Article

Method for Assessing the Development of Underground Hard Coal Mines on a Regional Basis: The Concept of Measurement and Research Results

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Received: 19 April 2018; Accepted: 25 May 2018; Published: 28 May 2018

Abstract: The functioning and development of the extractive industry depends on many unusual conditions that are not found in other industries, such as the size of deposits, the level of natural and technical hazards, geographic location, or the method of mineral extraction (open pit or underground). Therefore, it is difficult to use universal development assessment methods for such specific production units. As a result, the research undertaken in this article aims to develop an indicator method for evaluating the development potential of underground hard coal mines. This method is based on a theoretical and practical analysis of the conditions of functioning of hard coal mines, expert research, and multiple case studies verifying the operation of the presented development indicator. The first part of the article is devoted to identifying and analyzing the criteria for assessing the functioning of underground hard coal mines. Next, the essence and methodology of creating and interpreting the proposed indicator was presented. The second part of the article is empirical, and contains the results of the assessment carried out using the developed indicators for five Polish hard coal mines for the years 2011–2015. The results of the research indicate that the most important factors in the development of hard coal mines relate to the geological and mining conditions, and those concerning natural hazard levels. However, during the functioning, the financial conditions and related production conditions, which ultimately determine the survival and development of underground mining plants, gain in significance.

Keywords: non-renewable energy raw materials; hard coal mining; underground hard coal mine; assessment of the development of extractive enterprises

1. Introduction

When making decisions on commencing mining extraction, the assessment of the development possibilities of mining plants is usually evaluated in the context of profitability of investments, taking into account the sufficiency of the explored deposits and the technical possibilities of their extraction [1]. The classic approach to the methods of measuring economic efficiency is often complemented with the use of real options [2,3], which take into account the revenues of the mining enterprise after the forecast period established in the investment account process [4,5]. In the course of functioning of a mining enterprise, the economic and production indicators typical for the finances of enterprises, including primarily financial analysis, regarding economic effectiveness and production capacity, are used to assess the effects of its ongoing activity [6–9]. However, the listed accident parameters in the case of mining enterprises are affected by a number of diverse conditions that are not dependent on management decisions, and on which mining enterprises have no direct influence. These include the geological and mining conditions, geographic location, type, and level of natural hazards or the extraction method (underground, open pit). In such conditions, the assessment of development potential must be multidimensional, and cannot only include economic or production criteria [10].

This is also confirmed by a long-term analysis of the conditions for the functioning of underground hard coal mines in Poland. The Polish hard coal mining has been undergoing repair restructuring for over 25 years. In this process, mines were selected many times, dividing them into those that can and should develop and those that should be shut down, because they are inefficient and contribute to the losses of mining enterprises and, as a result, the entire industry as well. In principle, the level of profitability was assumed to be the main criterion, while treating the sufficiency of resources as a prerequisite for the continuation of mining exploitation [11,12]. However, prioritizing economic criteria led to the situation in which the group of mines with significant development potential included plants with a low unit cost of extraction per tonne, but the low quality of the extracted raw material caused selling problems in the future. In the last 10 years, the situation was additionally complicated by the tightening of climate requirements by the European Union, which increased the quality of hard coal quality priorities, including primarily calorific value as well as sulfur and ash content [13–17]. In such circumstances, profitable and efficient extraction in a long-term existence time horizon mine becomes insufficient to make a final assessment of the continuation or liquidation of exploitation. Evaluations of the further existence and development possibilities of hard coal mines need to be comprehensive and integrated while also legible, and include possible methods to assess their practical implementation and use. Therefore, the purpose of the research undertaken in this article is to develop an indicator method for assessing the development potential of underground hard coal mines.

This method is intended to:

- enable comprehensive assessment of the development possibilities of an underground hard coal mine on the basis of an integrated development indicator;
- allow for a synthetic partial evaluation of development possibilities in the following areas: geological, mining, threatening, production and economic;
- create attitudes to unambiguous and universal comparisons of underground hard coal mines;
- form the basis for management and investment decisions regarding the continuation or abandonment of extraction and financing of further development.

To attain the goal set in this manner, the further part of the article is divided into two parts. The first one is of a methodical nature, and presents the concept of an indicator of development of underground hard coal mines and the theoretical basis for its development. The second part contains the results of the assessment of the development possibilities of five Polish hard coal mines carried out using the proposed indicator. At the end of the article, the directions of further research, limitations in the use of the indicator, and recommendations for the investigated underground coal mines are presented.

2. Literature Review

In the literature, the development of underground hard coal mines is analyzed first of all in the context of geological and mining determinants. The most important factors influencing the establishment and functioning from a long-term perspective are mainly operational resources adequacy, their quality, and the possibility of extraction [18–21]. Important and frequently analyzed development determinants in underground hard coal mining are also the scale and the level of natural hazards that significantly influence the efficiency and effectiveness of mining production [22], [23,24]. Due to the above, the analysis and assessment of the development of hard coal mines takes place in the context of conditions of natural and technical character.

Nevertheless, due to the commercialization of the extraction industry in Europe, the literature on the development of underground hard coal mines also presents issues of economic character [25–27]. Additionally, the common implementation of sustainable development has resulted in less literature focused on technical aspects, in favor of the social and ecological issues are integrally linked with mining exploitation [28,29].

So, in economic publications, the development of hard coal mines has been analyzed in the context of mining enterprises values assessed with the use of modified discounted cash flows and the material options method [30,31]. In this context, financial factors such as sales revenues, operating costs, or the structure and cost of invested capital in mining enterprise are considered as key determinants of enterprise development. In such an approach, it is assumed that the development opportunities of underground hard coal mines are influenced by their current and future ability to generate revenues, which—taking into account multiple production determinants that are independent of mining enterprises—is a simplification of some kind.

