Analysis of the similarity of hard coal mines in terms of the number of dangerous incidents caused by the activation of natural hazards

doi:10.2478/mape-2019-0009
Date of submission to the Editor: 04/2018
Date of acceptance by the Editor: 07/2018
MAPE 2019, volume 2, issue 1, pp. 91-100

Magdalena Tutak*
ORCID ID: 0000-0003-4781-8697
Silesian University of Technology, **Poland**

INTRODUCTION

Due to a series of inherent hazards, underground mining exploitation is very dangerous. These hazards affect the safety level in the underground headings of hard coal mines and the unit costs of the exploitation process (Brodny, 2010; Brodny, 2011; Burtan et al., 2017; Korban, 2015; Tutak, 2017).

The majority of hazards related to underground hard coal exploitation are catastrophic in nature (Brodny and Tutak, 2016a; Brodny and Tutak 2016b; Brodny and Tutak 2016c; Brodny and Tutak, 2018, Brodny et al., 2018). Once they are activated in an underground mine heading, the consequences are, more often than not, extremely tragic. This particularly concerns the life and health of mine workers. It must also be stressed that, for mining enterprises, such incidents result in work stoppages, the necessity to isolate exploitation areas and many other inconveniences, which have a very negative impact on the effectiveness of mining operations (Brodny et al., 2018; Brodny et al., 2017; Burtan et al., 2017; Korban, 2015).

The most common natural hazards that affect hard coal mines in Poland include the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks (Brodny et al., 2018; Tutak and Brodny, 2018a; Tutak and Brodny, 2018b; Tutak and Brodny, 2017a; Tutak and Brodny, 2017b).

In recent years, despite the reduction of mining output, the prevalence rate of dangerous incidents related to the activation of natural hazards remains very high. In the years 2008–2018, there was a total of 150 dangerous incidents caused by the occurrence of these hazards in underground headings of hard coal mines (WUG, 2008-2018). A summary of dangerous incidents resulting from natural hazards in the years 2008-2018 in Polish coal mines and mining enterprises is presented in Figure 1.

Taking into consideration the prevalence of natural hazards in hard coal mines and their extremely negative consequences, it is necessary to conduct analyses and research aimed at identifying the most dangerous enterprises where such hazards are activated most frequently.

* magdalena.tutak@polsl.pl

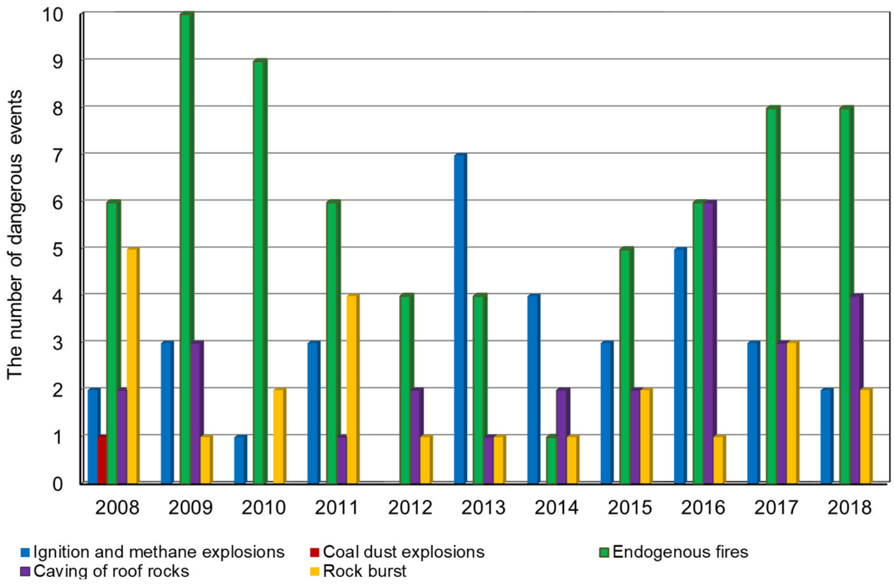

Fig. 1 A summary of dangerous incidents resulting from natural hazards in the years 2008-2018 in Polish mines and mining enterprises

