physical behavior of rock masses under varying conditions [8, 13, 14]. These simulations provide insights into stress distribution and potential failure zones, enhancing our understanding of the factors leading to roof falls.

Probabilistic models estimate the likelihood of roof falls by combining statistical analysis and simulation results. Techniques like Monte Carlo simulations are employed to quantify the uncertainty and variability in these predictions [15, 16]. Digital tools also offer powerful visualization capabilities, allowing engineers to create 3D models and virtual reality (VR) environments [17]. These visualizations enable the assessment of potential roof fall scenarios and the effectiveness of preventive measures, making the information more accessible and actionable for decision-makers.

Real-time monitoring systems, integrated with Internet of Things (IoT) devices and real-time data analytics, facilitate continuous monitoring of roof conditions [18]. This integration supports the development of early warning systems that provide timely alerts about potential roof falls, significantly enhancing safety measures. Additionally, decision support systems leveraging these digital tools offer actionable insights based on predictive models, assisting mine operators and engineers in planning and implementing effective safety strategies [19]. Through these advancements, digital tools significantly improve the accuracy and reliability of roof fall probability models, contributing to enhanced safety in mining and other industries reliant on stable roof conditions [20].

To determine the impact of roof falling on production costs, the team of the Division of Mineral Resources Acquisition of the Polish Academy of Sciences (IGSMiE PAN) in Cracow conducted detailed studies of the lithology of coal roof rocks in roadways and longwalls along with their progress. On their basis there was created a stratigraphic model and a block model of roof rocks that can be used to analyse the course of roof falling, estimate the mass of roof falling and calibrate a continuous system for measuring the quality of excavated material in mine workings.

1.1 Geology of the roof rocks in the LZW

In the literature on this subject [21, 22] geology of roof layer rocks of coal seams currently exploited in the Lublin Coal Basin (LZW) is relatively broadly described, and is usually represented by near-parallel, densely fractured ashy claystones with siderite concretions of various sizes, often with plant fossils, or clearly laminated and streaked with siderite substance (sideritic claystones). A frequent phenomenon is the occurrence of thin (1 ÷ 5 mm) layers of coal in layers of the claystone or slate roof, which determine the loss of cohesion of a part of the immediate roof. The claystone formations, when tapped with a hammer, are characterised by the so-called deafening sound, which indicates the presence of very numerous, even invisible (undisclosed) fractures, suggesting the danger or even certainty of falling of the roof rocks.

2 Methodology

2.1 Underground measurements and observations

The team of the Division of Mineral Resources Acquisition of the Polish Academy of Sciences carried out at LW “Bogdanka” S.A. a series of underground geological observations and measurements with the aim of making a block model of roof rock from the areas where mining was carried out with the use of ploughing technique. The main task of the project was to find out the genesis of the phenomenon itself and to develop algorithms for forecasting the occurrence of roof fall and technical possibilities of its prevention. A total of 68 profiles were made.

The mapping of the longwalls was carried out every 2 ÷ 3 days, corresponding to 13 ÷ 40 meters of longwall progress, thanks to which the variability of the seam in individual mining regions was observed. Due to the low variability of seam thickness and overburden, the frequency of measurements in galleries was set at 10 m intervals. Profiles were made every 5 m only in roadways where any disturbance, even the smallest one, was observed in the surrounding rocks layers, which is usually associated with sandstone. The measurements were realized based on the prepared and approved site manual using a laser rangefinder, measuring the thickness of the seam and of each separated lithological layer with the indication of roof fall in the bedrock. The results of the measurement were recorded together with a detailed lithological description of the roof rocks visible at the face of the excavation.

In addition, each time after exiting the wall, a linear meter was also measured in the second roadway, which was then profiled. The results of the geological observations were archived in the form of:

– numerical databases;
– profile drawings of longwalls and headings (Fig. 1);
– and subject in each case to the approval of the mining geologist to a service note.

Files were created in MS Excel in which the results of the measurements were entered for each longwall in separate sheets. The numerical data entered into the spreadsheets included information on the designation of the excavation (name of the longwall/heading), the longwall length on both headings (in linear metres of the longwall), the thickness of the measured layers, lithology, the number of the roof support at which the measurement was carried out, levelling measurements, the ratio of the thickness of the seam to the total thickness of partings disturbing it, the date, the amount of roof fall, as well as additional information observed during the observations, such as the results of additional levelling measurements, information on the occurrence of faults, etc.

