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CRITERIA FOR ASSESSING THE LONGEVITY OF HARD COAL MINES

The article presents the methodology for assessing the longevity of hard coal mines. Based on international experts' assessments, important criteria for determining mine viability have been presented. The results refer to Polish coal mines in the area of the Upper Silesian Coal Basin, however, the methodology itself can be applied to other geological and mining conditions of mines elsewhere.

The results of structural analyses carried out using the MICMAC method for factors related to the mining geo-environment that may determine the longevity of individual hard coal mines are presented. The analyses were based on the results of expert surveys carried out using the Delphi method. The experts participating in the survey came from various countries and had extensive experience related to work or cooperation with hard coal mining. The criterion factors examined were assigned to two systems (groups) for which structural analysis was performed. The first group includes factors related to the level of exploitation hampering, while the second group includes factors related to hard coal quality and the availability of resources. As a result of the analyses the following were determined: the key factors which have the most significant influence on the system, result and goal factors, factors affecting the system and autonomous factors which have little effect on the system.

The obtained results allowed to determine which factors should be taken into account in the process of determining the longevity of a hard coal mine.

Keywords: Longevity of coal mines, safety in mining operations, MICMAC method

1. Introduction

Underground coal mining in Poland, as of December 31, 2019, was taking place in 20 mines with 30 active operations. In the year 2019, Polish mines produced 61.623 million Mg (tons) of hard coal and employed 75,008 people. Simultaneously, 14 mining plants under liquidation were within the structures of the Spółka Restrukturyzacji Kopalń S.A.(SRK). Except for Bogdanka.

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mine located in the Lublin Coal Basin (LCB), all other hard coal mines (active and under liquidation) are located in the Upper Silesian Coal Basin (USCB). In the third coal basin located in Poland – the Lower Silesian Coal Basin (LSCB), all mines in the regions of Wałbrzych and Nowa Ruda were closed at the turn of the 21st century.

Restructuring in the mining industry started after 1989 and it resulted in a significant reduction in the number of mines and the volume of mining in the USCB area, where mining has been carried out continuously since the mid-eighteenth century. In the year 1989, 65 mining plants were active in the USCB area (not including Budryk mine which was under construction), and the annual production amounted to 171.4 million Mg of hard coal in these mines (Jureczka & Galos, 2007; Probierz, 2015). The carried out restructuring of coal mining involved closing mines (including all mines in the region of the Dąbrowski Basin, Siersza mine, Dębieńsko mine, Morcinek mine and Gliwice mine) or creating ‘mine complexes’ with two or more production plants under one administration and liquidating individual mines – for example, Operation II Piast mine (former Czeczott mine) or Operation I Rydułtowy-Anna mine (former Anna mine). The liquidation of mines/operations carried out in this way was usually associated with the liquidation of the infrastructure on the surface, including shafts. In practice, this made the use of underground infrastructure, whether for the resumption of mining or other purposes, impossible. At present, in the USCB area three private mining plants are active in the location of decommissioned mines: the PG Silesia mine in the former Silesia mine area, the Siltech mine in the mining area of the former Pstrowski mine and the Eko-Plus mine in the mining area of the former Powstańców Śląskich mine. To date, the mine closure in the USCB area proceeds in a way that does not involve the use of the existing resource and infrastructure potential of the liquidated mining plant, which is reflected in the provisions of geological and mining law. The exception to this rule is the use of former Dębieńsko mine infrastructure, where industrial and food salt using underground waters, which come from this mine and Budryk mine, is produced (Turek et al., 2018).

Mining enterprises wanting to close or no longer extracting coal from the a mine/operation are obliged to transfer the mining area of the liquidated plant along with the infrastructure to the SRK. This cause a reduction of the economic potential of the mine as transferred assets are no longer available for the mine. Therefore, it is reasonable for entrepreneurs to be able to use the resources and infrastructure of their own mines/operations after the end of traditional exploitation in an alternative way to the currently used methods of decommissioning. The current geopolitical situation related to the European Union’s (EU) approach to the use of fossil fuels is a big challenge for mining entrepreneurs who have to adapt to existing realities, and one way to do this is to introduce circular economy principles into business plans. However, to undertake such tasks it is necessary to know both the size and quality of resources and the threats arising from the underground mining of coal deposits. The assessment of hard coal deposit management according to the international JORC (JORC Code, 2012) standard and theoretical, economically justified resources (therefore also longevity) was presented, among others, by (Saługa et al., 2015; Sobczyk & Nieć, 2017). In each mine the conditions related to the geo-environment are variable. Therefore, it seems that for the full determination of mine longevity, in addition to geological aspects, the level of exploitation hampering and the quality of resources should be taken into account in terms of their availability. This article attempts to develop a method to assess the longevity of hard coal mines, not only in terms of the size and quality of resources but also concerning the associated natural hazards, using structural analysis methods (Villacorta et al., 2012).

2. Methodology

The research and analyses presented in this publication were based on the results of surveys carried out using the Delphi method, described in detail by (Krause & Krzemień, 2014).

In the procedure of group assessment carried out by experts, their competences are assessed according to the formula 1.

$$K_k = \frac{K_z + K_a}{2} \tag{1}$$

where:

K_k — an indicator of an expert's competence,
K_z — the factor determining the degree of knowledge held by the expert assessing the problem,
K_a — coefficient of argumentation.

The factor describing the degree of an expert's knowledge on the assessed problem and the coefficient of argumentation is determined for each expert. The coefficient K_z (Krzemień, 1991), wherein the degree of knowledge of the issues is expressed in points ranging from 0 to 10. The value read from the table K_z is multiplied by the value of 0.1.

The coefficient of argumentation K_a consists of three sources of argumentation:

1. Theoretical analysis – argumentation degree from 0.1 to 0.3.
2. Mining experience – argumentation degree from 0.2 to 0.5.
3. Intuition – argumentation degree 0.2.

In total, value $K_a = 1$ corresponds to a high coefficient of argumentation (Krause & Krzemień, 2014).

Twenty-five experts took part in the survey, among them five from Spain, three from Vietnam, one from United Kingdom, and sixteen from Poland. Coal mining industry was represented by 40% of experts, scientific entity by 56%, and 4% (one expert) was representing the State Mining Authority. Range of years of experience in coal mining related activities was from 15 to 43 years. Expert's competence calculated as K_k (formula 1) was from the range 0.7-1.0.

The proposed method of determining the longevity of active hard coal mines is based not only on the size of available resources and average mining volume but also on the characteristics for each mine's geological and mining factors, including the natural hazards occurring in them and the level of work safety associated with them.

The characteristic feature of this method is the fact that currently operating combined mines are treated as separate operations, which is important due to both the varied geological and mining conditions in the individual operations, as well as the historical conditions because often the current operations included in the complex mines functioned for a long period of time as independent mines.

The developed criteria (factors) were assigned to two groups

- Criteria describing the level of exploitation hampering.
- Criteria describing the quality of resources and the level of the availability of resources.

In the group of criteria describing the level of exploitation hampering, criteria determining the level and influence of natural hazards on the exploitation have been distinguished. The exploitation of hard coal in the USCB area is determined by natural hazards, such as methane, fire, seismic, rock bursts, dust, outbursts, water and climate (Kabiesz, 2002).