No analysis has been carried out so far to identify homogenous mines in terms of the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks. However, such measures seem reasonable to improve the work safety in mines. This is because it allows for developing a common scope of preventive measures and exchanging experiences between the particular enterprises. This, in turn, may contribute to the improvement of safety and effectiveness of the entire process of mining production – a process that – despite its negative environmental footprint – for many countries, including Poland, represents a very important source of a relatively cheap energy necessary for further development.
The article presents the results of a taxonomic analysis aimed at determining the similarity of hard coal mines and mining enterprises in Poland in terms of the dangerous incidents caused by the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks. The analysis was carried out for the 2008-2018 data and encompassed a total of 26 hard coal mines and mining enterprises located in the Upper Silesian Coal Basin.
The analysis was performed using the *k*-means method of non-hierarchical clustering. The main objective of the article was to determine homogenous groups (clusters) of mines exhibiting the greatest similarity in terms of dangerous incidents caused by the activation of natural hazards in the years 2008-2018.

METHODOLOGY OF RESEARCH

The analysis of the similarity level of hard coal mines in Poland in terms of the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks was carried out using the data from the statistics by the State Mining Authority (Wyższy Urząd Górniczy) (WUG.2008-2018). The classification analysis encompassed a total of 26 hard coal mines and mining enterprises, which were involved in exploitation activities in the years 2008-2018. It should be emphasised that the restructuring measures in the period under analysis led to the merging of mines into single mining plants. Therefore, the analysis in question took into consideration the statistical data for the already merged mines (if a dangerous incident had occurred, for example in KWK Ziemowit before it was merged with KWK Piast, the analysis was performed for the name of the mine after merging, i.e. KWK Piast-Ziemowit).

The values of the coefficients adopted for the analysis, determining a quantitative summary of the dangerous incidents occurring due to the activation of natural hazards in the particular mines, are summarised in Table 1. The variation coefficients for these data were also calculated.

The set of variables presented in Table 1 is characterised by a large spread of the variation coefficient – from 98.55% to 509.90%.

Table 1
A quantitative summary of the dangerous incidents occurring due to the activation of natural hazards in the particular mines

Coal mine/mining enterprises	Ignition and methane explosions	Coal dust explosions	Endogenous fires	Caving of roof rocks	Rock burst
KWK RUDA Ruch Bielszowice	2	0	6	3	3
KWK Budryk	2	0	0	3	0
KWK RUDA Ruch Halemba	1	0	2	3	2
KWK Knurów-Szczygłowice	1	0	4	0	0
KWK Sośnica	3	0	2	0	0
KWK RUDA RUCH Pokój	0	0	0		0
KWK Bolesław Śmiały	0	0	0	1	0
ZG Brzeszcze	2	0	1	0	0
KWK Silesia	0	0	0	0	0
KWK Murcki-Staszic	6	0	10	1	2
KWK Mysłowice-Wesoła	4	1	8	2	4
KWK Wujek	1	0	2	0	2
KWK Wieczorek	0	0	3	3	0
KWK ROW Ruch Rydułtowy	0	0	3	0	1
KWK ROW Ruch Chwałowice	1	0	1	0	0
KWK ROW Ruch Jankowice	0	0	2	0	0
KWK ROW Ruch Marcel	0	0	1	0	2
KWK Pniówek	0	0	2	3	0
KWK Krupiński	2	0	0	0	0
KWK Rydułtowy-Anna	2	0	0	0	2
KWK Piast-Ziemowit	0	0	3	3	0
ZG Janina	0	0	2	0	0
ZG Sobieski	0	0	5	0	0
KWK Kazimierz-Juliusz	0	0	2	0	0
KWK Bobrek-Piekary	0	0	4	2	2
Average	1.23	0.04	2.54	1.04	0.88
Standard deviation	1.68	0.20	2.50	1.31	1.24
Coefficient of variation, %	136.55	509.90	98.55	125.61	140.56

Source: Own study based on WUG, 2008-2018.