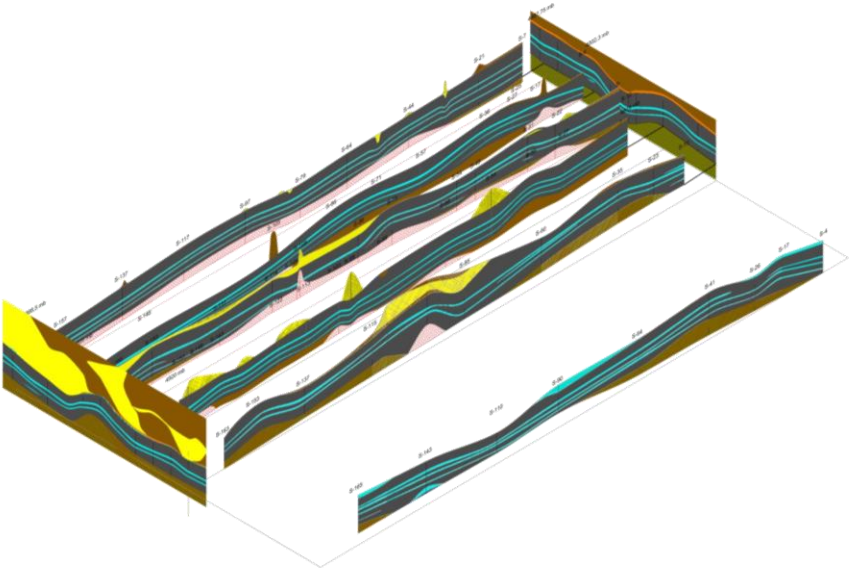


Fig. 1. Completed longwall and headings profiles.

2.2 Modelling of roof rocks of LW Bogdanka SA coal seams

Geological modelling of the deposit aims determine the geological structure of the deposit and the quantity and quality of the mineral within the mining area as well as possible. In this process digital deposit models play a crucial role in modern mining operations by providing comprehensive and up-to-date geological information to various mine departments. These models offer numerous advantages that facilitate efficient and effective mine planning and operations [23, 24]. They aid in the preparation of mine workings designs. By utilizing digital geological maps that contain detailed information on the structure and quality of the deposit, mining engineers can create precise and accurate designs [10, 25]. These maps ensure that all geological factors are considered, leading to safer and more efficient mine layouts.

The use of digital geological data allows for the faster and more efficient creation of schedules for preparatory and exploitation works [26]. The assumptions and results of these schedules can be based on modelled geological data, streamlining the planning process and reducing the time required to develop detailed work plans. This efficiency translates into significant cost savings and more responsive operations [27, 28].

In addition, digital deposit models enhance the ability to forecast the quality of extracted coal [29 – 32]. By analysing geological data and modelling various factors, mining operations can predict the properties of the coal they will extract [33]. This capability is crucial for meeting quality specifications and optimizing the processing and marketing of coal products. These models enable rapid responses to change in geological reconnaissance [34]. When new geological data necessitates updates to projects and schedules, digital models can quickly incorporate these changes, ensuring that all plans remain accurate and up-to-date [**Помилка! Джерело посилання не знайдено.**]. This adaptability is vital for maintaining the safety and efficiency of mining operations.

An important aspect of digital deposit models is their ability to provide information on anticipated roof rock falls. By analyzing geological conditions and modeling potential failure zones, these models help in predicting areas where roof falls are likely to occur. This information is critical for implementing preventive measures and enhancing the safety of underground workings.

In the literature on this subject [23, 26 – 33, 36] deposit model is defined as a spatial visualisation of the deposit and is the basis for the proper management of every mining plant. Currently, its role is becoming increasingly important also in the Polish mining industry [37]. Ultimately, the numerical model of ore deposits should support activities of geological surveys connected with designing and carrying out geological works and interpretation and documentation of geological structure of deposits [38].

So in this cese, the digital deposit model should provide other mine departments with complete and up-to-date geological information to:

– prepare designs of mine workings based on digital geological maps containing full information on the structure of the deposit and its quality [39];

– create schedules of preparatory and exploitation works faster and more efficiently, basing some schedule assumptions and calculation results on modelled geological data [40];

– forecast the quality of extracted coal;

– respond rapidly to changes in the geological reconnaissance of the deposit necessitating an update of projects and schedules;

– provide information on anticipated roof rocks fall.

There are many advantages to having a numerical geological model of the deposit, the most important of which are [8, 37 – 40]:

– the possibility of storing, within one coherent system, full geological information on surface, underground, geotechnical, and hydrogeological boreholes, profiles of underground workings, including scanned source documentation of the boreholes;

– the possibility of attaching geological maps to the profiles;

– the possibility of storing the results of coal quality analyses, geomechanical tests and hydrogeological observations;

– visualisation of borehole profiles in the form of borehole cards according to a defined template and creation of correlation lists and graphical correlation of strata;

– definition of stratigraphic model of a deposit (definition of individual coal seams and other stratigraphic units, definition of geological sequences, erosion surfaces – Carboniferous roof);

– possibility to model coal seam disturbances such as partings, thin-outs, washouts, outcrops and faults;

– possibility to model coal quality parameters (calorific value, sulphur and ash content and density);

– possibility to model the predicted roof fall based on a block model and a grid model made for selected fragments of the deposit;

– calculation of resources of the deposit and losses in these resources;

– adjustment/definition of presentation of results of geological modelling in accordance with applicable Polish standards (maps, geological cross-sections, headings profiles, etc.).

