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Coal and Gas Outburst Risk Assessment Using Cluster Analysis Method

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Abstract

Mining has historically been known as a high-risk industry. Coal and gas outbursts are one of the most significant accidents that occur in underground coal mines. Despite many years of research, the resources and mechanisms of this phenomenon are not well understood. Thus, it is difficult to forecast and control these events. As the mining depth and density increase, initial gas pressure and gas content of coal seams continue to increase, and the risk of explosion increases. Hence, explosion-prone areas expand gradually. As a result, a dynamic phenomenon has emerged in areas where there is no danger of outbursts. The risk of outbursts becomes more and more serious in coal mines. A coal outburst risk assessment includes evaluating the risk factors to what degree are present and then determining the risk areas of the mine. In this study, the Cluster Analysis method was implemented to identify the risk level of coal seams based on the evaluation of the outburst risk factors for an underground coal mine. Coal and gas outbursts occurring in Zonguldak hard coal basin were divided into two clusters, Cluster A and Cluster B. Coal seams in Cluster A were determined riskier than Cluster B coal seams.

Keywords

Coal and gas outburst, underground coal mine, risk index, Cluster Analysis

Introduction

Coal is a complicated material with a porous structure that can deposit large quantities of methane. It also contains small amounts of carbon dioxide, nitrogen, hydrogen sulphide, and sulphur dioxide in its micro-pores and natural cracks (Flores, 1998). Gas discharge from coal can occur in large quantities by suddenly leaking into the workplace. This condition is generally referred to as the outburst phenomenon (Beamish and Crosdale, 1998). The occurrences of outbursts are severe and instantaneous in the coal mines. Generally, they cause gas explosions and pollution of the mine environment due to carbon dioxide. The mechanism of coal and gas outbursts has been searched since 1852, but they continue to be a great hazard to mine safety (Guan et al., 2009). The coal and gas outburst is one of the most severe catastrophe events existing in coal mining. An outburst is an instantaneous burst of coal and gas from a coal face, which is a complex and dynamic phenomenon that includes coal, gas, and rock. Great quantities of coal and gas are ejected into the mining space in a very short time when coal and gas outbursts occur. Coal and gas outbursts can damage both ventilation systems, equipment in roadways, and coal miners. More significant results can also occur, such as coal dust and gas explosions (Zhai, 2016). Despite several prevention technologies and control techniques, coal and gas outbursts are mostly encountered with increasing depth and mining operations (Chaojun et al. 2017).

Although researches on coal and gas outbursts provide efficient consequences, these events have been a serious safety problem occurring in the world's different coal-manufacturer countries (Chen et al., 2018). Therefore, forecasting the probability of coal and gas outbursts is one of the most significant subjects to be considered. A successful prediction of these outburst hazards is important to provide safe mining operations and the permanence of mining production (Ruilin and Lowndes, 2010). The combination of many influencing factors and multiway interactions of them can lead to an outburst. Thus, predicting outburst events using a single parameter is substantially hard. Various factors cause the occurrence of coal and gas outbursts in the literature, such as stress, production, geological conditions, seam gas content, moisture content, sorption/desorption properties, coal strength, permeability, mining depth, in–situ stress conditions, seam thickness, inclination, gas pressure, and coal rank (Beamish and Crosdale, 1998; Lama and Bodziony, 1998; Cao et al., 2001; Chao et al., 2010; Ruilin and Lowndes 2010; Haifeng et al., 2013; Nie et al., 2014; Li et al., 2015; Jiabo et al., 2017; Chen et al., 2018). Due to the complex nature of coal and gas outbursts, it is essential to use a multivariate statistical technique in risk assessment. The Cluster Analysis, a multivariate statistical technique, divides data into meaningful, useful, or both groups (clusters). This method searches to discover the number and composition of the groups (Tan et al., 2014). The Cluster Analysis has been substantially used in several fields, including city planning, climate, health, and finance (Unal et al., 2003; Sánchez-Pérez et al., 2004; Campos and Oliveira, 2016; Tekin and Gümüş, 2017). The Cluster Analysis can classify a sample of subjects (or objects) based on a set of measured factors into a range of distinct groups such that similar objects are located in the same group. The general purpose of the Cluster Analysis is to reveal similar aspects of objects according to their specific characteristics and to divide the units into the correct categories based on these similarities (Özdamar, 2014).