The highest value of this coefficient is manifested by the variable of coal dust explosion, because in the years 2008-2018, all the mines and mining enterprises under analysis experienced one dangerous incident caused by the activation of this hazard. The lowest value of the variation coefficient is assumed by the variable of endogenous fires – 98.55%, which is due to the fact that there was the greatest number of dangerous incidents related to the activation of this hazard during the analysis period. It can therefore be assumed that the variables presented in Table 1 meet the requirement of diagnostic features which must demonstrate significant variations.

One of the methods for grouping mines in terms of their similarity concerning dangerous incidents related to the activation of natural hazards is the *k*-means method of non-hierarchical clustering.

The *k*-means algorithm tries to find the objective function extreme value, which is defined by the following relationship (Everitt, 2011):

$$J = \sum_{i=1}^{k} \sum_{d_t \in D_i} sim(c_i, d_t) \qquad (1)$$

where:

c is centroid of the set of objects “*D*”.

The algorithm of the research procedure consists of the following seven stages:

1. A priori determination of the number of concentrations (*K*).
2. Assignment of measurement samples to the particular clusters on the basis of the determined Euclidean distances d_{ij} of the individual samples P_i from the clusters' centres m_i:

$$d_{ij} = \|x_j - m_i\| = \sqrt{\sum_{l=1}^{k} (x_{lj} - m_{xlj})^2} \qquad (2)$$

3. Determination of new clusters' centres using the cumulative method is performed on the basis of the relationship:

$$m_{xl,i}(1) = \frac{1}{N_i} \sum_{j=1}^{N_i} x_{lj}\,(0) \qquad (3)$$

4. Determination of cluster shifts Δm:

$$\Delta m = \|m_i(0) - m_i(1)\| \qquad (4)$$

5. Assignment of measurement samples to new clusters
6. Determination of new clusters' centres.

The research algorithm is presented in Figure 2.

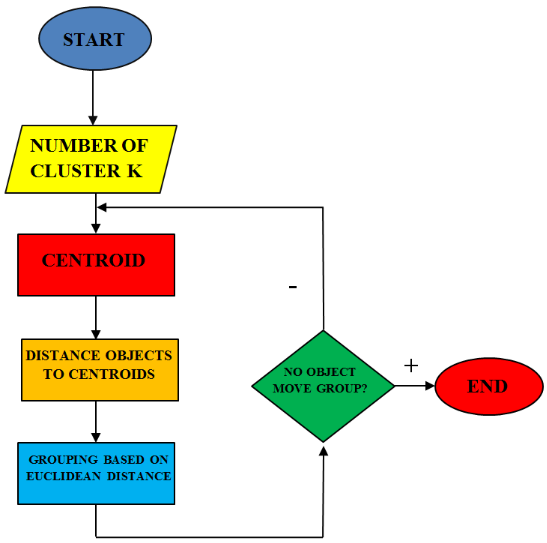

Fig. 2 Procedure algorithm in the k-means method

Source: (Brodny and Tutak, 2019).

RESULTS AND DISCUSSION

The *k*-menas method used for the analysis requires an a priori assumption of the number of clusters to which the mines and mining enterprises will be assigned.

The number of clusters adopted for further analysis was determined from the equation (Kijewska & Bluszcz, 2016; Mardia et al., 1979):

$$k \cong \sqrt{\frac{n}{2}} \tag{5}$$

where:

n is number of cases (coal mines/mining enterprises).

The preliminary grouping using Ward's method (hierarchical clustering), carried out in order to verify the number of clusters determined from equation (5), confirmed that further analysis using the k-average method should be conducted for four (4) clusters. The first centres of the clusters, to which the mines and mining enterprises were assigned, were determined on the basis of distance sorting. The resulting groups and the distances from the clusters' centres are presented in Table 2.