The following criteria were distinguished from the group of criteria describing the level of hampering of mining operation:

- The gas hazard criterion, defined as the number of ignitions or explosions of methane in a mine over a set period of time. Methane hazard, which is understood as the possibility of the ignition or explosion of methane which occurs with the risk of dust explosion, is the most catastrophic threat in hard coal mining (Trenczek et al., 2019). The methane threat grows with the increasing depth of exploitation and increased progress of the mining walls (Kędzior & Dreger, 2019).
- The fire hazard criterion, described by the number of endogenous fires in the mine over a set period of time. The threat of endogenous fires resulting from the natural propensity of coal to ignite applies to all hard coal mines, where, also many geological and mining factors increase this threat. The development of endogenous fires is not a rapid process, in contrast to exogenous fires which are caused by external factors. Detecting endogenous fires too late is a real threat to mine employees and causes substantial economic losses due to the need to shut down the mine area and to stop production (Kordos, 2019).
- Criteria for seismic hazard and rock bursts, including the number of high energy shocks with seismic energy of $E \geq 10^5$ J and the number of rock bursts occurring over a set period of time. The underground mining of coal deposits in the USCB causes an imbalance of the rock mass stress distribution, both in the immediate and distant surroundings of mining excavations. One consequence of this process is the occurrence of seismic shocks. The intensity of seismic phenomena that occur in several areas of the USCB (Bytom Basin, Main Saddle, Main Trough, and Jejkowice Basin) is very diverse, ranging from shocks that are imperceptible to people to strong shocks comparable to earthquakes (Bukowska, 2012; Patyńska & Stec, 2017).
- The dust hazard criterion which is defined as the number of coal dust explosions over a set period of time. In the area of the USCB, all mines use prevention methods in this area, either by dusting excavations with stone dust (Więckol-Ryk & Trojnar, 2015) or by washing the excavations with water (Prostański, 2013). In addition to methane and endogenous fire hazards, the threat of coal dust explosion is a cause of the greatest mining catastrophes. It should be emphasized that due to the use of appropriate prevention the most recent catastrophe related to the explosion of coal dust, not caused by the explosion of methane, took place in 2002 in JAS-MOS mine. Unfortunately, the most recent catastrophe associated with the explosion of coal dust combined with the explosion of methane took place in Mysłowice – Wesoła mine in 2008 (Trenczek et al., 2019).
- The climatic hazard criterion is described in the climate category, denoting the number of excavations with a high temperature in a given mine. Due to the depletion of coal deposits at the currently available levels, which are located at medium depths, mining is increasingly carried out below a depth of 1000 m. where the primary temperature of rocks is much higher, i.e. 40°C and often reaching 50°C, which significantly hinders continuous operation (Knechtel, 2007).
- The criterion of water hazard which is described by the number of uncontrolled outflows of water from fault zones or water leaks, or quicksand, into the mining excavations occurring over a set period of time. The water hazard in the mines of the USCB area is also

associated with mine waters with high salinity, as well as the need to protect active mines against mine waters from neighbouring, closed mines (Bondaruk et al., 2015; Niedbalska et al., 2015).

- The criterion of gas and rock outbursts hazard which is defined by the number of outbursts occurring over a set period of time. The threat of gas and rock outbursts was common in the coal mines of the Lower Silesian Coal Basin (Gogolewska, 2011). Currently, it also occurs in the area of the USCB in the mines belonging to Jastrzębska Spółka Węglowa S.A. (Bukowska & Gawryś, 2010). The most recent case related to gas and rock outburst took place in the Budryk mine in 2012 (Trenczek et al., 2019).
- The criterion of roof fall hazard is described by the number of roof falls that occurred over a set period of time. Threats associated with roof fall are a common problem in underground coal mines and are generally difficult to predict. This threat results from the geological and geomechanical conditions of the mine, which significantly impede predictions of this hazard (Düzgün, 2005).

In the second group of criteria, the factors characterizing the volume of resources of individual mines/operations, coal quality in the deposit, and – to some extent – their availability, were distinguished. Two criteria determine the longevity of mines, one relates to operational resources and the other takes into account the results of analyses made using the JORC code and is contained in (Saługa et al., 2015; Sobczyk et al., 2016; Sobczyk & Nieć, 2017). The resource base used was adopted according to data from the Polish Geological Institute – National Research Institute, while the information on production was based on data from the Industrial Development Agency S.A. and the data contained in the work of (Kabiesz, 2018).

The following elements have been distinguished from the group of criteria determining the quality of resources and their level of availability:

- The depth of exploitation, defined as the maximum depth of mining works carried out in the available exploitation levels. In 1989, the average depth of exploitation was 524 m, in 2010 it was approximately 700 m (Konopko, 2010), while in 2018 the average depth of exploitation was 788 m (Kabiesz, 2018). Thus, the average depth of exploitation increases each year by about 8÷10 m.
- The thickness of coal seams is defined as the thickness of seams that can be exploited at the available mining levels. The thickness of coal seams is the fundamental parameter determining the choice of exploitation technology. The minimum thickness of the seam, according to the current balance criteria, should be above 0.6 m. Due to the efficiency of exploitation, only seams with a thickness greater than 1.2÷1.5 m qualify as industrial resources. In some mines, which are striving to improve the efficiency of the mining process, this even leads to the abandonment of the mining of seams which are thinner than 1.5 m (Sobczyk et al., 2016).
- Coal type is defined as the dominant coal type in the mine's industrial resource base. Steam coal (in Polish classification of coal type 31-33) is the most prevalent in the total amount of industrial resources in all active hard coal mines. It represents 53.4% of the total resources and 58.3% of the available resources. The remaining part of the industrial resource base is coking coal, mainly type 34. Type 35 (orthocoking coal) makes up only 19% of total industrial resources, and type 36-38 is only approximately 1% of the available resources (Sobczyk et al., 2016).

- Sulphur content in coal is defined as the average sulphur content in extracted coal. Sulphur in coal is a highly undesirable element, because in addition to its harmful effects on the environment, it also causes the corrosion of heating surfaces, e.g. boilers and slags furnaces. The average sulphur content in hard coal mined in the USCB is approximately 1.2%, and the range of sulphur content in seams is quite varied, from 0.32 to 2.82% (Sobczyk et al., 2016).
- The size of the mining area is defined as the actual area of the mine where mining takes place. This criterion refers to possible difficulties of exploitation because the extent of the area leads to excessive elongation of access roads to longwall faces and makes coal haulage to shafts more expensive and time consuming.
- The period of the validity of mining licenses is defined as the time when coal mines own the concession for mining coal. This is an extremely important criterion, especially in the current situation when the local community can exert a great amount of influence on granting a concession to conduct or cease exploitation in an area.
- The average annual mine production over a set period of time. The average annual mine production should be conditioned by economic factors and should also be associated with the rational use of the deposit adequate to the world coal market situation.
- The volume of available resources can be defined as the operational resources that can be mined, without the need to provide new mining levels or expand the exploitation area. It can be assumed that only 30% of the resources of the developed deposits are used (Nieć & Salamon, 2016). However, the resource estimation following the JORC reporting standard requirements, carried out by (Saługa et al., 2015), showed that the volume of resource potential in the analysed USCB mines was at the level of 621 million Mg (tons), which constituted less than 22% of the operational reserves of the deposits at their disposal.
- Faults zones in a coal deposit in a mine. The Carboniferous rock mass in the USCB is characterized by numerous deformations and disturbances affecting the retention and thickness of hard coal seams. These disturbances negatively affect mining operations both at the design stage of the deposit development and later, during its exploitation. The appropriate recognition of the geological structure of the deposit enables the use of the most effective system and exploitation technology in the specific conditions (Drzewiecki, 2011). The hard coal deposits occurring within the boundaries of the USCB, in terms of fault rate, can be divided into degrees, from uncomplicated (1st degree) to very complex (6th degree) deposits (Marcisz, 2017).

The proposed method based on the analysis of two groups of criteria: describing the level of exploitation hampering and describing the quality of resources, and the level of their availability, makes it possible to assess the level of difficulty in the exploitation of deposits and with regards to the assessment of the mine/operation longevity, enables a critical and more objective assessment of the potential possibilities of hard coal exploitation to deplete resources.

