Using Statistical Methods to Assess Indicators Impacting Coal Ash Content for Underground Mining

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Abstract. This article dwells upon the improvement of coal ash content management efficiency for underground mining, which can help increase the efficiency of coal mining companies. The authors demonstrate that statistical methods are best suited for determining the key factors impacting the ash content of the produced coal. The authors selected the statistical methods to help solve the stated problems. To analyze the factors increasing the ash content of the coal mined underground, the authors used the Ishikawa method to identify problems and their causes. They used the expert method and ranked experts’ assessments obtained to select the most significant indicators in terms of their impact on the ash content of the coal mined underground for each of the indicator groups established. To select the most significant indicators, the authors used the Pareto method and ABC-analysis. As a result, they obtained indicator categories. The subsequent analysis within each of the categories helped formulate homogeneous indicator groups and select the ones that have the highest impact on the ash content of the coal produced underground. The set of the statistical methods used helped identify five indicators that have the greatest impact on the ash content of the coal produced in underground mines. These include the total thickness of intermediate rocks, mining face length, the operating width of the combine actuator, shear thickness, and bed thickness. These can be used to form an ash content management system for underground coal mining.

1. Introduction

Mining facilities are complex, and some technical, engineering, infrastructural, social, environmental, and other risks arise already during their design stage. Efficiency improvement for these facilities is a pressing issue because mineral production may yield significant incomes if proper approaches are used.

Low-cost coal quality management methods are one of the ways to improve the efficiency of coal mining companies. The price of coal depends on its ash content, humidity, and particle-size composition. It can be increased by 1.2-1.6 times through the combined use of winning technologies and the integration of coal mining techniques. With coal quality management, mining companies can quickly adapt to coal market instabilities, the requirements to the list of quality indicators and parameters, expand the list of consumers, and facilitate the controlled replacement of some coal grades with others in the metal industry and chemical recovery coal carbonization.
2. Relevance and scientific significance

Increasing the quality of the products is one of the key ways to improve production efficiency. Increasing product quality in the mining sector has some features that make it different from similar activities in the processing industry. This sector covers mineral commodities whose natural properties can vary significantly within the mining site or beyond it. Together with the increasing demand for mineral commodities, these features determine the solution to the quality problem in terms of the least social labor inputs and the most complete and rational use of mineral stocks.

The analysis of mining activities shows that the quality of mineral commodities changes significantly not only during the production but also during the economic and industrial assessments of deposits and designing mining facilities. The incorrect assessment of the mining product quality results in the low utilization of the recoverable reserves, as well as wrong decisions on the selection of mining sites and mining and processing facility locations and capacities. The economic losses attributed to the incorrect basic decisions cannot generally be compensated by some engineering solutions during the mining operations. [1-4]

There are various product quality control methods, including statistical ones. We understand a statistical method as a product quality assessment method that determines the product quality indicator values using the mathematical statistic techniques [5-6].

3. Problem statement

Coal quality is studied in its natural deposits and characterized by mining and geological factors. Rock development and deposit layers or sections’ percentage participation in coal mining activities is characterized by a set of production factors, while the methods of coal-face mining, preparation works, coal winning layouts, winning mechanism operating schedules, coal and rock drawing procedures from prepared entries (blocks) form the engineering factor groups. That being said, mining and geological factors cannot be changed, they can only be clarified if some new information emerges, while the engineering and production factors depend, among other things, on the engineering decisions made during deposit development. For instance, we can control rock capture during coal-face mining by using this or that technique, which has a direct impact on the ash content of the final product.

Thus, we set the following research objectives:
- Perform a comprehensive analysis of the factors increasing the ash content of the coal mined underground;
- Establish homogeneous indicator groups and assess the relationships between the indicators;
- Select the most significant indicators by their impact on the ash content of the coal produced underground.

To assess the deposit development indicators in terms of their impacts on the quality of the final product, we need to determine the degree of their impacts. To solve this problem, we need to select the method to identify the most significant indicators and the method to assess the impacts of these indicators on the quality of mining products. This problem is complex because there are many indicators that impact the quality of coal as a final product [7], and not all of the indicators can be assessed in numerical terms. Even if an indicator can be assessed in numerical terms, it is unclear how to compare several indicators that characterize different factors impacting the ash content of the produced coal, e.g. Deposit thickness and machinery and mechanism productivity. To solve these problems, we used statistical methods.