3 Results and discussions

The process of constructing the geological database commenced with the development of a tailored dataset designed to meet the specific requirements of the MineScape software. This initial step involved meticulously crafting the geological data in Excel tables, ensuring that all relevant information was accurately recorded and formatted for compatibility with MineScape. These Excel tables included detailed records of various geological parameters, such as rock types, stratigraphy, and lithological characteristics. Once the dataset was thoroughly prepared, it was loaded into the MineScape software’s Geological Database module (GDB) [41]. This module serves as a comprehensive repository for geological data, enabling efficient storage, management, and retrieval of information. The successful import of data into the GDB laid the groundwork for the subsequent stages of geological modelling.

With the geological data in place, the next step involved creating a stratigraphic model. This model provided a detailed representation of the vertical sequence of rock layers within the deposit, capturing the complexities of its geological structure. The stratigraphic model included information about the overburden, the coal seam, and the partings within the seam, offering a complete picture of the deposit's lithology. Building on the stratigraphic model, a block model was developed for a selected section of the deposit. The block model is a three-dimensional representation that divides the deposit into a grid of blocks, each containing specific geological attributes. This model was designed to depict the full lithology of the rocks, encompassing all the layers from the surface overburden down to the coal seam and its partings. The detailed nature of the block model allowed for a comprehensive understanding of the geological conditions across the deposit.

The creation of these models enabled the development of two distinct approaches to predicting roof fall. The first approach utilized the block model, leveraging its detailed spatial representation to assess the potential for roof falls within each block. By analysing the geological attributes and stress conditions in the block model, predictions could be made regarding areas of potential instability. The second approach employed a stratigraphic (grid) model, which focused on the vertical sequence of rock layers. This model facilitated the prediction of roof falls by examining the continuity and properties of the stratigraphic layers. By understanding how different layers interact and their susceptibility to failure, this approach provided valuable insights into potential roof fall zones.

Together, the block model and the stratigraphic (grid) model offered a robust framework for predicting roof falls. By combining these two approaches, a more comprehensive and accurate assessment of roof fall risks could be achieved, enhancing the safety and efficiency of mining operations. The integration of detailed geological data into MineScape and the development of these sophisticated models underscored the importance of advanced digital tools in modern geological modeling and mine planning.

3.1 Block model

For the construction of the block model of rock layers surrounding the seam, data on lithology within the analysed section of the deposit was exported from the Geological Database (GDB). The information on lithology used in the construction of the model was obtained from previously made profiles of roadways and longwalls. The range of the built block model was set at 4 m above the seam and 3 m below it, and as it turned out during modelling, the most interesting zone was a package of roof rocks about 2 m thick. The model built operated inside a solid that bounded its area, the size of the parent cell was set at 1 m × 1 m × 0.02 m. The attributes of each lithological unit were then added.

The interpolator used to model the lithology was the so-called influence polygon. It divides the distance between two boreholes in half. In one polygon, the computational blocks are only influenced by the lithology from one borehole. The software then assigns the lithology to the calculation blocks, right up to the boundary of the influence polygon, taking into account the bedding trend from the stratigraphic model. With this solution, the continuity of partings in the coal was maintained. An additional advantage of this solution was the possibility to interpolate both numerical and string values (e.g. lithocode). In order to visualise roof fall the suffix "O" was introduced into the lithology code to denote the fall measured during profiling in the longwall workings and the suffix "P" to denote the projected fall added on the basis of the headings profiling. By introducing designations and creating display specifications, the cross-sections showed: bedrock lithology, roof fall, or both at the same time, where rockfall and projected roof fall were indicated by a darker shade of the colour denoting the respective lithology. The built model allowed for the presentation of the roof fall pattern of the roof rock and calculation of the roof fall mass of the roof rock or selected lithology of the individual rock packages (Fig. 2).

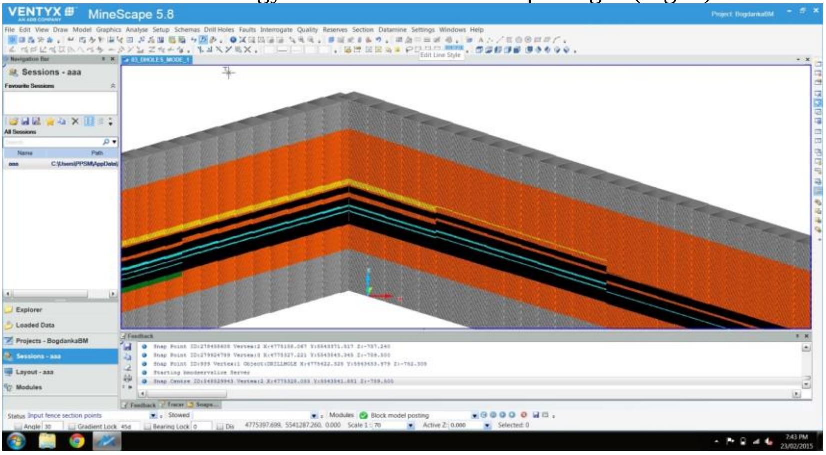


Fig. 2. Block model of roof fall in a longwall face.