The MICMAC (Matrice d'Impacts Croises Multiplication Appliquee a un Classement – cross-impact matrix multiplication applied to classification) analysis, i.e., cross-impact matrix multiplication applied to classification was developed by Duperrin and Godet (Duperrin & Godet, 1973, 1975) whose working principle is based on multiplication properties of matrices. The purpose of MICMAC analysis is to identify the variables according to their driving power (influence) and dependence (Lutyński & Blaschke, 2011; Mani et al., 2016; Srivastava & Dubey, 2014).

The MICMAC method for structural analysis is aimed at the determination of the most important variables within a system, among a set of variables specified by an expert committee. The MICMAC is composed of the following three steps:

- defining the relevant variables,
- specifying the relationships between the variables,
- identifying the key variables among all the variables proposed by the experts (Villacorta et al., 2012).

In the first stage, the variables in complex systems are defined according to the opinion of several experts, by brainstorming and following the literature review. An unsorted list of variables is obtained as a result of this phase. Of course, not all of the experts will agree on the importance of the variables or even which aspects should be recognised as a variable and which ones should not (Villacorta et al., 2012).

The experts from mining industry, scientific entities and national governments evaluated the following, defined in section 2, criteria:

- determining the level of hampered exploitation: gas hazard – methane ignition and explosion, fire hazard – endogenous hazard, seismic hazard – tremors associated with surface damage, rock burst hazard – tremors associated with damage underground, dust hazard – coal dust explosion, climatic hazard – high temperature in ventilation network, water hazard – water and quicksand inflow, outburst hazard – gas/coal/rock outburst and roof fall hazard.
- determining the quality of resources and the level of their availability are included the following variables: depth of exploitation, the thickness of coal seams, type of coal, sulphur content in coal, size of the mining area, duration of the concession to exploit coal, annual coal production, amount of coal reserves and fault zones.

In the second stage, the experts assess the interrelationships between the variables. For this purpose, matrices of direct influence (MDI) were developed, where the variables considered were placed in rows and columns. The main objective of filling the matrix consists of assessing the direct influence of one variable on other variables, using numerical values according to the following scale:

- no influence – 0;
- weak influence – 1;
- moderate influence – 2;
- strong (deciding) influence – 3;
- potential influence – P.

According to (Duperrin & Godet, 1973), in real systems, only about 30 % of the cells of the MDI have values different from 0 (Villacorta et al., 2012).

After determining the interrelationships between variables, the last stage is to determine the so-called key factors. The method of identifying the factors which describe the interaction of variables is presented in Figure 1 (Ambrosio-Albalá et al., 2009; Frejowski & Koteras, 2016).

Figure 1 is divided into 4 areas (quadrants) that determine the nature of the variables located therein.

- Quadrant I – key variables and objective variables. Key variables are factors with the highest influence, and the highest degree of dependence. Objective variables are those that depend on others more than they influence them.

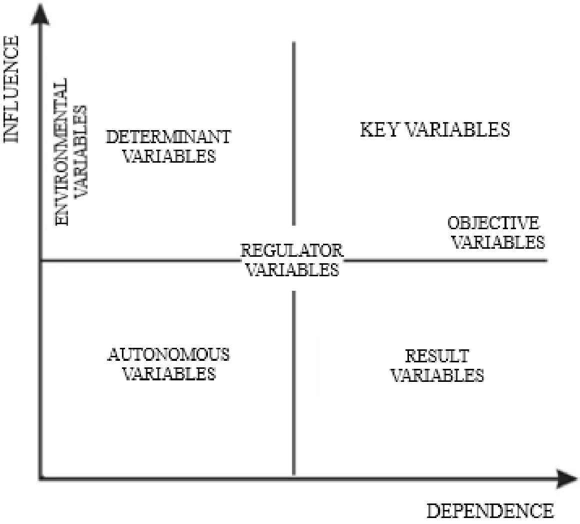

Fig. 1. Direct influence/dependence map

- Quadrant II – determinant variables and environmental variables (influence variables). Determinant variables are characterized by high influence and low dependence. Environmental variables are characterized by virtually no dependence and a high influence on the system.
- Quadrant III – autonomous variables that do not directly affect the system – these are variables with low influence and low dependence.
- Quadrant IV –- result objectives are characterized by having a low influence on other variables and a high degree of dependence.
- The central area of the matrix contains regulator variables, which are characterized by both moderate influence and moderate dependence (Frejowski & Koteras, 2016).

Using the MICMAC software, the interrelationships between variables are analysed and interpreted using the following methods (Frejowski & Koteras, 2016; Villacorta et al., 2012):

- MDI (Matrix of Direct Influence) – the direct method estimates the overall direct influence and direct dependence of a variable in the system, directly from the MDI matrix.
- MPDI (Matrix if Potential Direct Influence) – the potential direct method represents the present and potential influences and dependences between the variables. It complements the MDI by also considering the possible future relations.
- MII (Matrix of Indirect Influence) – the indirect method estimates the overall influence and dependence of a variable through other variables of the system, by successive iterations. The classification of the variables from this matrix emphasizes the most important variables of the system.
- MPII (Matrix of Potential Indirect Influence) – the potential indirect matrix corresponds to potential direct matrix enhanced in power, by successive iterations. From this matrix, a new classification of the variables emphasizes the potentially most important variables of the system.

Results of calculations by the above methods are presented as influence/dependence maps and influence graphs. Based on maps and graphs variables were assigned to appropriate groups of variables, especially to the most important group from the analysis point of view – key variables and objective variables, located in the first quadrant.

3. Results and discussion

3.1. The variables defining the level of the exploitation hampering

The following variables have been included in the group of variables which determine the level of exploitation hampering: gas hazard – methane ignition and explosion (H1), fire hazard – endogenous hazard (H2), seismic hazard – tremors associated with surface damage (H3), rock burst hazard – tremors associated with underground damage (H4), dust hazard – coal dust explosion (H5), climatic hazard – high temperature in the ventilation network (H6), water hazard – water and quicksand inflow (H7), outburst hazard – gas/coal/rock (H8) and roof fall hazard (H9).

3.1.1. Calculation from the Matrix of Direct Influence (MDI) and the Matrix of Indirect Influence (MII)

The structural analysis of direct influences of individual variables (MDI) determining the level of exploitation hampering (Fig. 2a) showed that the key and objective variables that can be prioritized are: gas hazard – methane ignitions and explosions (H1), fire hazard – endogenous hazard (H2) and outburst hazard – gas/coal/rock (H8). The influence variables (determinant and environmental variables), i.e. variables that affect the layout of the entire system, are rock burst hazard – tremors associated with underground damage (H4) and seismic hazard – tremors associated with surface damage (H3). Dust hazard – coal dust explosion (H5) and roof fall hazard (H9) were classified as result variables. Other variables do not have a significant influence on the system under consideration.

Taking into account the direct interrelationships (MDIs) between the variables determining the level of exploitation hampering (Fig. 2b), it can be seen that stronger influences occur between the key variable with the highest significance of gas hazard – methane ignitions and explosions (H1) – and fire hazard variables – endogenous hazard (H2) and dust hazard – coal dust explosion (H5).

The structural analysis of the influence of indirect variables (MII) describing the level of exploitation hampering (Fig. 3a) also confirmed that the following are key and objective variables: gas hazard – methane ignitions and explosions (H1), fire hazard – endogenous hazard (H2) and outburst hazard – gas/coal/rock (H8). Similarly, as in the case of the direct influence analysis, rock burst hazard factors – tremors associated with underground damage (H4) and seismic hazard – tremors associated with surface damage (H3) were classified as influence variables (determine and environmental variables). The dust hazard – coal dust explosion (H5) variables were again included in the result variables, however, unlike the analysis of the direct influences, the roof fall hazard (H9) variable was classified as an autonomous variable with no major influence on the system. Other variables have no significant influence on the system under consideration.