Table 2
Elements of clusters with distances form centres

Cluster 1 and distance from centre of cluster 1	Cluster 2 and distance from centre of cluster 2	Cluster 3 and distance from centre of cluster 3	Cluster 4 and distance from centre of cluster 4
KWK Murcki-Staszic (0.836660)	KWK Budryk (1.223232)	KWK RUDA Ruch Bielszowice (1.459662)	KWK Knurów-Szczygłowice (0.6324555)
KWK Mysłowice-Wesoła (0.83666)	KWK Sośnica (1.025598)	KWK RUDA Ruch Halemba (0.6452337)	KWK Wujek (0.8618916)
	KWK Bolesław Śmiały (0.7200823)	KWK Wieczorek (0.837879)	KWK ROW Ruch Rydułtowy (0.29277)
	ZG Brzeszcze (0.45542)	KWK Borynia-Zofiówka-Jastrzębie (1.894137)	KWK ROW Ruch Jankowice (0.4472136)
	KWK Silesia (0.704483)	KWK Pniówek (1.00813)	ZG Janina (0.4472136)
	KWK ROW Ruch Chwałowice (0.3751543)	KWK Piast-Ziemowit (0.8378788)	ZG Sobieski (0.9856108)
	KWK ROW Ruch Marcel (0.9583937)	KWK Bobrek-Piekary (0.728431)	KWK Kazimierz-Juliusz (0.4472136)
	KWK Krupiński (0.479197)		
	KWK Rydułtowy-Anna (0.821020)		

The most similar mines in terms of the number of dangerous incidents caused by the activation of natural hazards are those in cluster 1 (KWK Murcki-Staszic and KWK Mysłowice-Wesoła), because their distances from the cluster's centre have almost the same values. On the other hand, the enterprises in cluster 3 exhibit the greatest differences between each other because they have the greatest distances from the centre of the cluster which they were assigned to.

The descriptive statistics for the number of dangerous incidents related to the activation of natural hazards in the mines and mining enterprises assigned to the particular clusters for the period under analysis are presented in Table 3.

Table 3
Descriptive statistics of clusters on the basis data

Cluster 1 – 2 objects	Sum	Mean	Standard deviation	Variance
Ignition and methane explosions	10	5	1.414214	2
Coal dust explosions	1	0.5	0.7071068	0.5
Endogenous fires	18	9	1.414214	2
Caving of roof rocks	3	1.5	0.7071068	0.5
Rock burst	6	3	1.414214	2
Cluster 2 – 9 objects				
Ignition and methane explosions	15	1.333333	1.118034	1.25
Coal dust explosions	0	0	0	0
Endogenous fires	5	0.5555556	0.7264832	0.5277778
Caving of roof rocks	4	0.4444444	1.013794	1.027778
Rock burst	4	0.4444444	0.8819171	0.7777778
Cluster 3 – 7 objects				
Ignition and methane explosions	8	1.142857	1.864455	3.476191
Coal dust explosions	0	0	0	0
Endogenous fires	23	3.285714	1.380131	1.904762
Caving of roof rocks	19	2.714286	0.48795	0.2380952
Rock burst	10	1.428571	1.397276	1.952381
Cluster 4 -7 objects				
Ignition and methane explosions	2	0.2857143	0.48795	0.2380952
Coal dust explosions	0	0	0	0
Endogenous fires	20	2.857143	1.214986	1.47619
Caving of roof rocks	0	0	0	0
Rock burst	3	0.4285714	0.7867958	0.6190476