4. Theory

To assess the deposit development indicators in terms of their impacts on the quality of the final product, we need to determine the degree of their impacts. To do this, it is necessary to select assessment and comparison methods for the indicators impacting the ash content of the produced coal. Having reviewed the mathematical and statistical methods that are the most suitable for the problem stated, we managed to select the following statistical methods:
- To analyze the factors increasing the ash content of the coal mined underground, the authors used
the Ishikawa method to identify problems and their causes. In our case, the problem is managing coal ash content as the key coal quality indicator [8]. The impact factors were classified based on their capacity to impact the occurrence of or changes in the problem in question. Through the use of this method, we will obtain indicator categories, and the subsequent analysis within each of the categories shall help establish homogeneous indicator groups and assess the relationships between the indicators within them;

– We used the expert method to select the most significant indicators in terms of their impact on the ash content of the coal mined underground for each of the indicator groups established [9], and ranked experts’ assessments obtained. Ranking stands for the arrangement of indicators in the ascending or descending order based on a common property assessed by the experts who set a specific rank to each of the indicators in question. Ranking helps select the most significant indicator from their list. Recently, the ranking method has been widely used to measure product quality, assess research organizations and departments’ activities, etc. Simplicity is one of the advantages of this method as it does not require trained experts.

– We decided to use the Pareto method and the ABS analysis to select the most significant indicators in terms of their impacts on the ash content of the coal mined underground out of the list of the indicators in question. The Pareto diagram is a tool that allows to distribute the efforts to solve the problems and identify the key indicators that have to be processed first to obtain the results faster. The Pareto diagram and its analysis help confirm or correct the group of significant indicators that will be used as the basis for the ash content management system for the coal produced underground according to the objectives set. ABC-analysis stipulates the classification of all indicators into three groups with different significance levels: Group A includes the most significant indicators impacting the coal ash content, Group B includes the intermediate indicators, and Group C includes the indicators whose impact on the coal ash content is insignificant.

5. Research findings

5.1. The analysis of the factors increasing the ash content of the coal mined underground using the Ishikawa method

For the purposes of this research, we constructed an Ishikawa diagram (Figure 1): the current problem the diagram is based on is coal ash content management. The problem is written down in the rectangle on the right side of the diagram. On the left side, we identified the key categories of the indicators impacting the problem in question. Within the Ishikawa diagram, each of the categories forms a specific branch of the central (main) line. For each of the branches, we identified the causes of the problem (reducing the quality of the coal mined underground due to the increased ash content) using the set criteria and the indicators evaluating the problem in question. Each of the causes can be detailed in the same way, which may result in the appearance of lower-order branches. Cause detailing continues until the root cause is found, which allows us to process a large number of indicators.

In our case, the indicators can be classified based on their capacity to impact the occurrence of or changes in the problem in question. Thus, each of the categories established has some indicators that can be grouped by a set property. The first category (mining and geological indicators) includes the indicators impacting the quality of coal that cannot be changed. The second category (engineering indicators) includes the indicators that can be changed but as a rule only during the design (project adjustment) or facility renovation stage and are associated with relatively high costs. The third category (technical indicators) includes the indicators that can be changed at low costs in terms of deployment times and money inputs. Apart from these categories, the ash content of the coal can be influenced by the human factor, the incorrect results obtained at the coal chemistry lab, etc (Figure 1).
5.2. The selection of the most significant indicators in terms of their impact on the ash content of the coal mined underground for each of the indicator categories using the expert method

To assess the significance of the indicators within each of the categories using the selected expert method, we developed questionnaires including the indicators from the key categories on the Ishikawa diagram that were selected based on the following principles: the indicators should not be directly linked, the number of indicators must be at the minimum but sufficient to accomplish the goal set, and the indicators selected must have numerical values. The indicators are listed in Table 1. The letter code shows which group the indicator belongs to: Code E stands for the mining and geological indicators, Code D stands for the engineering indicators, and Code F stands for the technical indicators.

Taking into account the above and the specifics of the problem in question, we drew up a 25-strong team of experts. Each of the experts was given a questionnaire, in which they had to rank the indicators by their significance from 1 to n (where n is the number of indicators) in descending order. Mathematical processing stipulates ranking the indicators obtained, the processing of the ranking, and the identification of the most significant indicators (in our case, within each of the indicator groups).
Figure 2. Specific indicator raking histograms across the following groups: a – the mining and geological indicator group; b – the engineering indicator group; c – the technical indicator group.