Taking into account the indirect interrelationships (MIIs) between variables describing the level of exploitation hampering (Fig. 3b), it can be seen that the strongest influences occur

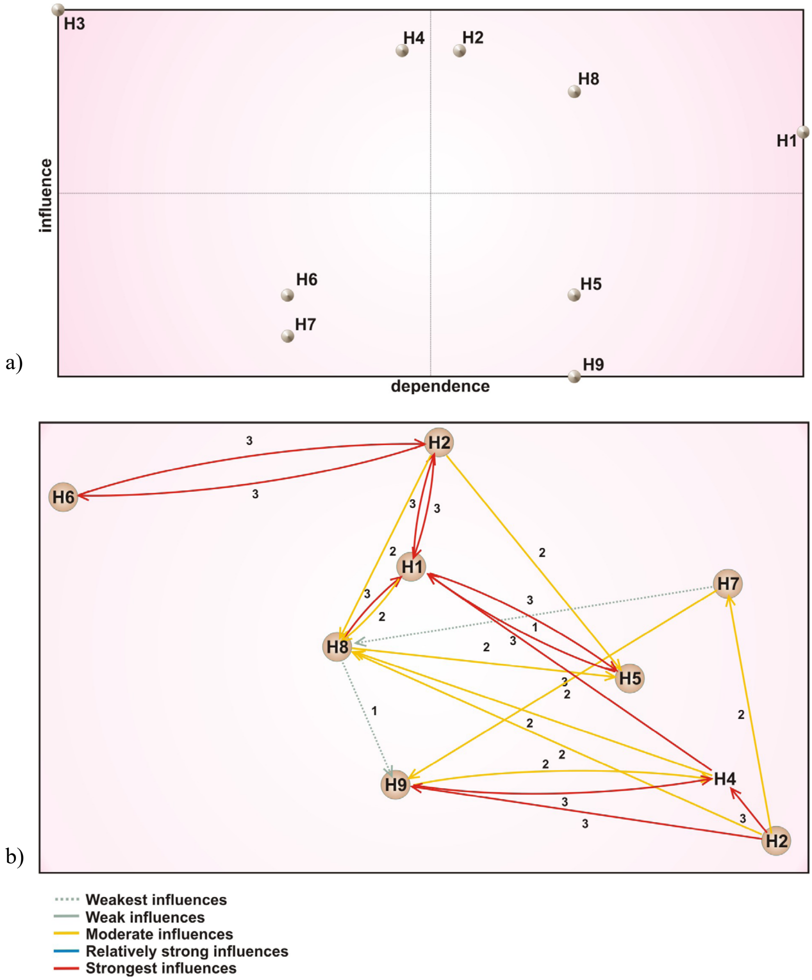

Fig. 2. Structural analysis of MDI of the level of exploitation hampering a) MDI direct influence/dependence map b) MDI direct influence graph

between the key variables of fire hazard – endogenous hazard (H2) and gas hazard – methane ignitions and explosions (H1).

3.1.2. Calculation from the Matrix of Potential Direct Influence (MPDI) and the Matrix of Potential Indirect Influence (MPII)

The structural analysis of the potential influences of direct variables (MPDI) which determine the level of exploitation hampering (Fig. 4a) showed that the most important, key and objective variables, are gas hazard – methane ignitions and explosions (H1) and outburst hazard – gas/coal/rock (H8). The group of variables which determines the system, i.e. influence variables

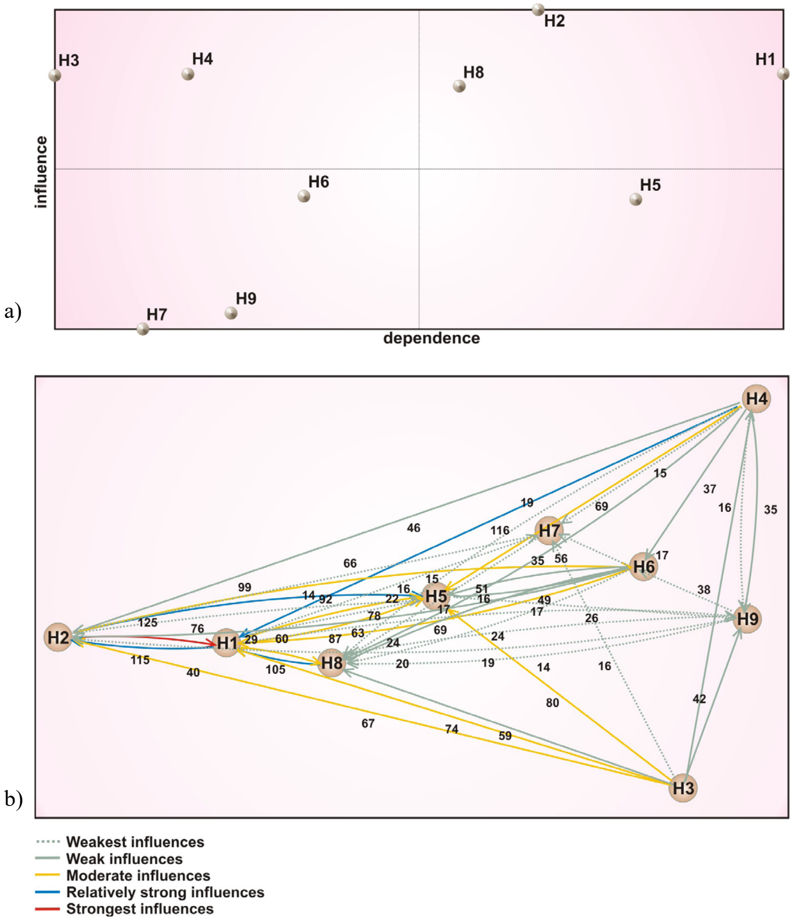

Fig. 3. Structural analysis of MII of the level of exploitation hampering a) MII indirect influence/dependence map b) MII indirect influence graph

(determine and environmental variables), includes fire hazard – endogenous hazard (H2), rock burst hazard – tremors associated with underground damage (H4) and seismic hazard – tremors associated with surface damage (H3). Dust hazard – coal dust explosion (H5) and roof fall hazard (H9) were included in the result variables. Other autonomous variables do not have a major influence on the system under consideration.

Taking into account the potential direct/indirect interrelationships (MPDIs) between variables determining the level of exploitation hampering (Fig. 4b), it can be seen that the strongest influences occur between the key variables: gas hazard – methane ignitions and explosions (H1) and fire hazard – endogenous hazard (H2), and the result factor dust hazard – coal dust explosion (H5) – which is the same as for the calculations made with the MDI method.