A complete geological model contains comprehensive data describing the deposit. Thus, such a model contains complete data on the quality and extent of the mineral resources in the deposit under consideration. In the mine area analysed during the project, the package of roof rocks comprised the largest percentage of siltstone (41.2% on average), with a slightly smaller share of claystone (38.0% on average), although in some areas claystone outweighed siltstone. Sandstones, on the other hand, accounted for a relatively small percentage of the rock mass in the analysed area of the mine – it ranged from 2.8 ÷ 20.1%, with an average of 12.8%.

As if to check the final effect of the block modelling of roof fall of the roof rocks, the thickness of each lithology in the roof fall was summed up based on the results of the performed longwall profiling and the information extracted from it, and *X*, *Y* coordinates were assigned to them. Having the distribution and volume of the measured roof fall, contour maps were generated on their basis (Fig. 3).

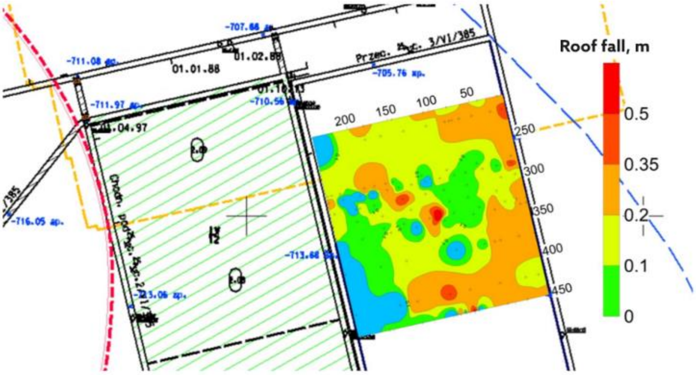


Fig. 3. Contour map of the volume of roof fall in the analysed section of the longwall face.

Maps were produced separately for each of the mining divisions analysed, using an interpolator of inverse distance to the power of 2 and an interpolation grid every 2 metres. Five class intervals were used in the generation of the maps, each with a different range of data. This was due to the high variability of roof fall ranging from 0 to 1.6 m, with most roof fall not exceeding 20 cm.

As a result of the modelling carried out, contour maps of the magnitude of the roof fall were obtained (see Fig. 3) on which the visible red colour represents the locations of its occurrence. As established by geological observations, the marked rock fall was caused by the occurrence of thin alternating layers of siltstone and coal-bedded sandstone in the roof, which fell along fault planes with a tendency to fall frequently.

3.2 Stratigraphic (grid) model

The numerical model of the deposit developed as part of the project, which includes information on roof fall, is a source of information not only for the geological department, but also for other departments of the mining plant, such as the mine production planning department, the deposit quality control department or the departments dealing with natural hazards, and its correctness and accuracy can have an impact on the choice of deposit exploitation method. A reliably executed and consistently updated deposit model enables the design of an optimal spatio-temporal depletion of the deposit resources in line with the desired commercial parameters of the coal.

The current roof fall model presented above in MineScape allows a model to be created of the surface of the roof-fall layers, ascertained through direct measurements in the workings. With the stratigraphic model of the overburden layers also available, it is possible to forecast the roof fall, which is an extremely important aspect in production planning, particularly when mining thin seams. Appropriate mining planning has a direct impact on the cost of coal extraction.

The following procedure allows the creation of a model of the surface of the roof rock fall layers, projected on the basis of a stratigraphic model of the overburden layers. The forecast is created as expression layers in two aspects:

1) The probability of roof fall occurring is based on the assumption that the thinner the layer with a thickness of less than 30 cm, the greater the probability of roof fall. Subsequent layers of this thickness increase the probability of roof fall occurrence.

2) The projected roof layer of the roof rock fall, according to the above assumptions.

The proposed methodology therefore has the following elements:

1) Creation of surfaces with an indicator of the probability of roof fall occurrence (an example of an expression surface for one coal seam is shown in Fig. 4).

2) Creation of a roof surface for the roof fall layer (Fig. 5).

3) Creation of a floor surface for the roof fall layer.