Although several techniques have been conducted to risk assessment in outburst hazards, such as artificial neural networks (ANN), bayesian discriminant, logistic regression model, regression analysis, catastrophe progression method, numerical simulation, and experimental analysis (Tian-jun et al., 2009; Chao et al., 2010; Ruilin and Lowndes, 2010; Li et al., 2015; Yin et al., 2016; Chaojun et al., 2017; Jiabo et al., 2017; Chen et al., 2018; Wang et al., 2018), the Cluster Analysis method has not been reported in coal and gas outburst risk assessment. Therefore, the main objective of the study is to determine the risk level of coal seams by applying the Cluster Analysis according to their specific characteristics. The risk levels of the seams were identified for Zonguldak hard coal basin.

Risk Evaluation of Coal and Gas Outbursts

Although Turkey's coal mining industry continues to take measures to prevent work-related accidents in recent years, coal and gas outbursts are significant events. The severity of major outburst accidents is important in comparison with other types of coal mine accidents. As shown in Fig. 1, 90 accidents occurred in Zonguldak hard coal basin between 1969 and 2013.

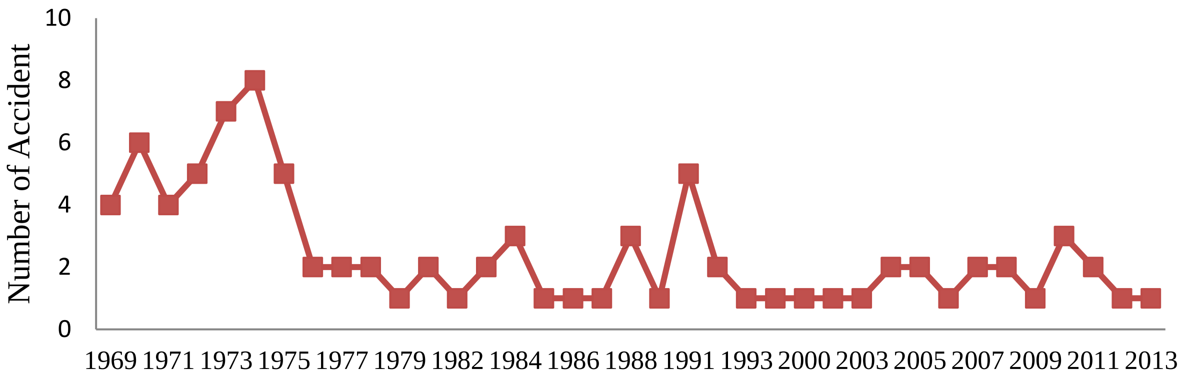

Fig.1. The annual number of outburst accidents in the Zonguldak coal basin.

Coal and gas outburst forecast methods can commonly be categorized as empirical, experimental, analytical, and numerical. Different researchers choose different factors as evaluation criteria, and the classification of outburst risk also differs from each other. Each criterion is developed according to specific geomechanical and geological conditions of mines. Therefore, it is difficult to define a universal and practical parameter. The results of various prediction factors should be comprehensively examined (Wang et al., 2018). Outburst hazard influences the choice of suitable excavation support, face advance, and especially mining method (conventional or mechanized). Coal and gas outbursts may arise during the drilling, cutting, and blasting process and after an operation is ceased (Beamish and Crosdale, 1998). Coal and gas outbursts are a profoundly complicated dynamic event in coal mining, and they can throw large amounts of coal and gas from the coal pile to the working area in a short time. Thus, a comprehensive risk evaluation of coal and gas outbursts is one of the significant issues for mine safety (Li et al., 2015). Literature exploration regarding the prediction of outbursts was presented in Tab. 1.

Table 1. Literature exploration on risk assessment of outbursts.