The structural analysis of the potential influence of indirect variables (MPII) which determine the level of exploitation hampering (Fig. 5a) showed that the key and objective variables are

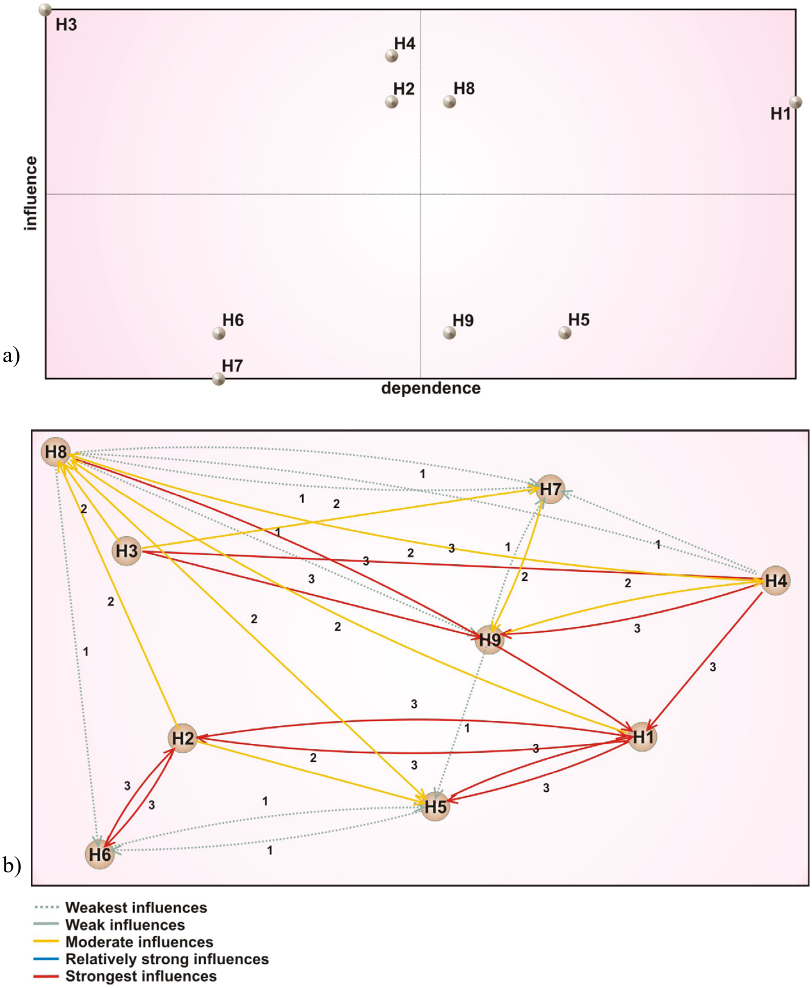

Fig. 4. Structural analysis of MPDI of factors determining the level of exploitation hampering a) MPDI potential direct influence/dependence map b) MPDI potential direct influence graph

gas hazard – methane ignitions and explosions (H1), and fire hazard – endogenous hazard (H2). The outburst hazard variable – gas/coal/rock (H8), similarly to the following: rock burst hazard – tremors associated with damage underground (H4) and seismic hazard – tremors associated with surface damage (H3), were classified as influence variables (determine and environmental variables). The dust hazard – coal dust explosion (H5) was classified as a result variable. Other variables do not have a significant influence on the system under consideration.

Taking into account the mutual potential indirect relationships (MPII) between the criteria determining the level of exploitation hampering (Fig. 5b), it can be seen that the strongest influences occur between the key variable, gas hazard – methane ignitions and explosions (H1), and the influence variable, rock burst hazard – tremors associated with damage underground (H4).

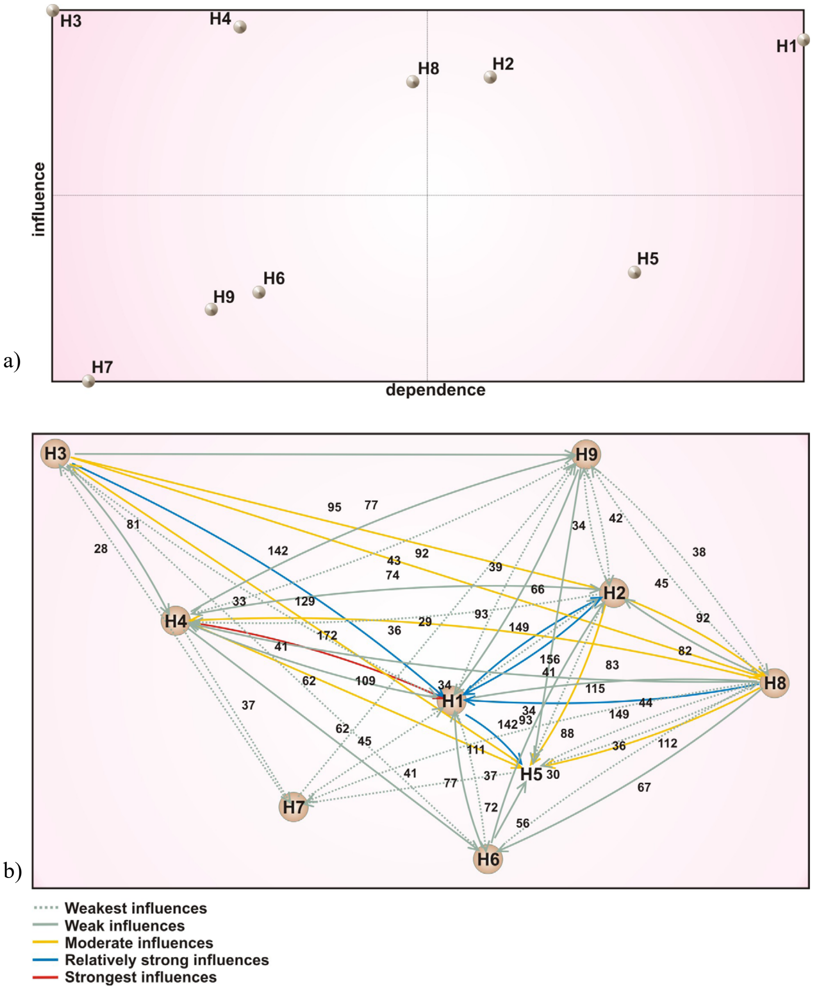

Fig. 5. Structural analysis of MPII of the level of exploitation hampering a) MPII potential indirect influence/dependence map b) MPII potential indirect influence graph

3.2. The variables defining the quality of resources and the level of their availability

The group of variables (criteria) determining the quality of resources and the level of their availability include the following variables: depth of exploitation (P1), the thickness of coal seams (P2), type of coal (coking, household, industrial, thermal, etc.) (P3), sulphur content in coal (P4), size of the mining area (P5), duration of the concession to exploit coal (P6), annual coal production (P7), amount of coal reserves (P8) and fault zones (P9).

3.2.1. Calculation from the Matrix of Direct Influence (MDI) and the Matrix of Indirect Influence (MII)

The structural analysis of the influence of the direct variables (MDI) which determine the quality of resources and the level of their availability (Fig. 6a) showed that the key and objective variables which are most important for the system are depth of exploitation (P1), annual coal production (P7) and amount of coal reserves (P8). The influence variables (determine and environmental variables) include the size of the mining area (P5). The variable of the duration of the concession to exploit coal (P6) was included in the result variables. Other variables classified as autonomous variables do not have a clear influence on the system under consideration.

Taking into account the direct interrelationships (MDI) between the variables which determine the quality of resources and the level of their availability (Fig. 6b), it can be seen that the