In turn, research of social and environmental character has emphasized that the development opportunities of underground hard coal mines are influenced by the scope and quality of the relations with local and regional stakeholders [32–34]. The effective shaping of these relations by eliminating unfavorable social and environmental effects of mining extraction is a necessary condition for the mining enterprise to exist and develop in a given region. A sufficient—yet difficult to attain—condition is to provide the stakeholders with a benefits package that exceeds the hard coal extraction costs borne by the residents and environment. Having in mind that the protests of local communities or environmental societies often lead to stoppage of extraction, one can clearly state that social and environmental conditions significantly influence the decision-making process on the commissioning and continuation of extraction in underground hard coal mines, and determine their developmental opportunities [35,36].

In accordance with the above, in the literature on mining industry functioning, the developmental possibilities of hard coal mines are analyzed in the context of particular conditions defining the areas of sustainable development of an organization and covering technical, economic, social, and environmental aspects. Among such classified issues, the technical theme dominates, complemented by publications on economic subjects. Social and environmental aspects are not so widely discussed on the one hand, which results from a relatively short tradition of their presentation in research and discussion, and on the other hand results from their immeasurability, lack of evidence and data on social and environmental character, all of which are necessary to carry out complex analyses and comparisons.

Having in mind a certain fragmentation of analysis of issues concerning the development of underground hard coal mines, this article attempts to approach the assessment of their development opportunities comprehensively. This is because the proposed method covers the areas of geological and mining, production, and economic assessment. Social conditions are taken into account indirectly by assuming that the local and regional community accepted the underground hard coal mines (the assessment covers already functioning mining enterprises), and by way of indicators taking into account the rate of employment (it is assumed that the basic benefit for local and regional communities is the establishment and maintenance of jobs). In the proposed method, the ecological factors in the context of hard coal quality (sulfur and ash content) are analyzed and assessed indirectly. Moreover, within the analysis and assessment of unit costs, the environmental charges, exploitation taxes, costs of mining damages removal, as well as decommissioning fund mines contributions, are taken into account.

3. Materials and Method

3.1. Research Methodology and Stages

The concept of an integrated indicator of assessment of the development of hard coal mines assumes the integration of four areas and the 20 criteria described below into one measure reflecting the level of current or future development possibilities (1):

$$ID_{UMC} = \sum_{i=1}^n (s_i \times \frac{\sum_{k=1}^m c_k}{100}) \quad (1)$$

where:

ID_{UCM} —the indicator of development of underground hard coal mine,

s_i —the weight of individual areas from 0% to 100% (for areas $i \in \{I, II, III, IV\}$),

c_k —the assessment of subsequent criteria from 0 to 100 points (for criteria $k \in \{1, 2, \dots, 21\}$).

Basically, the indicator is a weighted average, in which individual areas (from I to IV) are assigned previously defined weights. On the other hand, individual criteria (from 1 to 21) are rated on a scale from 1 to 100, depending on the objective rules of their assessment, resulting both from well-established theoretical or legal principles, and the current results of research conducted in hard coal mining. The presented indicator can take values from 0 to 100. The higher the value of the indicator, the higher the development possibilities of the analyzed hard coal mine.

The advantages of such a method include: the multiple aspects of the evaluation, the syntheticity of the measure, universality, and comparability. Nevertheless, the indicator requires creating a reference base, which may be a group of mines operating in a given region or country. It is also necessary to determine the importance of individual calculation areas and detailed rules for assessing the selected criteria. In connection with these two arguments, the indicator will always be characterized by a certain subjectivism, which undoubtedly constitutes its disadvantage. The further part of the article presents its creation and use for a group of mines operating in Poland.

The research included four main stages: (A) determining the importance of individual areas of assessment; (B) defining the evaluation criteria in individual areas; (C) defining the conditions in which the group of analyzed mines operates; and (D) conducting the assessment in the group of analyzed underground hard coal mines. Stages A and B, are theoretical and are described in the methodological part of the article. Stages C and D are empirical, and are presented in the results section.

In the first stage, (A), heuristic methods were used and expert questionnaire surveys were conducted among a group of 24 experts in the field of hard coal mining in Poland (senior management and professors in the field of mining and engineering geology). The consistency of the opinions of analyzed experts was determined using the Kendall's and Smith's coefficient of concordance:

$$W = \frac{12 \times S}{n^2 \times (k^3 - k)} \quad (2)$$

where:

n —the number of experts,

k —the number of assessment variants,

and S :

$$S = \sum_{j=1}^k \left(\sum_{i=1}^n x_{ij} - \frac{1}{k} \sum \sum x_{ij} \right) \quad (3)$$

where:

x_{ij} —indications of experts.

The modified chi square test was used to assess the significance.

The assessment criteria (B) referred to existing measurement scales or the average values calculated for the entire analyzed group, which were used as a reference point of the formulated evaluations. In the area of defining the conditions in which the group of analyzed mines (C) operates, a descriptive method was used to present the situation of the hard coal mining sector in the analyzed period covering the years 2011–2015. Then, in the research illustrating the use of the indicator, a multiple case study involving four hard coal mines was applied. The assessment of the level of development was carried out for data from 2011, when the very good sector conditions prevailed in

the Polish hard coal mining, and in 2015, when, after a deep crisis lasting for two years, a decision was made to close some unprofitable hard coal mines. The analysis of these two phases made it possible to additionally evaluate the impact of external conditions on the development prospects of the analyzed mines.

3.2. The Concept of the Indicator and the Individual Areas of Assessment (Stage A)

While developing the indicator of assessment, four evaluation groups were identified. The first one concerns **geological and mining conditions (I)**, which determine the possibilities of extracting the raw material, and without which the creation and functioning of the mine would not be possible at all [37]. Generally, these conditions concern the size of the deposit, taking into account the division into industrial and non-industrial resources, as well as the quality of the extracted raw material. In addition to the abundance of the deposit for underground mining, an extremely important issue is the level of natural hazards that may endanger the continuity and profitability of extraction. Therefore, it was considered that the factors conditioning the continuation of mining production are the levels of natural hazards, including primarily gas, water, dust, fire and rock burst hazards, which are typical of underground hard coal mining [38–42]. Therefore, the second group of assessment includes **natural hazards (II)**. The first two groups of evaluation determine the creation of a hard coal mine; this can be treated as necessary to start the mining production. They are also primary factors that influence the discontinuation of exploitation due to the depletion of the deposit or conditions preventing the safe extraction of raw material.