Outburst Index Technique	Evaluation Factor	Reference
Bayesian discriminant analysis	Initial methane diffusion speed Consistent coal coefficient Gas pressure Devastating style of coal Mining depth	Chao et al. (2010)
Regression analysis	Mining depth Seam thickness Seam dip Tectonic structure Mining method	Chen et al. (2018)
General overview	Depth of cover Pillar design Multiple seam interactions Roof-floor condition History of bursts	Christopher and Michael (2016)
Regression analysis	Moisture Geostress Porosity Gas pressure	Jiabo et al. (2017)
Historic data, Experimental analysis	Gas content Seam thickness Gas emission Gas desorption index	Jianchun et al. (2012)
Logistic regression	Gas emission Seam thickness Electromagnetic radiation intensity Gas desorption index Electromagnetic radiation Drilling cutting weight	Li et al. (2015)
Fault tree analysis, Artificial neural network	Gas pressure Coal strength	Ruilin and Lowndes (2010)

	Fracture degree of coal Permeability Branched property of coal seam Alterations of seam thickness Tectonic stress Interlayer slippage in coal seam	

Outburst Index Technique	Evaluation Factor	Reference
Catastrophe progression method	Mining depth Seam thickness Coal solidity coefficient Gas content Gas pressure	Tian-jun et al. (2009)
Experimental analysis	Briquetting pressure In situ stress Briquette coal thickness Gas pressure Total coal quality Ambient temperature	Wang et al. (2018)
Experimental analysis	Stress conditions Gas pressure Moisture content	Yin et.al. (2016)
Field statistics	Tectonic structure Mining depth Variation of seam thickness Structure of roof and floor Mode of operation	Zhai et al. (2016)

Description of Zonguldak Hard Coal Basin

Zonguldak's hard coal basin is located on the Western Black Sea coast between Eregli and Inebolu, approximately 160 km east-west (Fig. 2). Mining production of the basin started in 1848. The mines have been produced by Turkish Hard Coal Enterprise (THCE) since 1983. There are five production enterprises in the basin, such as Kozlu, Karadon, Üzülmez, Armutçuk, and Amasra (Kursunoglu and Onder, 2019). The geological structure of the Zonguldak hard coal basin is very complicated because of the existence of various faults, anticlines, and synclines. The longwall mining method is implemented in all five mines of the basin. Coal seam thicknesses of the basin range from 1 to 10 m. The altitude of the coal seams differs between 100 and 560 m in the basin. The total coal reserve of the basin is 1.3 billion tonnes. The quantity of proven reserve in the basin is approximately 500 million tonnes, and 7.5 million tonnes of coal can be produced as of February 2016. The two coal mines, Amasra and Karadon, have the highest coal reserves, 406 and 409 million tonnes, respectively (Erdogan et al., 2019). Seam inclinations of the mines range from 15˚ to 90˚. The average coal seam gas contents of the basin are approximately 12 m^3/t based on the laboratory measurements on coal samples applied in canisters, but the measurements in the mines have indicated that gas contents of the coals are between 1 and 14 m^3/t (Karacan and Okandan, 2000). The generalized stratigraphic section of the Zonguldak hard coal basin is demonstrated in Fig. 3.

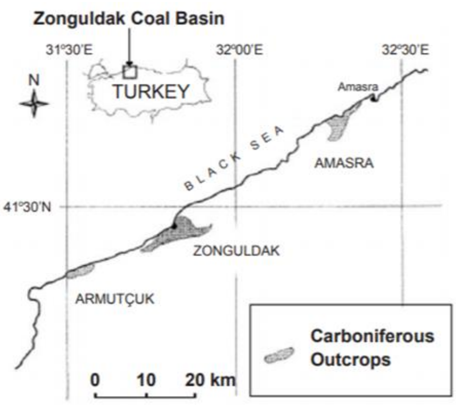

Fig. 2. Location of the Zonguldak hard coal basin (Düzgün, 2005)