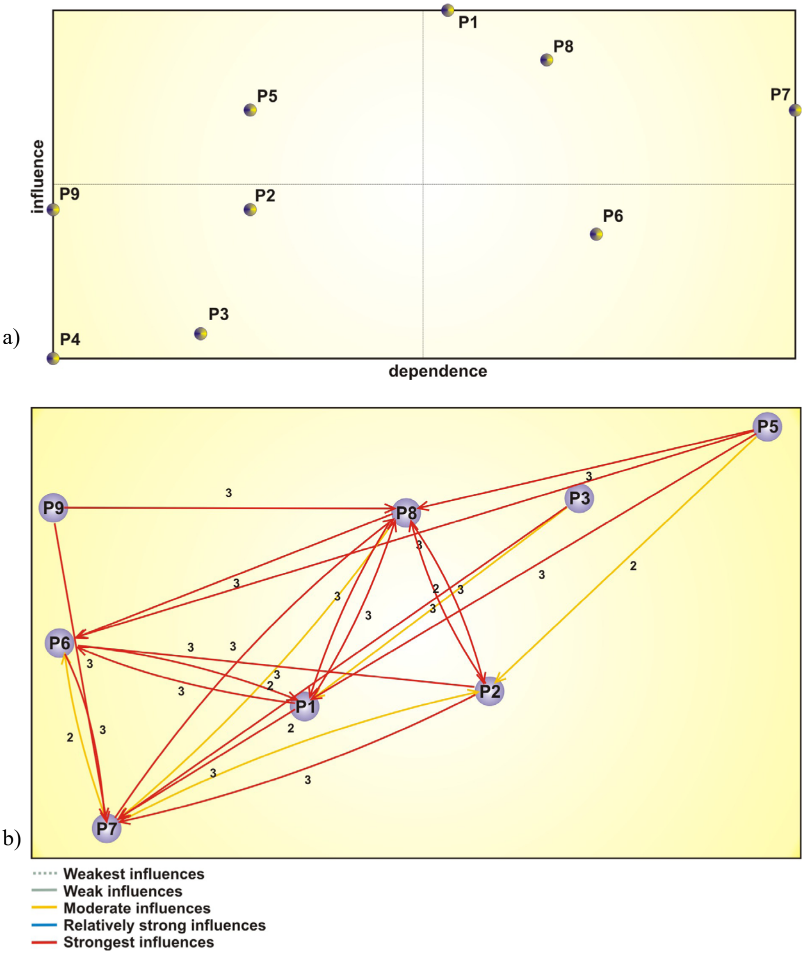

Fig. 6. Structural analysis of MDI of the quality of resources and the level of their availability a) MDI direct influence/dependence map b) MDI direct influence graph

strongest influences occur between the key variable, depth of exploitation (P1), and variables of the duration of the concession to exploit coal (P6) and the amount of coal reserves (P8).

The structural analysis of the influence of indirect variables (MII) which determine the quality of resources and the level of their availability (Fig. 7b) showed that the key and objective variables are depth of exploitation (P1), duration of the concession to exploit coal (P6), annual coal production (P7) and the amount of coal reserves (P8). The influence variables (determine and environmental variables) are the size of the mining area (P5), the thickness of coal seams (P2) and fault zones (P9). Other autonomous variables do not exert significant influence on the system under consideration.

By analysing interrelationships (MIIs) between the criteria determining the quality of resources and the level of their availability (Fig. 7b), it can be seen that the strongest influences occur between the key variables: depth of exploitation (P1) and the annual coal production (P7).

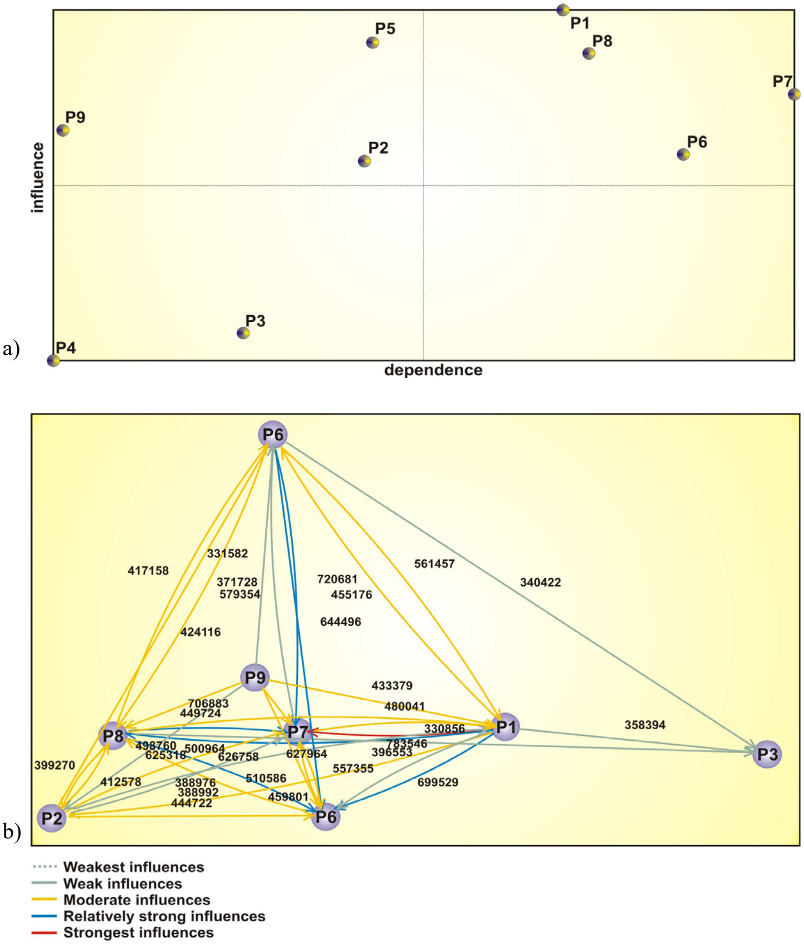

Fig. 7. Structural analysis of MII of the quality of resources and the level of their availability a) MII indirect influence/dependence map b) MII indirect influence graph

3.2.2. Calculation from the Matrix of Potential Direct Influence (MPDI) and the Matrix of Potential Indirect Influence (MPII)

The structural analysis of the potential influences of direct variables (MPDI) which determine the quality of resources and the level of their availability (Fig. 8a) showed that the key and objective variables are depth of exploitation (P1), duration of the concession to exploit coal (P6), annual coal production (P7) and the amount of coal reserves (P8). The size of the mining area (P5) was classified as an influence variable (determine variables). Other variables have no significant effect on the system under consideration.

Taking into account the mutual potential direct relationships (MPDI) between the variables determining the quality of resources and the level of their availability (Fig. 8b), it can be seen

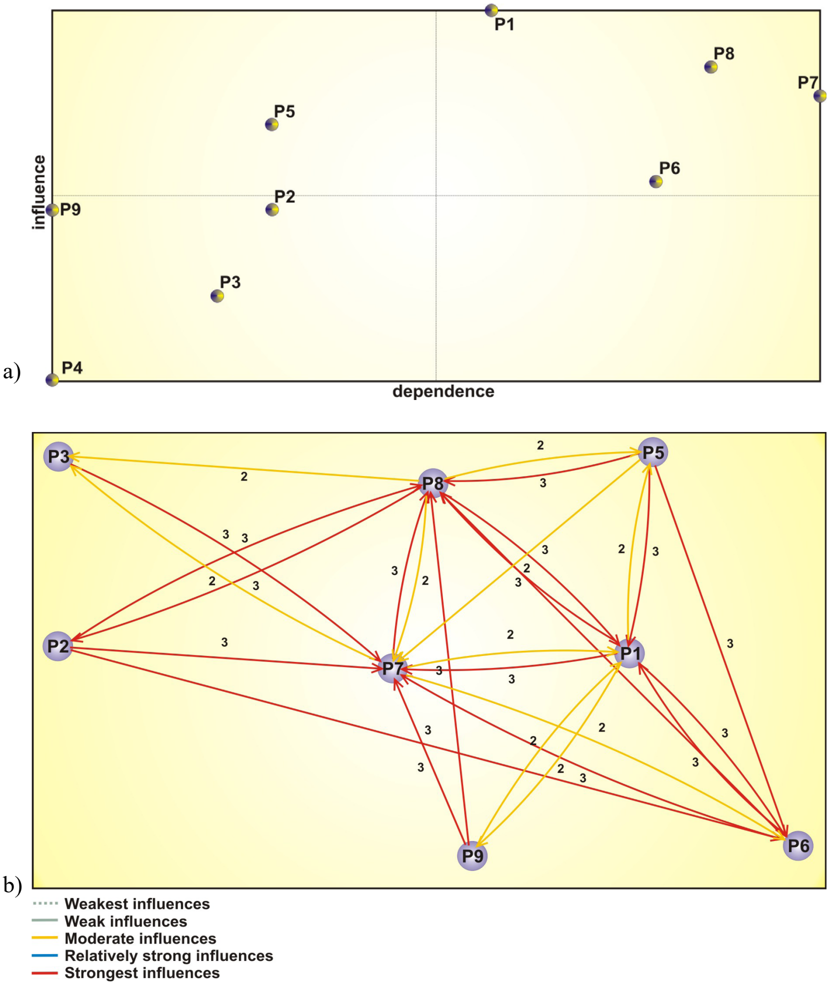

Fig. 8. Structural analysis of MPDI of the quality of resources and the level of their availability a) MPDI potential direct influence/dependence map b) MPDI potential direct influence graph

that the strongest influences occur between the key variable, depth of exploitation (P1), and the amount of coal reserves (P8) and the duration of the concession to exploit coal (P6).