The results presented in Table 3 show unequivocally that the highest number of dangerous incidents related to the activation of natural hazards in underground hard coal mines and mining enterprises in the years 2008-2018 occurred in the mines assigned to cluster 3, which encompassed 7 mines and mining enterprises (KWK RUDA Ruch Bielszowice, KWK RUDA Ruch Halemba, KWK Wieczorek, KWK Borynia-Zofiówka-Jastrzębie, KWK Pniówek, KWK Piast-Ziemowit and KWK Bobrek-Piekary). In the years 2008-2018, those mines experienced a total of 60 dangerous incidents caused by the activation of natural hazards. The lowest number of such incidents during the analysis period occurred in the mines/mining enterprises assigned to cluster 4 (KWK Knurów-Szczygłowice, KWK Wujek, KWK ROW Ruch Rydułtowy, KWK ROW Ruch Jankowice, ZG Janina, ZG Sobieski and KWK Kazimierz-Juliusz). Within the period under analysis, these enterprises experienced 25 dangerous incidents related to natural hazards.

Table 4 also presents the measures of intra-cluster and inter-cluster diversity of the variables , along with the degrees of freedom (df). The F statistics, being the ratio of variance amongst the clusters to the variance within the clusters, make it possible to identify variables in terms of their discriminatory power.

The variance analysis indicated that the greatest role in assigning the mines and mining enterprises to the particular clusters was played by the variable specifying the number of endogenous fires ($F = 32.55$). The least important for this division was the rock burst variable, for which the F value amounted to only 4.20. In Table 5 there are presented information on the Euclidean distance between clusters centers.

Table 4
Analysis of variance

	Between SS	df	Inside SS	df	F	Significance p
Ignition and methane explosions	34.75428	3	34.28572	21	7.10	0.001797918
Coal dust explosions	0.46	3	0.5	21	6.44	0.002903712
Endogenous fires	123.2521	3	26.50794	21	32.55	0.00000004401333
Caving of roof rocks	30.80921	3	10.15079	21	21.25	0.000001448154
Rock burst	14.18921	3	23.65079	21	4.20	0,01781117

Table 5
Euclidean distances of clusters (under the diagonal) and squares of distance (above the diagonal

Numer of clusters	No 1	No 2	No 3	No 4
No 1	0	18.52963	10.3449	13.81429
No 2	4.304605	0	2.722147	1.318518
No 3	3.216349	1.649893	0	1.857143
No 4	3.716757	1.148268	1.36277	0

Figure 3 presents the graphs of average values for each cluster for the dangerous incidents under analysis.

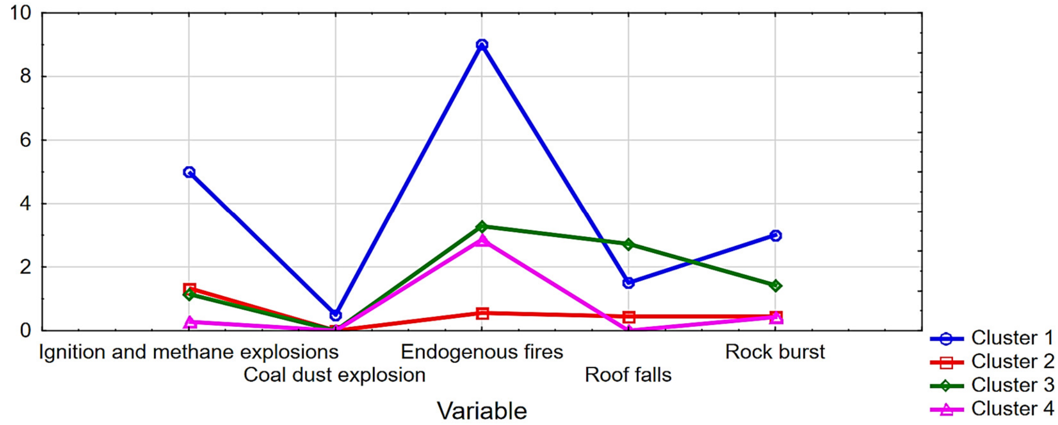

Fig. 3 Average values for each cluster for the dangerous incidents under analysis

CONCLUSION

The Polish hard coal mining is characterised by the occurrence of all natural hazards (also referred to as catastrophic hazards) that are typical of underground hard coal exploitation. The activation of these hazards leads to dangerous incidents which are frequently responsible for serious mining catastrophes, causing accidents at work, failures, and stoppages of hard coal production.