Two further assessment groups include factors affecting the competitiveness of mining production, and relate to the efficiency of human resources and underground infrastructure, as well as the economic profitability of extraction [43–47]. (The establishment and maintenance of a mining enterprise requires huge investment outlays, and its infrastructure is usually extensive as well as capital-intensive and cost-intensive [48–50]. Therefore, the share of fixed costs in production costs is high, and above average compared with other heavy industries. In such circumstances, it is extremely important to fully and as much as possible use existing infrastructure and human potential, ensuring the reduction of unit production costs due to the maximum distribution of fixed costs. Bearing in mind the above circumstances, the third group of evaluation criteria includes the **production conditions (III)** of a performance nature, and the fourth group includes **economic conditions (IV)** that are dependent on the mining enterprise, and are therefore related to the level and changes in production costs.

The individual groups of criteria enable answering the following questions, which condition the development of a hard coal mine operating as an independent mining company or functioning within the group of mines:

- Are hard coal resources in a hard coal mine sufficient for its further development? What is the quality of these resources?
- Is the extraction possible with the existing state of natural hazards, and to what extent does this state determine the continuity and efficiency of extraction?
- Is a hard coal mine characterized by favorable competitive production conditions?
- Is a hard coal mine characterized by favorable competitive financial conditions?

Within the aforementioned groups, detailed calculation criteria were defined based on key partial parameters characterizing geological and mining conditions, the level of natural hazards, as well as the production and economic conditions. A detailed assessment model is presented in Figure 1, and the description is included in the next section of the article.

Figure 1. Areas and criteria for the construction of an integrated indicator for assessment of the development of an underground hard coal mine. Own study.

In this stage of examination, an assessment was carried out with a questionnaire to determine the importance of ranks assigned to the given groups (from I to IV) covering the selected criteria: geological and mining, natural hazard, production, and economic. Twenty-four experts in hard coal mining representing the academic and business environment evaluated the importance of the selected groups on a scale from 0% to 100%, with an accuracy of 10%. The results obtained were characterized with Kendall and Smith's coefficient of concordance on the level of 0.6369 (for $p < 0.05$), which allows determining the level of the experts' compliance as a good one. So, the importance of mining and geological criteria was estimated at 30%, the importance of natural hazards was estimated at 30%, the importance of production was 20%, and the importance of economic issues was also 20%. Such a distribution of answers shows clear domination of the conditions necessary for the existence and development of hard coal mines, concerning the possibilities and conditions for carrying out

exploitation. The criteria referring to the quality, efficiency, and cost effectiveness of mining production were considered by the experts as less significant.

3.3. Detailed Criteria for Assessing the Development of an Underground Hard Coal Mine (Stage B)

3.3.1. Geological and Mining Area

The first of the areas shown in Figure 1 includes the geological and mining criteria (I). They determine the ability to extract and sell coal, and were selected based on the following investment questions:

- Does the sufficiency of the deposit guarantee the return of investment and the long-term lifetime of a coal mine? (criterion 1—the mining plant lifetime);
- Is it possible to safely and profitably extract coal using available techniques of excavation? (criterion 2—the thickness of seams of the deposit; criterion 3—the inclination of seams of the deposit);
- Does the quality of coal meet the market requirements? (criterion 4—the calorific value of commercial coal; criterion 5—ash content in commercial coal; criterion 6—sulfur content in commercial coal).

The detailed definitions of above criteria and the rules of their assessment are given below.

The mining plant (1) lifetime is understood as the period of sufficiency of total operational resources expressed in years, and is indicated as the first detailed assessment parameter. At the same time, the operational resources are that part of the geological resources of the deposit that is suitable for exploitation on an industrial scale; this can be managed after taking into account technical and economic conditions and reduced by losses. The lifetime of a hard coal mine therefore determines the time horizon of its existence, and has a direct impact on its development possibilities [51,52]. Parameters related to the natural, mining, and geological conditions of the deposit's exploitation also include the thickness and inclination of seams in the deposit, which determine the possibilities and techniques of extraction, thus affecting the efficiency and effectiveness of mining production [53,54]. The thickness (2) is the basic feature describing the seam, and it is the thickness of the hard coal layer measured between the ceiling and the floor. In turn, the inclination of hard coal seams (3) is the angle formed by the ceiling or floor plane with the horizontal plane [55,56].

The natural features of hard coal, determined by the properties of the deposit, also include: calorific value, sulfur content, and ash content. The mentioned features determine the quality of hard coal; thus, they have a direct impact on the possibility of the disposal of the raw material [57–59]. In recent years, their importance in the development of hard coal mines has increased due to the increasing environmental restrictions and growing requirements of the energy and heating sectors. Thus, the calorific value (4) is understood as the heat of combustion reduced by the evaporation heat of water emitted during the combustion of coal, and resulting from the hydrogen contained in coal expressed in kJ/kg or MJ/kg (kilojoules or mega joules per kilogram). It is also worth adding that the calorific value of hard coal varies from 16 MJ/kg to 32 MJ/kg. In turn, the ash content (5) is the ash residue after coal calcination expressed, which similarly to the sulfur content (6) (total, i.e., covering the organic sulfur bound to the carbon-forming organic matter and inorganic sulfur bound to the carbon-forming mineral matter) is expressed in percentages [60].

The first geological and mining criteria (group I)—**lifetime** (1)—was determined based on the data on the sufficiency of total operational resources in the Polish hard coal mines. In terms of the criterion, the score range from <0;40> was assumed. The maximum note of 40 points determines the top mine lifetime limit, which is 75 years. Other periods were calculated proportionally to the top limit (For example: 40 points—75 years; x points—36 years; then: $75x = 36 \times 40$ and $x = 19.2$ points).

The second geological criterion—the **thickness of the seam** (2)—was evaluated based on the seam thickness class. Having, in theory, four classes at the disposal, a maximum of the following

points was awarded: 10 points for very thick seams (over 7 m), eight points for thick ones (from 3.5 to 7 m), five points for those of average thickness (from 1.5 to 3.5 m), and three for thin seams (less than 1.5 m) [61,62].