The structural analysis of the potential influences of indirect variables (MPII) which determine the quality of resources and the level of their availability (Fig. 9a) showed that the key and objective variables are depth of exploitation (P1), duration of the concession to exploit coal (P6), annual coal production (P7) and the amount of coal reserves (P8). The influence variables (determine and environmental variables) included the size of the mining area (P5), the thickness of coal seams (P2) and fault zones (P9). Other variables do not have a significant influence on the system under consideration.

Taking into account the mutual potential indirect relationships (MPII) between variables which determine the quality of resources and the level of their availability (Fig. 9b), it can be

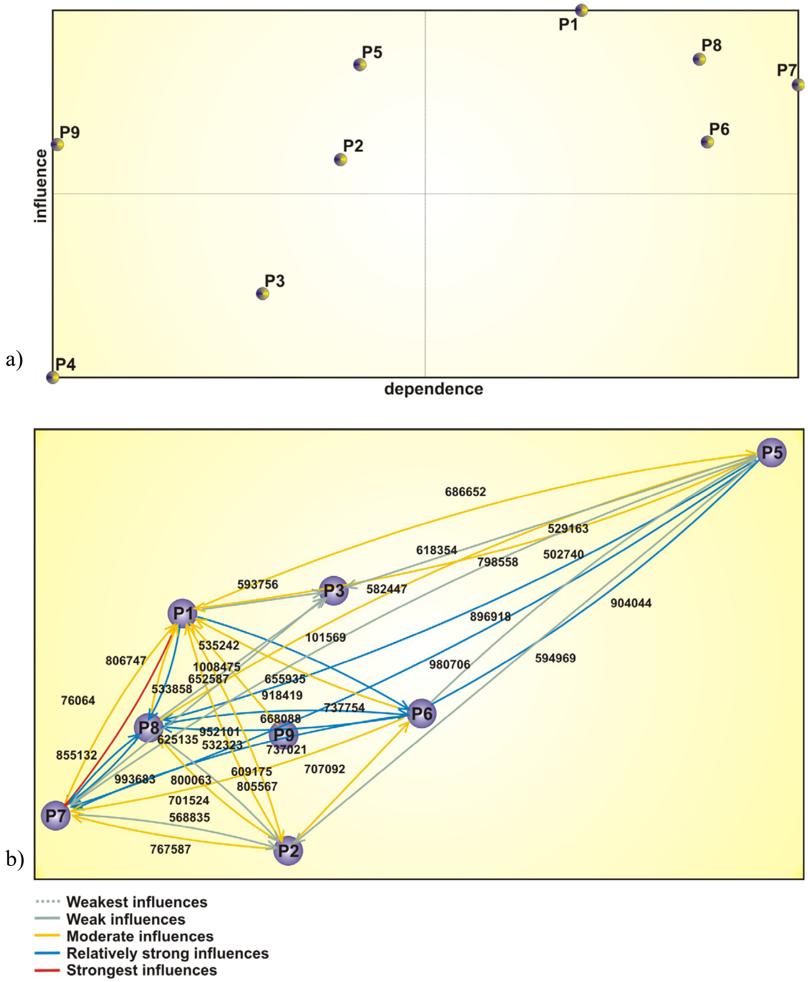

Fig. 9. Structural analysis of MPII of the quality of resources and the level of their availability a) MPII potential indirect influence/dependence map b) MPII potential indirect influence graph

seen that the strongest influences occur between the depth of exploitation (P1) and the annual coal production (P7).

4. Conclusions

The research carried out and the results obtained enabled the establishment of the relationship between:

- natural hazards affecting the level of exploitation hampering,
- geological and mining variables affecting the quality of hard coal and the level of its availability, occurring in hard coal mines, in terms of the potential assessment of the longevity of the active hard coal mines in the USCB area.

The criteria developed with the participation of experts from or related to the mining industry and based on survey results were the basis for the structural analysis of mutual influences determined by the MICMAC method.

The analysis for each of the two considered groups of variables was carried out using four methods:

- Matrix of Direct Influences (MDI).
- Matrix of Indirect Influences (MII).
- Matrix of Potential Direct Influences (MPDI).
- Matrix of Potential Indirect Influences (MPII).

It has been established that in terms of variables related to the level of exploitation hampering, the key and objective variables are gas hazard – methane ignitions and explosions (H1), fire hazard – endogenous hazard (H2) and outburst hazard – gas/coal/rock (H8). The influence variables, i.e. decisive variables exerting a great influence on the system (determine and environmental variables) are rock burst hazard – tremors associated with damage underground (H4) and seismic hazard – tremors associated with surface damage (H3). The result variables in the studied system are dust hazard – coal dust explosion (H5) and roof fall hazard (H9). Other variables have no significant effect on the system. The strongest mutual influence occurs between the key variables gas hazard – methane ignitions and explosions (H1) and fire hazard – endogenous hazard (H2).

It was established that in terms of the quality of resources and the level of their availability, the key and objective variables, i.e. the most important in the system, are depth of exploitation (P1), duration of the concession to exploit coal (P6), annual coal production (P7) and the amount of coal reserves (P8). The variables that have a strong influence on the system, i.e. the variables of influence (determine and environmental variables), are the size of the mining area (P5), the thickness of coal seams (P2) and fault zones (P9). Other variables have no significant effect on the system. The strongest mutual influences occur between the key variable, depth of exploitation (P1), and the duration of the concession to exploit coal (P6) and the amount of coal reserves (P8).

The obtained results indicate which variables will have a significant influence on determining the longevity of hard coal mines. This will enable the inclusion of hard coal mines in the assessment of longevity, in addition to the amount of resources and volume of extraction, as well as variables related to criteria describing the level of exploitation hampering and to criteria describing the quality of resources and the level of their availability.

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References

Ambrosio-Albalá M., Martín Lozano J.M., Pérez Hernández P.P., Martin-Lozano J.M., Perez-Hernández P.P., 2009. *Prospective Structural Analysis: An application to Rural Development Strategies*. 83rd Annual Conference of the Agricultural Economics Society, April, 1-17.

Bondaruk J., Janson E., Wysocka M., Chałupnik S., 2015. *Identification of hazards for water environment in the Upper Silesian Coal Basin caused by the discharge of salt mine water containing particularly harmful substances and radionuclides.* Journal of Sustainable Mining **14** (4), 179-187. https://doi.org/10.1016/j.jsm.2016.01.001

Bukowska M., 2012. *The rockbursts in the Upper Silesian Coal Basin in Poland.* Journal of Mining Science **48** (3), 445-456. https://doi.org/10.1134/S1062739148030070

Bukowska M., Gawryś J., 2010. *Właściwości fizyczne węgli GZW w aspekcie wyrzutów gazów i skał (Physical prosperities of coal in the USCB in the aspect of gas and rock outburst).* Górnictwo i Geoinżynieria **34** (2), 121-129.

Drzewiecki J., 2011. *Wpływ parametrów uskoku na zasięg jego oddziaływania (Influence of fault parameters on the range of its impact).* Górnictwo i Geoinżynieria **35** (11), 183-190.