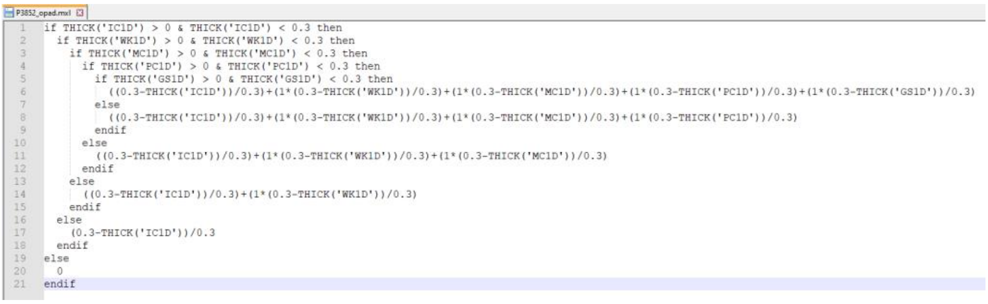
The floor of the rockfall (i.e. the surface of the production seam roof) can take a variety of forms. In the extreme case, it may simply be the production seam roof area. However, in the case of split seams, the production roof should be considered. This could be, for example, a complete roof for the upper bench and composite seam, or a roof for the lower bench and composite seam when the upper bench is not productive. For our case, the surfaces of the upper bench and composite seam were created by using the expression “Totalroof”.

4) Creation of a roof fall rocks layer.

The roof fall layer will be described according to the guidelines: the floor of the roof fall layer will follow the roof of the production seam - according to the layer created above. On the other hand, the roof of the roof fall layer will follow the roof of the last analysed layer with a thickness less than the set one – the roof of this layer was created as a surface in one of the previous steps (Fig. 4).

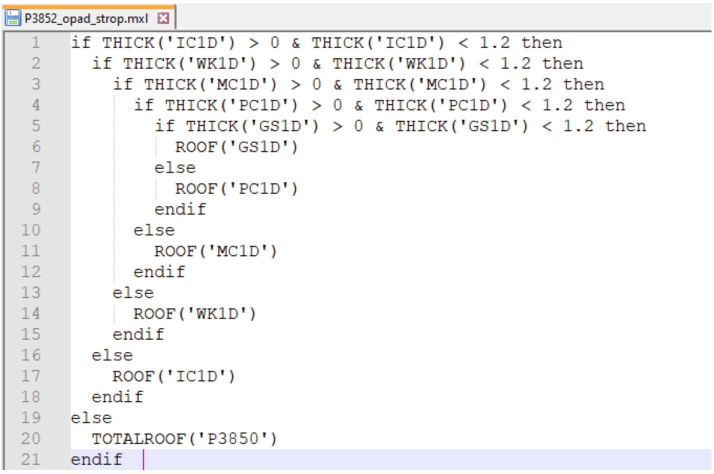
5) Creation of contours of roof fall probability.

6) Creation of contours of the thickness of the roof fall layer (Fig. 6).



```
if THICK('IC1D') > 0 & THICK('IC1D') < 0.3 then
  if THICK('WK1D') > 0 & THICK('WK1D') < 0.3 then
    if THICK('MC1D') > 0 & THICK('MC1D') < 0.3 then
      if THICK('PC1D') > 0 & THICK('PC1D') < 0.3 then
        if THICK('GS1D') > 0 & THICK('GS1D') < 0.3 then
          ((0.3-THICK('IC1D'))/0.3)+(1*(0.3-THICK('WK1D'))/0.3)+(1*(0.3-THICK('MC1D'))/0.3)+(1*(0.3-THICK('PC1D'))/0.3)+(1*(0.3-THICK('GS1D'))/0.3)
        else
          ((0.3-THICK('IC1D'))/0.3)+(1*(0.3-THICK('WK1D'))/0.3)+(1*(0.3-THICK('MC1D'))/0.3)+(1*(0.3-THICK('PC1D'))/0.3)
        endif
      else
        ((0.3-THICK('IC1D'))/0.3)+(1*(0.3-THICK('WK1D'))/0.3)+(1*(0.3-THICK('MC1D'))/0.3)
      endif
    else
      ((0.3-THICK('IC1D'))/0.3)+(1*(0.3-THICK('WK1D'))/0.3)
    endif
  else
    (0.3-THICK('IC1D'))/0.3
  endif
else
  0
endif
```

Fig. 4. Logical function for the creation of a probability surface for the occurrence of the roof fall.