Inclination (3) was assessed using a four-level categorization in practice, awarding the maximum of 10 points in the category. So, 10 points was given for horizontal seams (up to 10°), eight for poorly inclined seams (from 10° to 35°), five for very steep seams (from 35° to 45°), and 0 for steep ones (over 45°) [63].

Another examined parameter—**calorific value (4)**—was measured based on the characteristics of hard coal calorific value. Between 0 and 20 points were awarded for the criterion. The maximum assessment of 20 points, which corresponded to the top level of calorific value that is 32,000 kJ/kg. The points for the given mining plants were awarded proportionally to the top limit (as in the example, which referred to lifespan).

In the case of another geological criterion—**ash content (5)**—the coal purity categories were applied awarding 10 points for high-purity coal (ash content below 10%), six points for medium-purity coal (ash content from 10 to 20%), four points for low-purity coal (ash content from 20 to 30%), two points for very low-purity coal (ash content from 30 to 50%), and 0 points for coal slates (ash content from 50 to 80%) [64].

The last of the examined geological and mining criterion—**sulfur content (6)**—was assessed on a scale from 0 to 10. The following principles of detailed scoring were assumed [65]:

- 10 points for the content from 0% to 0.20%,
- 8 points for the content from 0.21% to 0.40%,
- 6 points for the content from 0.41% to 0.60%,
- 4 points for the content from 0.61% to 0.80%,
- 2 points for the content from 0.81% to 1.00%,
- 0 points for the content above 1.01%.

In Table 1, the principles for evaluating geological and mining criteria have been presented synthetically.

Table 1. The principles for assessing geological and mining criteria.

Criterion Number	Criterion Name	Score Range	Criterion Description
1.	the mining plant lifetime	0–40	40 points for 75 years. Other plants proportionally to the upper limit.
2.	the thickness of seams of the deposit	0–10	Pursuant to the valid thickness categorization. Maximum 10 points for very thick seams, 8 for thick seams, 5 for those of average thickness, and 3 for thin seams.
3.	inclination	0–10	Pursuant to the valid inclination categorization. 10 for horizontal seams, 8 for poorly inclined ones, 5 for very steep seams, and 0 for steep seams.
4.	the calorific value of commercial coal	0–20	The maximum assessment of 20 points corresponds to the top level of calorific value, which is 32 MJ/kg. Other plants proportionally to the upper limit.
5.	ash content in commercial coal	0–10	Coal purity categories have been applied. 10 points for high-purity coal, six points for medium-purity coal, four points for low-purity coal, two points for very low-purity coal, and 0 points for coal slates.
6.	sulfur content in commercial coal	0–10	The analysis of sulfur content in coal was used, and five points were awarded for the content from 0% to 0.50%, four points were awarded for the content from 0.21% to 0.40%, three points for the content from 0.41% to 0.60%, two points for the content from 0.61% to 0.8%, one point for the content from 0.81% to 1.00%, and 0 points for content over 1%.
TOTAL			100 points

Source: own work.

3.3.2. Natural Hazards Area

The second group of assessments presented in Figure 1 includes natural hazards characteristic for underground hard coal mining (II). Their occurrence and intensity significantly affect the possibilities and continuity of extraction, and as a consequence affect the productivity of work and the efficiency of mining production. These criteria determine the continuity of mining production; in particular it examines the factors that significantly affect productivity and efficiency as well as the safety of excavation. Consequently, together with geological and mining conditions, they are the necessary conditions of existence of the coal mine.

So, the most common natural hazards in underground mines include gas hazards (7). They are associated with the presence of toxic gases in the mine air, such as: CO, NO, NO₂, H₂S, CO₂, and N₂, which are released during the exploitation of deposits and pose a threat to the life and health of the crew [66,67]. Among the listed gas hazards, methane is the most important factor for mining activity. The methane hazard is primarily related to the presence of methane in the rock mass, and its release as a result of mining activity. This threat increases with exploitation depth, the methane-bearing capacity of the seams, and decreasing rock permeability. The ignition and explosion of methane is particularly dangerous, being the source of numerous mining disasters, in which many miners lose their lives and health [68].

Coal dust explosion (8) is also a serious threat to mining activity. In underground hard coal mines, technological processes related to the exploitation of minerals, tunneling of corridor mining workings, and the transport of excavated material are accompanied by the unfavorable phenomenon of dust production and emission; this phenomenon is a source of dust hazard [69,70]. The generated dust rises in the mine atmosphere, and is moved along with the air currents, whereby some of the dust is deposited on various surfaces (e.g., the floor) or devices. The concept of dust hazard covers two different threats:

- coal dust explosion hazard,
- dust harmful to health hazards.

The major natural hazards in the mining activity of the mining enterprise also include the rock burst hazards (9), which means the possibility of the occurrence of a rock burst, that is, a dynamic phenomenon caused by rock mass vibration, as a result of which the mining working or its section becomes severely damaged or destroyed [71,72]. As a consequence, its functionality or safety of use is completely or partially lost. In order for a rock burst to occur, the rock mass should be characterized by the so-called tendency for rock bursts. The tendency of the rock mass and rocks to burst means the ability to accumulate elastic energy in the rock mass or rocks, and its sudden release at the moment of changing or destroying their structure.

Another natural threat included in assessing the development possibilities of underground hard coal mines is the fire hazard (10). Underground fires have always been a major threat to underground hard coal mines. Gases formed during the fire contain poisonous and suffocating components, and their fairly easy spreading in underground workings poses a threat to the crew [73–75]. Three factors contribute to the outbreak of fire: the presence of combustible material, ignition (initiation), and the appropriate amount of oxygen delivered to the source of fire. Fires in mining working conditions with fresh air current are a particularly serious threat. These fires spread very quickly, filling all of the mining workings on the way to the ventilation shaft with smoke. It is worth mentioning here that fires in mines are divided into two basic categories, i.e., exogenous and endogenous fires. Exogenous fires (caused due to external causes) can, in principle, break out anywhere in the mine. They usually appear suddenly and develop rapidly, with the release of a large amount of gases and smoke. Endogenous fires occur during the self-ignition of coal in the seam or batches. This phenomenon is caused by the oxidation of carbon at ambient temperature, resulting in the loss of oxygen in the air and the emergence of gases such as carbon dioxide, carbon monoxide, aliphatic hydrocarbons, and aromatic

hydrocarbons, both saturated (ethane, propane, butane) and unsaturated (ethylene, propylene and acetylene). This process is also accompanied by a positive heating effect [76].