Duperrin J.C., Godet M., 1973. *Methode de hierarchisation des elements d'un systeme (Method for hierarchizing the elements of a system)*. Raport CEA-R-4541, 41-45.

Duperrin J.C., Godet M., 1975. *SMIC 74-a method for constructing and ranking scenarios.* Futures **7** (4), 302-312.

Düzgün H.S.B., 2005. *Analysis of roof fall hazards and risk assessment for Zonguldak coal basin underground mines*. International Journal of Coal Geology **64** (1-2), 104-115. https://doi.org/10.1016/j.coal.2005.03.008

Frejowski A., Koteras A., 2016. *Kryteria warunków lokalizacji georeaktora PZW w górotworze karbońskim naruszonym eksploatacją górniczą (Criteria for location conditions of UCG generator in the Carboniferous rockmass disturbed by mining operations).* Wiadomości Górnicze **67** (1), 29-38.

Gogolewska A., 2011. *Analiza zagrożenia wyrzutami gazów i skał w złożu węgla kamiennego w niecce wałbrzyskiej z zastosowaniem narzędzi GIS (Analysis of gas and rock outburst hazard in coal deposit within Wałbrzych Coal Nasin using GIS tools).* Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej **133** (40), 49-73.

JORC Code (Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. Australia.). (2012). http://www.jorc.org.

Jureczka J., Galos K., 2007. *Niektóre aspekty ponownego zagospodarowania zlikwidowanych kopalń węgla kamiennego w Górnoślaskim Zagłebiu Węglowym (Some aspects of redevelopment of selected hard coal deposits of closed mines in the USCB)*. Polityka Energetyczna **10** (2), 645-662.

Kabiesz J., 2002. *Współwystępowanie i wzajemne oddziaływanie naturalnych zagrożeń górniczych.* Prace Naukowe GIG Górnictwo i Srodowisko **1**, 35-53.

Kabiesz J., 2018. Raport roczny o stanie podstawowych zagrożeń naturalnych i technicznych w górnictwie węgla kamiennego (Annual report on the state of basic natural and technical hazards in hard coal mining).

Kędzior S., Dreger M., 2019. *Methane occurrence, emissions and hazards in the Upper Silesian Coal Basin, Poland.* International Journal of Coal Geology, 211 (June), 103226. https://doi.org/10.1016/j.coal.2019.103226

Knechtel J.,. 2007. *Przewidywane zagrożenie klimatyczne w kopalniach i związane z tym zapotrzebowanie na moc chłodniczą (Foreseen climatic hazard in mines and associated cooling power demand).* Prace Naukowe GIG Górnictwo i Srodowisko **1**, 59-70.

Konopko W., 2010. *Warunki bezpiecznej eksploatacji pokładów węgla zagrożonych metanem, tąpaniami i pożarami endogenicznymi (Conditions for the safe exploitation of coal seams endangered by methane, rock bursts and endogenous fires.* Wydawnictwo GIG Katowice.

Kordos J., 2019. *Tests of new method of monitoring endogenous fire hazard in hard coal mines. J*ournal of Sustainable Mining **18** (3), 134-141. https://doi.org/10.1016/j.jsm.2019.04.002

Krause E., Krzemień K., 2014. *Methane Risk Assessment in Underground Mines by Means of a Survey by the Panel of Experts (Sope).* Journal of Sustainable Mining **13** (2), 6-13. https://doi.org/10.7424/jsm140202

Krzemień S., 1991. *Systemowo-informacyjne modele oceny stanu zagrożenia wstrząsami górniczymi w kopalniach węgla kamiennego (System-information models for assessing the state of mining tremors hazards in hard coal mines).* Zeszyty Naukowe Politechniki Sląskiej, Seria Górnictwo (198).

Lutyński A., Blaschke W., 2011. *Czynniki wpływające na rozwój innowacyjnych technologii zagospodarowania odpadów pochodzących z górnictwa węgla kamiennego (Factors with impact on development of innovative hard coal waste disposal technologies).* Górnictwo i Geologia **6** (2), 95-107.

Mani V., Agrawal R., Sharma V., 2016. *Impediments to Social Sustainability Adoption in the Supply Chain: An ISM and MICMAC Analysis in Indian Manufacturing Industries.* Global Journal of Flexible Systems Management **17** (2), 135-156. https://doi.org/10.1007/s40171-015-0106-0

Marcisz M., 2017. S*topień zuskokowania złóż węgla kamiennego Górnośląskiego Zagłębia Węglowego (Degree of faulting of hard coal deposit of USCB).* Gospodarka Surowcami Mineralnymi / Mineral Resources Management **33** (2), 97-112. https://doi.org/10.1515/gospo-2017-0013

Nieć M., Salamon E., 2016. *Zmiany zasobów paliw kopalnych (kopalin energetycznych) w Polsce w ostatnim półwieczu.* Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk **96**, 201-228.

Niedbalska K., Bukowski P., Szczepański A., 2015. S*tan zagrożeń wodnych w kopalniach węgla kamiennego w związku z ich restrukturyzacją (State of water hazard in hard coal mines in connection with their restructuring).* Przegląd Geologiczny **63** (10), 616-621.

Patyńska R., Stec K., 2017. *Aktywność sejsmiczna Górnosląskiego Zagłebia Węglowego a zagrożenie tąpaniami w latach 2001-2015 (The seismic activity of mines in the USCB and rockburst hazard in the years 2001-2015).* Zeszyty Naukowe – Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN **97**, 135-144.

Probierz K., 2015. *Górnictwo węgla kamiennego w Polsce u progu 2015 roku, szanse i zagrożenia (Polish coal mining in 2015 – opportunities and threats).* Przegląd Górniczy **4**, 22-37.

Prostański D., 2013. U*se of Air-and-Water Spraying Systems for Improving Dust Control in Mines*. Journal of Sustainable Mining **12** (2), 29-34. https://doi.org/10.7424/jsm130204

Saługa P.W., Sobczyk E.J., Kicki J., 2015. *Wykazywanie zasobów węgla kamiennego w polsce zgodnie z JORC code (Reporting of hard coal reserves and resources in Poland on the basis of the JORC code).* Gospodarka Surowcami Mineralnymi / Mineral Resources Management **31** (2), 5-30. https://doi.org/10.1515/gospo-2015-0019

Sobczyk E.J., Kicki J., Jarosz J., 2016. *Gospodarka zasobami złóż węgla kamiennego w Polsce w latach 1990-2015 (The management of hard coal reserves in Poland in the years 1990-2015).* Zeszyty Naukowe – Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN **92**, 37-56.

Sobczyk E.J., Nieć M., 2017. *Praktyczne zastosowanie zasad kodeksu JORC na przykładzie polskich złóz węgla kamiennego (Practical application of JORC code – polish bituminous coal deposit case history)*. Górnictwo Odkrywkowe **4**, 61-67.

Srivastava S., Dubey R., 2014. Supply Chain Skill Gap Modelling using Interpretive. 2007.

Trenczek S., Mann R., Krause E., 2019. *Mining the sparking rocks in the context of most frequent cases of methane ignition.* New Trends in Production Engineering **2** (1), 460-471. https://doi.org/10.2478/ntpe-2019-0049

Turek M., Laskowska E., Mitko K., Jakóbik-Kolon A., 2018. *Mało energochłonna utylizacja zasolonych wód kopalnianych w zintegrowanym systemie membranowo – wyparnym (Low energy utilization of mine saline water in the integrated membrane-evaporative system).* Maszyny Górnicze **1**, 39-48.

Villacorta P.J., Masegosa A.D., Castellanos D., Lamata M.T., 2012. *A Linguistic Approach to Structural Analysis in Prospective Studies*. In Advances on Computational Intelligence (pp. 150-159).