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if THICK('IC1D') > 0 & THICK('IC1D') < 1.2 then
  if THICK('WK1D') > 0 & THICK('WK1D') < 1.2 then
    if THICK('MC1D') > 0 & THICK('MC1D') < 1.2 then
      if THICK('PC1D') > 0 & THICK('PC1D') < 1.2 then
        if THICK('GS1D') > 0 & THICK('GS1D') < 1.2 then
          ROOF('GS1D')
        else
          ROOF('PC1D')
        endif
      else
        ROOF('MC1D')
      endif
    else
      ROOF('WK1D')
    endif
  else
    ROOF('IC1D')
  endif
else
  TOTALROOF('P3850')
endif
```

Fig. 5. Logic function to create layers of predicted roof fall.

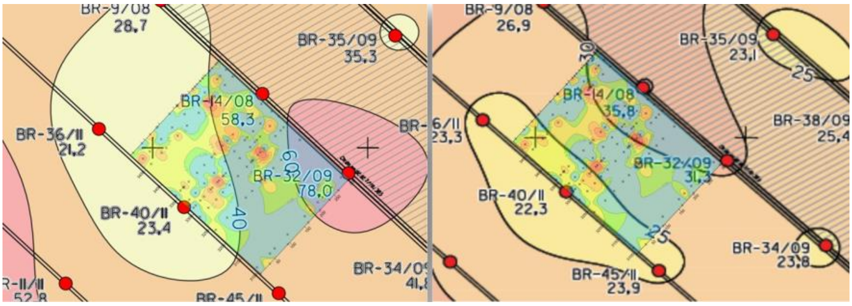

Fig. 6. Map of roof fall layer thickness against RQD contour maps (left) and compressive strength ratio R_c (right).

The way in which the expression layer predicting roof fall is constructed is in every aspect modifiable (e.g. limiting thicknesses for individual layers, test layers, probability weights, conditions, etc.).

In the current version, the roof fall probability surface is built on the analysis of the 5 layers above the production seam and can take values from 0 (lowest probability) to 5 (highest probability). The surface of the roof of the rockfall layer analogously analyses the 5 layers above and follows the roof of the last of these 5 layers, which has a thickness lower than the limitation thickness (currently 0.3 m).

4 Conclusions

LW “Bogdanka” S.A. is one of the few hard coal mines in Poland where a software package is used for production planning and scheduling, enabling the generation of work schedules for a given exploitation variant based on the deposit model in possession. During studies aimed at determining the genesis of roof rock fall at the LW “Bogdanka” S.A., all coal seams together with their parameters (roof, floor, seam thickness, partings, quality parameters, etc.) were modelled as three-dimensional grid models. This has resulted in a huge database of the deposit, which can be quickly and easily updated as new data arrives, for example from reconnaissance drilling.

The system, which consists of a number of IT tools, has made it possible to develop new methodologies for designing and scheduling production in close connection with information on the structure of the deposit and its quality; this has been directly translated into optimised planning and control of the exploitation and control of the coal extraction process, with a consequent effective impact on the rational management of the deposit on a mine-wide scale.

In conclusion, it should be stated that the block model built jointly by the teams of IGSMiE PAN and LW “Bogdanka” S.A. fulfils the tasks for which it was created. Moreover, it can and should be developed by implementing the logic of current observations of geologists and miners of LWB, so that in case of occurrence of a lithological layer smaller than 20 cm directly above the coal, the software could automatically mark this layer as a forecasted fall of roof rocks.

The second methodology developed, based on a stratigraphic model of the overburden layers, also makes it possible to build a model of the roof surface of the rock fall layers and thus predict the roof fall. It complements and verifies the first methodology based on block model data.

References

1. Vervoort, A. (1991). Study of shield support characteristics and their influence on the roof behaviour in coal longwalls. *Mining Science and Technology*, *13*(3), 315-322. https://doi.org/10.1016/0167-9031(91)90571-s
2. Dychkovskiy, R., & Bondarenko, V. (2006). Methods of Extraction of Thin and Rather Thin Coal Seams in the Works of the Scientists of the Underground Mining Faculty (National Mining University). *International Mining Forum 2006*, *New Technological Solutions in Underground Mining*, 21-25. https://doi.org/10.1201/noe0415401173.ch3
3. Kononenko, M., Khomenko, O., Kosenko, A., Myronova, I., Bash, V., & Pazynich, Y. (2024). Raises advance using emulsion explosives. *E3S Web of Conferences*, (526), 01010. https://doi.org/10.1051/e3sconf/202452601010
4. Dyczko, A. (2023). Real-time forecasting of key coking coal quality parameters using neural networks and artificial intelligence. *Rudarsko-Geološko-Naftni Zbornik*, *38*(3), 105-117. https://doi.org/10.17794/rgn.2023.3.9