The last hazard that was taken into consideration in the analysis of the development possibilities of hard coal mines is the water hazard (11). It is the possibility of sudden break-in of water, and a mixture of water and loose rock material to mining workings, posing a threat to workers [77,78]. The water hazard may come from the underground tanks, as well as rainwater in the case of shallow underground exploitation or open-pit mines. The degree of the water hazard depends on: the size of the tank from which water can enter, the size of the inlet, and the type of mining working.

For the second group (II) referring to natural hazards, experts mostly based their selections on the significance of the listed hazards for the functioning of the mining plant, and presented classes, categories, and levels of the hazards that were commonly applied in hard coal mining and possible to determine for each of the examined mining plants. They had 100 points at their disposal, just as it was in the previous group of conditions.

The methane hazard (7), which was assigned with the range from 0 to 40 points, was considered the most significant. Between 0–20 points were given to coal dust explosion hazard (8) and rock burst hazard (9). Fire hazard (10) and water hazard (11) were present not so frequently; they generated a lower risk for the functioning of the plant, thus were awarded with less points—between 0–10 points [79,80]. The detailed principles for awarding the points to the given criteria referring to natural hazard are presented in Table 2.

It is worth adding that the above classifications are applied for seams present in the given plant. This is why in the case of some categories (degrees, classes, groups) assigned to one plant, the maximum value of the given hazard was applied, which allowed assessing the plant as a whole equipped in a few seams.

Table 2. The principles for assessing criteria referring to natural hazard.

Criterion Number	Criterion Name	Score Range	Criterion Description
7.	methane hazard category	0–40	unthreatened: 40 points Category I: 30 points Category II: 20 points Category III: 10 points Category IV: 0 points
8.	coal dust explosion hazard class	0–20	unthreatened: 20 points Class A: 10 points Class B: 0 points
9.	rock burst hazard degree	0–20	unthreatened: 20 points I degree: 10 points II degree: 5 points III degree: 0 points
10.	self-ignitability of coal group	0–10	Group I: 10 points Group II: 8 points Group III: 6 points Group IV: 2 points Group V: 0 points
11.	water hazard degree	0–10	unthreatened: 10 points I degree: 8 points II degree: 4 points III degree: 0 points
TOTAL			100 points

Source: own work.

3.3.3. Production Area

As already mentioned, ensuring the sufficiency of the extraction and safety of mining crews—considered within the first two areas discussed above—is a prerequisite for the existence and development of an underground hard coal mine. However, it is also necessary to take into account the criteria that affect the competitiveness of the market of raw materials extracted in the evaluated mines, which is why the two subsequent assessment areas refer to production and economic conditions.

So, in the production area (III), by means of commonly known extraction performance indicators, principles considering the production capacity of underground hard coal mines were developed. To this end, the exploitation volume per employee (12), showing the overall efficiency of human resources, was used [81,82]. In addition, the technical infrastructure existing in the hard coal mine was also taken into account, which is characterized by the volume of extraction from one wall (13) and the volume of extraction per seam in use (14). These parameters determine the operational production capabilities. In a full assessment of production capacities, it is also necessary to refer to strategic investment capabilities, which are defined by the number of walls reinforced annually (15) and the intensity of preparatory works (16). The relative values constructed in this way allowed us to objectify the value of extraction and take into account the potential of human resources and the existing and emerging technical infrastructure [83–85].

In this area, the volume of extraction was applied as follows: per employee (12), from one wall (13), and per seam in use (14). In order to evaluate the categories, the maximum value assigned was 30 points for the first two criteria, and 20 points for the third one. Other plants were assessed proportionally to the upper limit of the established scale. Moreover, the group also included infrastructure in terms of the number of walls reinforced annually (15) and the intensity of preparation works (16). Between 0–10 points were assigned for the criteria, and the given plants were awarded them pursuant to the principles specified above. The detailed principles for awarding the points to the given criteria referred to production conditions, and are presented in Table 3.

Table 3. Principles for assessing production criteria.

Criterion Number	Criterion Name	Score Range	Criterion Description
12.	the volume of extraction per employee	0–30	In order to assess the category, in terms of each criterion, the maximum value was established based on the data from all of the hard coal mines functioning in Poland, awarding 30 points, 20 points, or 10 points, respectively. Other plants were assessed proportionally to the upper limit of the presented scale.
13.	the volume of extraction from one wall	0–30	
14.	the volume of extraction per seam in use	0–20	
15.	the intensity of preparation works	0–10	
16.	the number of walls reinforced annually	0–10	
TOTAL			100 points

Source: own work.

3.3.4. Economic Area

The last area of criteria determining the development of an underground hard coal mine is the economic conditions (IV), which affect the price attractiveness and efficiency of hard coal extraction from a given mine [86–88]. The first indicator in this group is the relation of price of one tonne to the cost of extraction of one tonne (17). This relation allows determining the efficiency of extraction by expressing the gross margin. The profitability limit is determined by the value 1; the higher it is, the higher the profit for the mining plant generated by one tonne of extraction. A value lower than one indicates the unprofitability of the mining production. For the development of the mine, this is an important financial condition, as profit is the basic source of capital that determines the day-to-day functioning and conducting of investment activity. The second indicator in the group of financial conditions is the relation between the cost of extracting one tonne in total hard coal mining in a given mining region and the cost of extracting one tonne in the evaluated mine (18). This relation enables assessing the cost competitiveness of the analyzed mining plant against the total regional mining. The value of indicator 1 means that the cost of mining in a mining plant is equal to the cost of extraction in the total region. The higher the value of the indicator, the higher the cost competitiveness of a given hard coal mine.