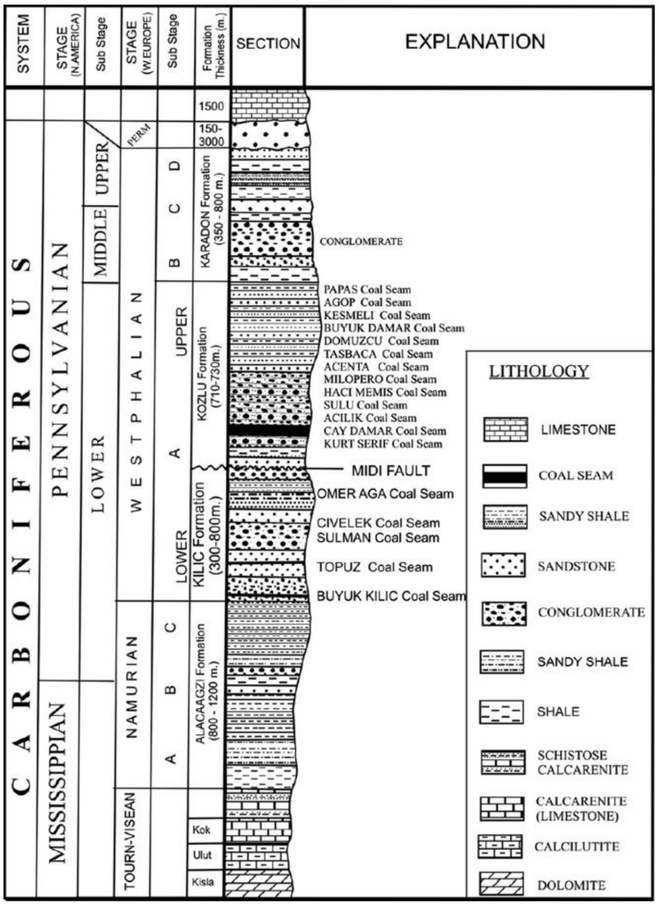

Fig. 3. Generalized stratigraphic section of Zonguldak hard coal basin (Toprak, 2009)

Material and Methods

Cluster Analysis method

The Cluster Analysis method groups data subjects based on information that exists in the data, which identifies the objects and their relationships. The method aims to classify the objects within a group that are similar or related to one another and different from or unrelated to the objects in other groups. The Cluster Analysis collects individuals or objects that are more similar to each other than the others in terms of selected properties. Thus, homogeneity in clusters and heterogeneities among clusters are maximum. If the clustering operation is successful, while the objects in the cluster are close to each other, the objects in other clusters will be away from each other. The main purpose of the Cluster Analysis is to divide into two or more groups based on the similarities of observations obtained as a result of the research. Cluster Analysis is frequently used to develop the classification process objectively (Tan et al., 2007). The main objective of Cluster Analysis is to identify the similarities between the units based on their unique properties and to categorize the units based on these similarities correctly. This component of the analysis is comparable to Discriminant Analysis, one of the multivariate analysis techniques. Contrary to Discriminant Analysis, future predictions cannot be made with Cluster Analysis because the instantaneous condition of the units is observed. On the other hand, Discriminant Analysis enables future predictions. Cluster Analysis is used to determine the structures of subgroups in situations where there is a lack of clear knowledge of their natural classification, while Discriminant Analysis is used to examine subsets in societies where natural categories are well understood. When compared to Factor Analysis, Clustering Analysis groups the data based on closeness rather than changes in the data. The hierarchical clustering method is beneficial because it enables researchers to identify structures and relationships in the data set that were not previously obvious. For this reason, the Cluster Analysis method was preferred in the study. The Cluster Analysis methods and application steps are explained below.

Clustering methods

Two main groups are constructed in clustering methods, hierarchical and non-hierarchical. The common purpose of both methods is to achieve the highest differences between clusters and intra-cluster similarities. Clustering methods were explained as follows (Tan et al., 2007):

Hierarchical methods: Hierarchical clustering methods are particularly suitable for small samples ($n < 250$), and they are convenient methods when the researcher does not know how many groups are initially found in the data set. This method is also useful because it allows researchers to observe the previously untested relationships in the data set and to discover the principles. These clustering techniques are divided into two types:

1. Agglomerative method: In the agglomerative hierarchical clustering method, initially, each observation or unit creates its separate cluster. In this method, different approaches (clustering algorithms) are applied to the interconnection of units, such as the nearest neighbour method, furthest neighbour method, average linkage method, centroid method, and ward's method. The ward's method is generally accepted as the best method among these methods. Ward's method reveals more meaningful cluster structures (Hands and Everitt, 1987; Ferreira and Hitchcock, 2009). The method is the only technique that allows the formation of clusters by minimizing intragroup distribution based on the classical sum of squares criteria (Murtagh and Legendre, 2014).