5. Vu, T.T (2022). Solutions to prevent face spall and roof falling in fully mechanized longwall at underground mines, Vietnam. *Mining of Mineral Deposits*, *16*(1), 127-134. https://doi.org/10.33271/mining16.01.127
6. Kopacz, M. (2015). The impact assessment of quality parameters of coal and waste rock on the value of mining investment projects – hard coal deposits. *Gospodarka Surowcami Mineralnymi*, *31*(4), 161-188. https://doi.org/10.1515/gospo-2015-0037
7. Dyczko, A. (2023). Production management system in a modern coal and coke company based on the demand and quality of the exploited raw material in the aspect of building a service-oriented architecture. *Journal of Sustainable Mining*, *22*(1), 2-19. https://doi.org/10.46873/2300-3960.1371

8. Galica, D. (2023). *Cyfrowy model geologiczny złoża jako narzędzie wspomagania decyzji w działalności kopalni węgla kamiennego*. Kraków: Instytut Gospodarki Surowcami Mineralnymi i Energią PAN, 203 s.
9. Malinowski, L. (2019). Influence of chosen technical constraints on stability of 3D geological model-based schedule in a complex longwall operation. *E3S Web of Conferences*, (123), 01024. https://doi.org/10.1051/e3sconf/201912301024
10. Dyczko, A., Galica, D., & Sypniowski, S. (2012). Deposit model as a first step in mining production scheduling. *Geomechanical Processes During Underground Mining – Proceedings of the School of Underground Mining*, 231-247. https://doi.org/10.1201/b13157-39
11. Kentucky Case Report. (2019). *Gutter installer dies after falling from roof.* Retrieved from https://www.cdc.gov/niosh/face/pdfs/19ky034.pdf
12. Khuangan, N., Asainov, S., Khojayev, T., Azimbayeva, Z., Atageldiyev, K., Nurshaiykova, G., & Akylbayeva, A. (2024). Predicting the magnitude of technogenic earthquakes during underground mining of the Zhezkazgan ore field. *Mining of Mineral Deposits*, *18*(1), 45-53. https://doi.org/10.33271/mining18.01.045
13. Schafer, D. (2013). Electret microphone modeling and optimization by combined finite element analysis (FEA) and lumped-element techniques. *Proceedings of Meetings on Acoustics*, (19), 1-8 https://doi.org/10.1121/1.4801049
14. Vladyko, O., Maltsev, D., Sala, D., Cichoń, D., Buketov, V., & Dychkovskyi, R. (2022). Simulation of leaching processes of polymetallic ores using the similarity theorem. *Rudarsko-Geološko-Naftni Zbornik*, *37*(5), 169-180. https://doi.org/10.17794/rgn.2022.5.14
15. Sala, D., & Bieda, B. (2022). Stochastic approach based on Monte Carlo (MC) simulation used for Life Cycle Inventory (LCI) uncertainty analysis in Rare Earth Elements (REEs) recovery. *E3S Web of Conferences*, (349), 01013. https://doi.org/10.1051/e3sconf/202234901013
16. Sala, D., & Bieda, B. (2022). Application of uncertainty analysis based on Monte Carlo (MC) simulation for life cycle inventory (LCI). *Inżynieria Mineralna*, *2*(2). https://doi.org/10.29227/im-2019-02-80
17. Wei, C., Yu, D., & Dingier, T. (2020). Reading on 3D Surfaces in Virtual Environments. *IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* https://doi.org/10.1109/vr46266.2020.1581590322523
18. Rosero-Montalvo, P., & Alvear-Puertas, V. (2022). Efficient Lightweight Cryptography Algorithm in IoT Devices with Real-time Criteria. *Proceedings of the 7th International Conference on Internet of Things, Big Data and Security*, (1), 103-109. https://doi.org/10.5220/0010922800003194
19. Russkikh, V., Demchenko, Yu., Salli, S., & Shevchenko, O. (2013). New technical solutions during mining C_5 coal seam under complex hydro-geological conditions of western Donbass. *Annual Scientific-Technical Collection – Mining of Mineral Deposits*, 257-260. https://doi.org/10.1201/b16354-47
20. Polyanska, A., Pazynich, Y., Poplavska, Z., Kashchenko, Y., Psiuk, V., & Martynets, V. (2024). Conditions of Remote Work to Ensure Mobility in Project Activity. *Lecture Notes in Mechanical Engineering*, 151-166. https://doi.org/10.1007/978-3-031-56474-1_12
21. Siata, E., & Ptak, E. (2007). *Dodatek nr 3 do dokumentacji geologicznej złoża węgla kamiennego "Bogdanka" w kategoriach A, B, C1 i C2*. PRGW Sp. z o.o., Sosnowiec, 84 s.
22. Gabzdyl, W. (1994). *Geologia złóż węgla*. Warszawa: Polska Agencja Ekologiczna, 381 s.
23. Kopacz, M., Kulpa, J., Galica, D., Dyczko, A., & Jarosz, J. (2019). Economic valuation of coal deposits – The value of geological information in the resource recognition process. *Resources Policy*, (63), 101450. https://doi.org/10.1016/j.resourpol.2019.101450