The results of the taxonomic analysis presented in the paper were intended to determine the similarity of the hard coal mines and mining enterprises in Poland in terms of the dangerous incidents caused by various types of hazards. The paper examines all the most significant hazards in this regard, i.e. the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks.

The analysis was carried out for the 2008-2018 data and encompassed a total of 26 hard coal mines and mining enterprises located in the Upper Silesian Coal Basin. The analysis was performed using the *k*-means method of non-hierarchical clustering.
The results of the analysis assigned the mines and mining enterprises to 4 clusters. Each cluster contains mines that exhibit the highest similarity to each other in terms of the number of dangerous incidents caused by the activation of natural hazards. At the same time, the mines/mining enterprises within one cluster differred significantly from those assigned to the other clusters.
Based on the analyses and their results, it can be concluded that the number of dangerous incidents related to the activation of natural hazards is of a diverse nature. Their highest incidence in the years 2008-2018 was reported in the mines assigned to cluster 3, while the lowest – in those from cluster 4.
The results indicate which mines/mining enterprises exhibit the highest similarity to each other in terms of the dangerous incidents related to the activation of natural hazards. The analysis revealed that the greatest similarity was exhibited by territorially neighbouring mines, such as KWK Murcki-Staszic and KWK Myslowice-Wesoła. During the analysis period, these mines experienced a very similar number of dangerous incidents related to natural hazards. At the same time, the analysis demonstrates how significant the issue of work safety in Polish mines is. The natural hazards occurring in mines make the process of mining production in underground headings extremely dangerous and totally different from the production in other industries.
It is therefore reasonable to conduct research and analyses aimed at improving the safety level of this production and its effectiveness. Despite the ongoing changes, hard coal continues to be the main energy resource in many countries. Coking coal, on the other hand, is the basic raw material for the metallurgic industry, which is also very important for the global economy.

ACKNOWLEDGEMENTS

This research was funded by Ministry of Science and Higher Education, grant number 06/030/BKM_18/0041 and The Silesian University of Technology, grant number 06/030/RGJ18/0028 (Rector's Grants in Research and Development).

REFEENCES

Brodny, J. (2010). Determining the working characteristic of a friction joint in a yielding support. Arch. Min. Sci., 55(4), pp. 733-746.
Brodny, J. (2011). Tests of Friction Joints in Mining Yielding Supports Under Dynamic Load. Arch. Min. Sci., 56(2), pp. 303-318.
Brodny, J. and Tutak, M. (2016a). Analysis of methane emission into the atmosphere as a result of mining activity. Proceedings of 16th International Multidisciplinary Scientific GeoConference SGEM 2016, DOI: 10.5593/SGEM2016/HB43/S06.012.
Brodny, J. and Tutak, M. (2016b). Analysis of gases emitted into the atmosphere during an endogenous fire. Proceedings of 16th International Multidisciplinary Scientific GeoConference SGEM 2016, pp. 75-82. DOI: 10.5593/SGEM2016/HB43/S06.011.
Brodny, J. and Tutak, M. (2016c). The impact of the flow volume flow ventilation to the location of the special hazard spontaneous fire zone in goaf with caving of operating longwalls. 16th Proceedings of International Multidisciplinary Scientific GeoConference SGEM 2016, pp. 897-904. DOI:10.5593/SGEM2016/B12/S03.115.
Brodny, J., Krystek, J., Alszer, S. and Tutak, M.: (2017). Availability analysis of selected mining machinery. Arch. Control Sci., 27(2), pp. 197-201.