The analysis of the statistics using the ranking method (Figure 2) shows that the most significant indicator in the mining face length (D5) is the most significant indicator in the engineering group, the total thickness of intermediate rocks (E2) is the most significant one in the mining and geological group, and the operating width of the combine actuator (F1) and the shear thickness (F5) are the most significant among the technical indicators.
5.3. The selection of the most significant indicators in terms of their impacts on the ash content of the coal mined underground out of the list of the indicators in question using the Pareto method and the ABS-analysis

We determined the most significant indicators in terms of coal ash content management in the mine for each of the categories but the further accomplishment of the objectives set requires testing their significance compared to the entire list. To do this, we integrate the group rankings in a single table (Table 1) and construct the Pareto diagram by calculating the increasing percentage following the expert assessments: the higher the expert assessment within the integrated rank matrix, the higher the contribution of the indicator in question in the coal ash content management system.

Table 1. The data used for the construction of the Pareto diagram and the ABC analysis of the indicators.

| Indicator code | Indicators                                      | Sum of ranks for expert method | Increasing percentage, % | ABC-analysis |
|----------------|-------------------------------------------------|-------------------------------|--------------------------|--------------|
| F1             | Operating width of combine actuator              | 203                           | 7.45                     | A            |
| E2             | Total thickness of intermediate rocks            | 181.5                         | 14.11                    | A            |
| D5             | Mining face length                              | 175                           | 20.53                    | A            |
| E1             | Deposit thickness                               | 160                           | 26.40                    | A            |
| F5             | Shear thickness                                 | 159                           | 32.24                    | A            |
| E4             | Fault throw                                     | 151                           | 37.78                    | B            |
| D3             | Post parameters                                 | 148.5                         | 43.23                    | B            |
| D2             | Mining face progression rate                    | 145.5                         | 48.57                    | B            |
| F2             | Number of coal transloading                     | 141.5                         | 53.76                    | B            |
| F3             | Number of long faces operating at the same time | 118.5                         | 58.11                    | B            |
| D1             | Minefield length and width                      | 113.5                         | 62.28                    | B            |
| E3             | Seam inclination                                | 105                           | 66.13                    | B            |
| E5             | Adjacent rock hardness                          | 102                           | 69.87                    | C            |
| D6             | Transportation distance                         | 101.5                         | 73.60                    | C            |
| F7             | Combine cutting (self-cutting) section length   | 96.5                          | 77.14                    | C            |
| D4             | Advance working progression rates               | 88.5                          | 80.39                    | C            |
| E6             | Seam gas content                               | 87                            | 83.58                    | C            |
| E7             | Water influx                                    | 86.5                          | 86.75                    | C            |
| F4             | Machine and mechanism productivity              | 86                            | 89.91                    | C            |
| D7             | Mining face (horizon) output                    | 68.5                          | 92.42                    | C            |
| F6             | Maximum combine operating and flitting rates    | 68                            | 94.92                    | C            |
| F8             | Transportation vehicle                          | 51.5                          | 96.81                    | C            |
To identify the most significant indicators impacting coal ash content, used the significance of each of the indicators in the expert assessment to construct a Pareto diagram (Figure 3). This diagram shows that the indicators selected as the most significant using the expert method are located at the beginning of the diagram.

According to the ABC-analysis, Group A gets the most significant indicators determined earlier within the groups (4 indicators out of 24). However, the four previously identified indicators (total thickness of intermediate rocks, mining face length, operating width of combine actuator, and shear thickness) within the main indicator group are complemented with one more (deposit thickness) in the Pareto diagram.

The percentages of the groups in the ABC-analysis also depend on the specific problem in question. In our case, the increasing percentage for Group A is 32, and the group includes 5 indicators. Following the requirement for the equal distribution of the remaining indicators between Group B and Group C in terms of their significance, Group B got 7 indicators Group C got 12 indicators, which satisfies the Pareto principle.

![Figure 3. The Pareto diagram and the ABC-analysis of the indicators impacting the ash content of the coal mined underground.](image)
6. Conclusion
Judging by the specifics of the problem in question, the critical analysis and generalization of the existing coal quality management techniques, and the mine operation practices, there is no need to implement a large number of activities in one specific mine. However, to determine the most efficient activities, it is necessary to identify the indicators with the highest impact on the quality indicators of the coal produced by the mine. Statistical methods are the most efficient ones in the identification of the indicators that have the highest impacts on the ash content of the coal mined underground. We used a set of methods like the Ishikawa method, expert method, Pareto principle, and ABC analysis to show that ash content management systems for underground coal mining must, first of all, solve the problems related to five indicators: the total thickness of intermediate rocks, the mining face length, the operating width of the combine indicator, the shear thickness, and the deposit thickness.

The obtained results will be used to develop a coal ash content management system and its mathematical model to assess the degree of ash content management capacities for underground coal mining, as well as the efficiency of mine operations taking into account the operational and design indicators.

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