2. Divisive methods: These methods gradually divide units into 1, 2, 3, ..., $n - r$, $n - 3$, $n - 2$, $n - 1$, n clusters, assuming that all units initially form a cluster. Agglomerative methods are utilized more frequently than divisive methods (Tan et al., 2007).

Non-hierarchical methods (K means clustering): These methods are used when the number of sets is known by the researcher. In other words, if the researcher has prior knowledge of the cluster numbers or has decided on the cluster numbers, these methods are recommended. Non-hierarchical methods can be used for larger data sets concerning hierarchical methods.

Distance and similarity measurements in Cluster Analysis

The clustering of the objects in a data set is performed according to the similarities or distances of each of these units. Distance measurements show how far the two observations are from each other. Similar distances between observations are less. Similarity measurements show how similar the two observations are. The measurement methods that can be used for metric data in the Cluster Analysis are euclidean, squared euclidean, cosine, Pearson correlation, chebychev, block, and minkowski (Tan et al., 2007). The most commonly used distance measurements are euclidean and square euclidean (Kalayci, 2009). Euclidean distance identifies distances in a dimensional data matrix between i. and j. units (observations, objects) directly in the form of measure or in the form of square distances. When Ward's method is applied, Square Euclid distances must be calculated (Özdamar, 2014).

Standardization and transformation of variables

Since the units of measurement directly affect the result, the raw data need to be converted to a standardized form. Data transformation occurs in the form of standardization. Techniques used to transform data are z-scores, range -1 to 1, range 0 to 1, the maximum magnitude of 1, mean of 1, and standard deviation of 1. The most widely used transformation method is Z-scores (Kalayci, 2009).

Determination of cluster number and cluster validity

No algorithm gives exactly how many clusters the data set should be agglomerated in the Cluster Analysis. It completely depends on what the analyst wants to do with the data. It also belongs to the analyst to evaluate the meaning of the resulting classes. In determining the number of clusters, coefficients in the agglomeration schedule or dendrogram graph (tree diagrams) can be used as a guiding tool at this stage (Kalayci, 2009).

Application of Cluster Analysis

Determination of risk variables

Coal and gas outbursts occur as a result of a combination of many factors and variables in different regions. For this reason, the factors affecting outburst events were determined at first. Kursunoglu and Onder (2019) used outburst variables such as depth of mining, coal seam gas content, moisture content, seam thickness, the inclination of the seam, and distance from fault to evaluate outbursts in Zonguldak hard coal basin. Mining depth (MD), coal seam gas content (GC), moisture content (MC), and distance from fault (DFF) were determined as efficient factors in the occurrence of outbursts using the Structural Equation Modeling method in their study. These efficient variables were used in the present article to constitute the risk index for Zonguldak hard coal basin. The framework of the study is presented in Fig. 4.