24. Wang, J., Apel, D. B., Dyczko, A., Walentek, A., Prusek, S., Xu, H., & Wei, C. (2021). Investigation of the Rockburst Mechanism of Driving Roadways in Close-Distance Coal Seam Mining Using Numerical Modeling Method. *Mining, Metallurgy & Exploration*, *38*(5), 1899-1921. https://doi.org/10.1007/s42461-021-00471-2
25. Dychkovskyi, R.O., Lozynskyi, V.H., Saik, P.B., & Dubiei, Yu.V. (2019). Technological, lithological and economic aspects of data geometrization in coal mining. *Naukovyi Visnyk*

Natsionalnoho Hirnychoho Universytetu, (5), 22-28. https://doi.org/10.29202/nvngu/2019-5/4

26. 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*(1), 186-196. https://doi.org/10.2478/ntpe-2020-0015
27. Kowalczyk, D., & Kulpa, J. (2024). A new perspective on the geological prospection of the Bzie-Dębina deposit, with an emphasis on the correlation of seams and coal quality parameters. *E3S Web of Conferences*, (526), 01020. https://doi.org/10.1051/e3sconf/202452601020
28. Kassymkanova, K.K., Rysbekov, K.B., Nurpeissova, M.B., Kyrgizbayeva, G.M., Amralinova, B.B., Soltabaeva, S.T., Salkynov, A., & Jangulova, G. (2023). Geophysical studies of rock distortion in mining operations in complex geological conditions. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, (48), 57-62. https://doi.org/10.5194/isprs-archives-XLVIII-5-W2-2023-57-2023
29. Bazaluk, O., Ashcheulova, O., Mamaikin, O., Khorolskyi, A., Lozynskyi, V., & Saik, P. (2022). Innovative activities in the sphere of mining process management. *Frontiers in Environmental Science*, (10), 878977. https://doi.org/10.3389/fenvs.2022.878977
30. Haidai, O., Ruskykh, V., Ulanova, N., Prykhodko, V., Cabana, E. C., Dychkovskyi, R., ... & Smolinski, A. (2022). Mine field preparation and coal mining in western Donbas: Energy security of Ukraine – a case study. *Energies, 15*(13), 4653. https://doi.org/10.3390/en15134653
31. Alpysbay, M.A., Orynbassarova, E.O., Sydyk, N.K., Adebiyet, B., & Kamza A. (2024). Mining mapping and exploration using remote sensing data in Kazakhstan: a review. *Engineering Journal of Satbayev University*, *146*(2), 37-46. https://doi.org/10.51301/ejsu.2024.i2.05
32. Bazaluk, O., Sadovenko, I., Zahrytsenko, A., Saik, P., Lozynskyi, V., & Dychkovskyi, R. (2021). Forecasting Underground Water Dynamics within the Technogenic Environment of a Mine Field: Case Study. *Sustainability*, *13*(13), 7161. https://doi.org/10.3390/su13137161
33. Sosnowski, P., Dyczko, A., & Kamiński, P. (2024). Quality management in a 3D geological model – reliability of predicted hard coal quality parameters. *E3S Web of Conferences*, (526), 01003. https://doi.org/10.1051/e3sconf/202452601003
34. Vlasov, S., Moldavanov, Y., Dychkovskyi, R., Cabana, E., Howaniec, N., Widera, K., Bąk, A., & Smoliński, A. (2022). A Generalized View of Longwall Emergency Stop Prevention (Ukraine). *Processes*, *10*(5), 878. https://doi.org/10.3390/pr10050878
35. Yilmaz, F., Ozturk, M., & Selbas, R. (2019). Design and thermodynamic analysis of coal-gasification assisted multigeneration system with hydrogen production and liquefaction. Energy Conversion and Management, 186, 229–240. https://doi.org/10.1016/j.enconman.2019.02.053
36. Wang, Z., Qu, H., Wu, Z., Yang, H., & Du, Q. (2016). Formal representation of 3D structural geological models. *Computers & Geosciences,* (90), 10-23. https://doi.org/10.1016/j.cageo.2016.02.007
37. Sobczyk, E.J., Galica, D., Kopacz, M., & Sobczyk, W. (2022). Selecting the Optimal Exploitation Option Using a Digital Deposit Model and the Ahp. *SSRN Electronic Journal*, (78), 102952. https://doi.org/10.2139/ssrn.4047752
38. Sideri, D., Roumpos, C., Pavloudakis, F., Paraskevis, N., & Modis, K. (2020). Multivariate Geostatistical Modeling of Lower Calorific Value in Multi-Seam Coal Deposits. *Applied Sciences*, *10*(18), 6208. https://doi.org/10.3390/app10186208
39. Hillier, M.J., de Kemp, E.A., & Schetselaar, E.M. (2017). Implicit 3D modelling of geological surfaces with the Generalized Radial Basis Functions (GRBF) algorithm. *Natural Resources Canada/CMSS/Information Management*, 7814. https://doi.org/10.4095/301665
40. 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
41. Munson, J.C. (1996). Software faults, software failures and software reliability modeling. *Information and Software Technology*, *38*(11), 687-699. https://doi.org/10.1016/0950-5849(96)01117-2