Brodny, J. and Tutak, M. (2018). Analysis of methane hazard conditions in mine headings. Tehnički vjesnik/Technical Gazette, 25(1), pp. 271-276. DOI:10.17559/TV-20160322194812.
Brodny, J., Tutak, M. and John, A. (2018). Analysis of Influence of Types of Rocks Forming the Goaf with Caving on the Physical Parameters of Air Stream Flowing Through These Gob and Adjacent Headings. Mechanics, 24, pp. 43-49.
Brodny, J. and Tutak, M. (2019). Analysis of the diversity in emissions of selected gaseous and particulate pollutants in the European Union countries. Journal of Environmental Management, 231, pp. 582-595.
Burtan, Z., Stasica, J. and Rak Z. (2017). Wpływ katastrofogennych zagrożeń naturalnych na bezpieczeństwo pracy w górnictwie węgla kamiennego w latach 2000-2016. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, 101, pp. 7-18.
Everitt, B.S., Landau, S., Leese M. and Stahl, D. (2011). Cluster Analysis. Wiley, London.
Kijewska, A. and Bluszcz, A. (2016). Research of varying levels of greenhouse gas emissions in European countries using the k-means method. Atmos. Pollut. Res., 7(5), pp. 935-944.
Korban, Z. (2015). Quality assessment of occupational health and safety management at the level of business units making up the organizational structure of a coal mine: a case study. Int. J. Occup. Saf. Ergon., 21(3), pp. 373-381.
Mardia, K.V., Kent, J.T. and Bibby, J.M. (1979). Multivariate Analysis. Probability and Mathematical Statistics. Academic Press.
Tutak, M. and Brodny, J. (2017a): Analysis of Influence of Goaf Sealing from Tailgate On the Me-thane Concentration at the Outlet from the Longwall. IOP Conf. Series: Earth and Environmental Science 95 042025 DOI:10.1088/1755-1315/95/4/042025.
Tutak, M. and Brodny, J. (2017b): Determination of Particular Endogenous Fires Hazard Zones in Goaf with Caving of Longwall. IOP Conf. Series: Earth and Environmental Science 95 (2017) 042026 DOI:10.1088/1755-1315/95/4/042026.
Tutak, M. (2017). Assessment of hydrodynamics of gas flow through the porous rock structures. Proceedings of 17th International Multidisciplinary Scientific GeoConference SGEM 201717 Vienna GREEN, 17(15) pp.53-60.DOI: 10.5593/sgem2017H/15/S06.007.
Tutak, M. and Brodny, J. (2018a). Analysis of the impact of auxiliary ventilation equipment on the distribution and concentration of methane in the tailgate. Energies, 11(11), pp. 1-28. DOI:10.3390/en11113076.
Tutak, M. and Brodny, J. (2018b). Impact of type of the roof rocks on location and range of endogenous fires particular hazard zone by in goaf with caving. E3S Web Conferences Volume 29. DOI:10.1051/e3sconf/20182900005.
Wyższy Urząd Górniczy, (2008-2018). Niebezpieczne zdarzenia, Available at: http://www.wug.gov.pl/bhp/zdarzenia [Accessed 1 May 2019].

Abstract. Hard coal mines and mining enterprises involved in hard coal exploitation in the area of the Upper Silesian Coal Basin (Górnośląskie Zagłębie Węglowe) are characterised by the presence of natural hazards typical of this type of exploitation. These hazards include the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks. The article presents the results of a taxonomic analysis aimed at determining the similarity of hard coal mines and mining enterprises in Poland in terms of the dangerous incidents caused by the risks related to methane, coal dust explosion, endogenous fires, as well as rock burst and caving of roof rocks. The analysis was carried out for the 2008-2018 data and encompassed a total of 26 hard coal mines and mining enterprises located in the Upper Silesian Coal Basin. The analysis was performed using the k-means method of non-hierarchical clustering. The main objective of the article was to determine homogenous groups (clusters) of mines exhibiting the greatest similarity in terms of dangerous incidents caused by the activation of natural hazards in the years 2008-2018. These data can be successfully used for the development of preventive measures and risk analyses for these enterprises.

Keywords: coal mine, natural hazards, cluster analysis, taxonomic methods, analysis of similarity