Bearing in mind that in the measurement of effectiveness, not only the volume of extraction is important, but also the quality of the raw material, the cost of 1 GJ (19) was also taken into account in the evaluation of development possibilities. Hard coal mines extract different types of coal, so comparing only the unit costs of extraction can be hardly objective. The economic criteria also indicate the share of fixed costs in total costs (20), assuming that mining plants with a lower share of these costs in the

cost structure may operate more flexibly and competitively. These features are undoubtedly conducive to the development of hard coal mines [89,90].

In the group of economic conditions (IV), four of the above-mentioned criteria were taken into account based mostly on extraction costs and/or hard coal price. First, 100 points was assumed in the group to be divided (just as in the two previous ones). So, the relation of **price of one tonne to the costs of extraction of one tonne (17)** (*price/cost; P/C*) was assessed within the range from 0 to 25 points. For the value of the coefficient smaller than or equal to one, 0 points were awarded, as it meant that the production is uneconomic. The values for which points were awarded started from the coefficient higher than one. The maximum number of points—25—was awarded to the plant of the highest value of the examined coefficient in the group (P/C_{max}); the remaining plants were given points proportionally to the upper limit determined for the best mine operating in the given period of time in Poland.

A similar evaluation is carried out for the ratio of the cost of extracting one tonne in the coal mining industry in total to the cost of extracting one tonne in the examined mining plant (18) (*cost in mining/cost in coal mine; C_M/C_{CM}*). The criterion was assessed in the range from 0 to 25 points. Zero points were awarded if the coefficient value was less than 1, as it meant that the costs were higher than the whole mining industry. Then, C_M/C_{CMmax} was determined, for which 25 points were awarded. Other plants were evaluated proportionally to the upper limit of the coefficient.

Another economic criterion was the cost of 1 GJ (19) (*cost of GJ; C_{GJ}*), for which between 0–30 points were awarded. In terms of the criterion, the average value for all of the examined mining plants (C_{GJav}) and the lowest cost of 1 GJ (C_{GJmin}) were determined. The range from C_{GJmin} to C_{GJav} was obtained in such a way that it was divided into 10 internal ranges. For C_{GJmin} , 30 points were awarded, and for the share of the cost of the given plant in the subsequent internal range, three points less were given up to the average value assessed as 0.

The share of fixed costs (20) in the structure of total costs was assessed on a scale from 0 to 20 points. From the group of mining plants operating in Poland, the plant with the lowest share of fixed costs (*fixed costs/total costs; FC/TC*) was selected, which obtained 20 points. Other mines were settled proportionally, depending on the share of fixed costs in the total costs.

The detailed principles for awarding the points to the given criteria referring to economic conditions are presented in Table 4.

Table 4. Principles for assessing economic criteria.

Criterion Number	Criterion Name	Score Range	Criterion Description
17.	the price of 1 tonne to the costs of extraction of 1 tonne ratio (P/C)	0–25	For the value of the coefficient smaller than or equal to one, 0 points were awarded. The maximum number of points—25—was awarded to the mine of the highest value of the examined coefficient (P/C_{max}); the remaining mines were given points proportionally to the upper limit determined for the best mine.
18.	the cost of extracting 1 tonne in the hard coal mining industry in general to the cost of extracting 1 tonne in the examined mining plant (C_M/C_{CM})	0–25	For the value of the coefficient below one, 0 points were awarded. Then, C_M/C_{CM} , was determined, for which 25 points were awarded. Other plants were assessed proportionally to the upper limit of the coefficient.
19.	the cost of 1 GJ (C_{GJ})	0–30	The average value for all of the examined mining plants (C_{GJav}); the lowest cost of one GJ (C_{GJmin}) was determined. The range from C_{GJmin} to C_{GJav} obtained in such a way was divided into 10 internal ranges. For C_{GJmin} , 30 points were awarded, and for the share of the cost of the given plant in the subsequent internal range, three points less were given up to the average value assessed as 0.
20.	the share of fixed costs in the structure of costs in total (ft/tc_{min})	0–20	From the mining plants examined, a plant with the lowest share of fixed costs (FT/TC_{min}) was selected, which obtained 10 points. Other plants were settled proportionally depending on the share of the fixed costs in the total costs.
TOTAL			100 points

Source: own work.

4. Results

4.1. Polish Hard Coal Mining in Poland in the Years 1990–2016 (Stage C)

For the purposes of detailed empirical analysis of the development situation of the examined mines, firstly it is necessary to analyze the market conditions in which they are operating. This is why this part of the article includes the synthetic evaluation of the Polish hard coal mining industry functioning in the years 1990–2016. Hard coal mining in Poland has been the branch of strategic industrial and power importance for many years. Poland has been and still is one of the biggest manufacturers of hard coal in the world. Unfortunately, since the end of the 1990s, hard coal extraction in Poland has been systematically decreasing, which is connected with limitations relating to the raw material consumption in Europe, tightening environmental restrictions, and the worsening price competitiveness of hard coal in Poland. So, within 27 years, the size of the mining production decreased by almost 40% from over 147 million of tonnes in 1990 to less than 90 million of tonnes in 2016. Since 2006, the decreasing extraction is also accompanied by the decline of the general efficiency per employee (Figure 2), which has a disadvantageous influence on the effectiveness of extraction, and is caused by the slowing down of the employment restructuring speed, leading to the non-adjustment of the employment level to the decreasing market demand.

The decreasing effectiveness has a negative impact on the unit extraction cost, which in Polish hard coal mining has been systematically increasing from 2014 (Figure 3). So, the sudden hard coal price collapsed, which resulted in the biggest level of ineffectiveness in Polish hard coal mining in history (profit gross margin for sale is over -37%), and the most serious industrial crisis. As a result of the crisis, a significant number of operating mines was liquidated, and the remaining ones were integrated with the power sector in order to disperse the risk of their further operation. In such market conditionings, in order to ensure the further functioning and development of hard coal mining in Poland, the priority is to gain the economic effectiveness back, and improve the efficiency, that is, reinforce the developmental criteria from the third and fourth group identified and characterized in terms of the evaluation methodology.

Figure 2. Hard coal production [in millions of tonnes] and efficiency [daily in tonnes per employee] in Poland in the years 1990–2016.

The principles of assessment that were referred to in the paragraph have been used in the article for the purposes of evaluating the selected hard coal mines in 2011, when the Polish mining industry

has been functioning in good economic conditions, and in 2016, after the deep reform finished with liquidation of some of the operating mining plants.

Figure 3. Unit production costs and unit sale price of hard coal in Poland in the years 1990–2016.

4.2. The Results of the Assessment of the Development Level of the Selected Mines (Stage D)

As has already been mentioned, in the process of the evaluation of the developmental possibilities, four hard coal mines have been used. Three of them have been assessed in 2016 as the ones that bode well for the future, and were included in the central mining enterprise consolidated with the power sector, while the other two have been liquidated. The detailed results of the evaluation of all 20 criteria for the examined mines in 2011 (before crisis) and in 2016 (before the consolidation with power industry and liquidation) have been presented in Tables 5 and 6, respectively. Moreover, Figures 4–8 show the results obtained by the examined mines in the given groups: geological and mining, natural hazard, production, and economic, as well as the final score expressed as a coefficient of the developmental possibilities of the underground hard coal mines.

Table 5. The assessment of the given developmental criteria in the examined hard coal mines in 2011.

No.	Criterion	CM1	CM2	CM3	CM4	CM5
1.	the mining plant lifetime	19.7	34.1	27.7	17.1	9.1
2.	the thickness of seams of the deposit	10.0	10.0	10.0	10.0	10.0
3.	inclination	10.0	10.0	5.0	2.0	8.0
4.	the calorific value of commercial coal	13.6	16.4	14.4	17.3	15.6
5.	ash content in commercial coal	6.0	6.0	6.0	10.0	4.0
6.	sulfur content in commercial coal	0.0	4.0	4.0	6.0	4.0
7.	methane hazard category	40.0	0.0	10.0	0.0	20.0
8.	coal dust explosion hazard class	10.0	0.0	0.0	0.0	0.0
9.	rock burst hazard degree	0.0	0.0	20.0	10.0	0.0
10.	self-ignitability of coal group	0.0	6.0	2.0	6.0	2.0
11.	water hazard degree	0.0	4.0	8.0	4.0	4.0
12.	the volume of extraction per employee	13.7	9.5	11.0	13.1	9.8
13.	the volume of extraction from one wall	6.1	4	4.4	4.8	4.3
14.	the volume of extraction per seam in use	12.4	5.5	4.4	4.7	4.1
15.	the intensity of preparation works	5.1	5.4	8.5	6.3	7.1
16.	the number of walls reinforced annually	2	2.5	2.5	2	2.5
17.	the price of one tonne to the costs of extraction of one tonne ratio (P/C)	8.2	0	8.4	10	0
18.	the cost of extracting one tonne in the hard coal mining industry in general to the cost of extracting one tonne in the examined mining plant (C_m/C_{cm})	17.9	0	18.5	18.5	0
19.	the cost of one GJ (C_{gj})	0	0	6	21	0
20.	the share of fixed costs in the structure of costs in total (Ft/Tc_{min})	9.3	10.1	9.7	9.3	9.5

Source: own work.

Table 6. The assessment of the given developmental criteria in the examined hard coal mines in 2016.

No.	Criterion	CM1	CM2	CM3	CM4	CM5
1.	the mining plant lifetime	21.3	36.8	29.9	13.3	14.4
2.	the thickness of seams of the deposit	10.0	10.0	10.0	10.0	10.0
3.	inclination	10.0	10.0	5.0	2.0	8.0
4.	the calorific value of commercial coal	15.8	19.0	17.2	19.2	18.7
5.	ash content in commercial coal	6.0	6.0	6.0	10.0	6.0
6.	sulfur content in commercial coal	0.0	4.0	4.0	4.0	4.0
7.	methane hazard category	40.0	0.0	10.0	10.0	20.0
8.	coal dust explosion hazard class	10.0	0.0	0.0	0.0	0.0
9.	rock burst hazard degree	10.0	0.0	20.0	5.0	0.0
10.	self-ignitability of coal group	0.0	6.0	0.0	6.0	6.0
11.	water hazard degree	0.0	4.0	4.0	4.0	4.0
12.	the volume of extraction per one employee	12.3	12.6	14.7	15.8	12.6
13.	the volume of extraction from one wall	6.2	5.5	6.6	6.4	4.5
14.	the volume of extraction per seam in use	9	4	3.2	3.5	3
15.	the intensity of preparation works	7.1	5.2	7.1	7.1	8.5
16.	the number of walls reinforced annually	2	2	3.3	1.3	2.5
17.	the price of one tonne to the costs of extraction of one tonne ratio (P/C)	0	0	9	10.5	0
18.	the cost of extracting one tonne in the hard coal mining industry in general to the cost of extracting one tonne in the examined mining plant (C_m/C_{cm})	17.6	0	22.3	23.6	17.3
19.	the cost of one GJ (C_{gj})	0	3	18	27	9
20.	the share of fixed costs in the structure of costs in total (Ft/Tc_{min})	10.4	9.8	11.4	10.8	10.1

Source: own work.

So, pursuant to Figure 4, the best geological and mining conditions characterize mine CM2 and CM3, which results from their significant lifespan and good extraction conditions (thickness, inclination), as well as from the high quality of the extracted raw material. Another three mines in the 100-point scale obtained between 51–63 points, which results from the shorter period of sufficiency of operational resources than in CM2 and CM3. Moreover, the lower numbers also came from low calorific value in CM1, the significant inclination of the seams in CM4, and the high ash content in the commercial coal in CM5.

Figure 4. The results of the assessment of geological and mining criteria in 2011 and 2016 in the examined hard coal mines. Source: own work.

In the case of the assessment of natural hazards, the highest developmental potential connected with the low level of the hazard—or their lack—characterized mine CM1, which ensures the continuity of extraction and safety of mining team operation and is an important positive developmental condition. In the mine, there is no methane hazard, and the coal dust explosion hazard and rock burst hazard are

very low. In other mines, the assessment of natural hazard is below 50 points, which indicates their high level. The situation in this group of criteria is improved in mines CM4 and CM5, and it results from the reduction of methane hazard (CM4) and fire hazard (CM5), respectively. The highest level of natural hazard is present in mine CM2; it refers to methane hazard, coal dust explosion hazard, and rock burst hazard, which makes the extraction conditions in the plant very disadvantageous.

The assessment of production criteria is quite low in all of the examined hard coal mines, which results from the huge distance between the examined mines and the best mining plant operating in Poland. So, in accordance to Figure 6, the best, in terms of efficiency, in the examined group are mines CM1, CM3, and CM4. Meanwhile, it has to be underlined that the production criteria improved in four out of five examined mining plants, which resulted mostly from the increase of extraction per employee (employment restructuring) and extraction from one wall (concentration).

Figure 5. The results of the assessment of natural hazard in 2011 and 2016 in the examined hard coal mines. Source: own work.

Figure 6. The results of the assessment of production criteria in 2011 and 2016 in the examined hard coal mines. Source: own work.

In connection with the improvement of efficiency in mines CM4 and CM5, the economic criteria, which in both periods were characterized with the highest and growing assessment in the examined group at the time, also improved (Figure 7). In the mines, the unit production cost calculated per tonne and GJ was significantly reduced, which allowed for a positive assessment of their further chances for development. Mines CM2 and CM5, which were characterized with a high level of unit costs and a very high share of fixed costs in the total costs, were definitely the weakest ones as far as economic criteria are concerned.

Figure 7. The results of the assessment of economic criteria in 2011 and 2016 in the examined hard coal mines. Source: own work.

Figure 8. The results of the assessment of developmental possibilities in 2011 and 2016 in the examined hard coal mines. Source: own work.

A synthetic analysis of all of the criteria is presented in Figure 8, based on which it may be concluded that the two best mines are mines CM1 and CM3. In the case of CM1, the source of the developmental dominance is a low level of natural hazard, and a very good assessment of production criteria. In the case of CM3, the good evaluation of developmental possibilities is influenced in a quite balanced manner by the good assessment in each of the selected areas. In the final evaluation of developmental possibilities, mine CM4, which was characterized with very good economic and

production conditions, as well as very good geological and mining conditions, slightly diverged from the two leading mines. All three of the above-mentioned mines were in 2016 included in the central mining enterprise and consolidated with the Polish power industry, which allowed for a positive verification of the proposed methodology.

Mines CM2 and CM5, which received the lowest notes, have been liquidated. In the case of mine CM2, the very high level of natural hazard and very bad economic results had the decisive impact on the negative assessment. In the case of CM5, the worst notes were due to its production and economic conditions, which boded ill for its further development.

5. Discussion

The presented assessment of the developmental possibilities of hard coal mines allows for a synthetic evaluation of the chances for the development of an examined mine, as well as the analysis of the given areas and criteria referring to its operation in the geological and mining, natural hazard, production, and economic aspects. This way, it may be used not only as a tool for dividing mines into those that bode well and those that are intended for liquidation, but also as a diagnostic tool allowing for the identification of areas which require improvements. The method may also become the basis for mine benchmarking in the given economic region. One of its key advantages is the universality resulting from taking into account all the factors that are important for the functioning of the underground mining plants development.

Nevertheless—as every method—it has also disadvantages and limitations, which surely include subjectivism resulting from the experts' opinion and referring production and economic criteria to the leaders in the given group of mines. In connection with the above, in each individualized case, it is necessary to adapt the offered method to regional needs through the performance of a repeated experts' assessment and designation of a group of examined mining plants in which the leader will be the reference.

The directions for further studies in terms of the offered method may then be referred to: (1) adjustment of its different regional conditions; (2) modification of criteria allowing for its use in other underground mines of mineral resources; or (3) normalization of the developmental coefficient value.

6. Conclusions

The conclusions from the studies and considerations may be contained in three general groups: a universal one referring to the assessment method presentation, a regional one referring to the conditions of the hard coal mining industry operation in Poland, and a practical one covering the directions for the mines that survived and shall strengthen their chances for further development. In terms of universal conclusions, it shall be stated that:

- the evaluation of the development of underground hard coal mines requires a multi-aspect research approach;
- geological and mining conditions as well as the level and intensity of natural hazard shall be considered as necessary conditions for the development of an underground hard coal mine;
- production and economic conditions that influence on the mining production marketability and profitability shall be considered as additional conditions for the development of underground hard coal mines, the importance of which in the recent years has been systematically growing;
- the method of assessing the developmental possibilities of the underground hard coal mine presented in the article takes into account all four above-mentioned areas evaluated jointly in terms of 20 detailed criteria.

In terms of conclusion of regional character, it can be stated that:

- Polish hard coal mining industry has been in a condition of deep branch crisis since 2014;

- the crisis was caused by the sudden hard coal price collapse on the world market, and a systematic increase of the unit production cost in Polish underground hard coal mines;
- the developmental and restructuring possibilities of Polish mines are disadvantageously influenced by the high and growing level of natural hazard as extraction deepens;
- in terms of remedial restructuring in 2016, the liquidation of non-profitable mines and the consolidation of others with the power industry took place,
- further branch restructuring requires the improvement of production and economic conditions due to the increasing market competition of global character.

In terms of the practical conclusions, guidelines referring to the reinforcement of the developmental potential of the examined mines were formulated:

- recommendations for mine CM1: carrying out prophylactic actions in terms of fire and water hazards, and increasing the general efficiency, which includes extraction per employee and a reduction of unit production costs,
- recommendations for mine CM3: carrying out prophylactic actions in terms of methane, fire, and coal dust explosion hazards, and reducing unit cost for GJ,
- recommendations for mine CM4: carrying out prophylactic actions in terms of methane, rock burst, and water hazards, and balancing of the distance in terms of production and economic parameters in relation to the leader of Polish hard coal mines.

Author Contributions: Izabela Jonek-Kowalska is the only author of the article. Her contribution to preparing the paper and presented research is 100%.

Funding: This article was funded by statutory research of the Faculty of Organization and Management of the Silesian University of Technology no. BK-231/ROZ1/2018 and BK-235/ROZ0/2018.

Conflicts of Interest: The authors declare no conflict of interest.

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