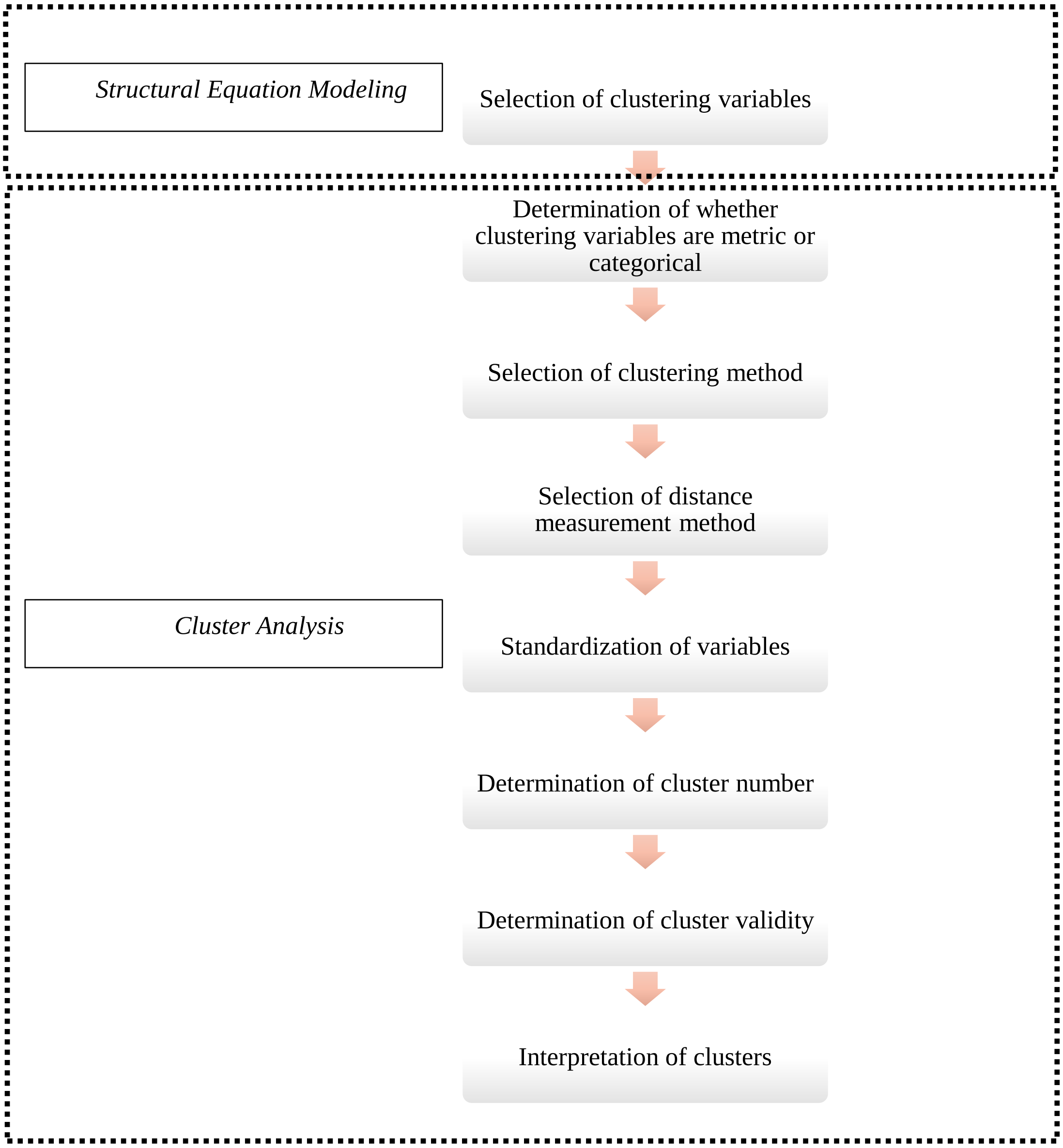

Fig. 4. The framework of the study

Data analysis

To perform the risk assessment using the Cluster Analysis method, data of 90 outburst events occurring in the Zonguldak hard coal basin were analyzed using the SPSS 24 package program. Data analysis was applied according to explanations discussed in the section Material and Methods. Since the initial number of clusters was not known, the hierarchical clustering method was chosen. Ward's method was used to separate coal seams into clusters, and squared euclidean distance was used as a distance measure. Since the units of measurement directly affect the result, the raw data is converted to a standardized form. Therefore, z-scores were applied to the variables. Cluster numbers were determined according to the dendrogram graph. Data from the study is given in Tab. 2.

Table 2. Coal and gas outburst data of Zonguldak hard coal basin

Outburst No	Area of Outburst	Mining Depth [m]	Gas Content (m^3/t) [ar]	Moisture Content (%) [ar]	Distance From Fault [m]
1	-360/42400 Drifting road	364	7	0.69	50
2	-360/42417 Drifting road	360	7	0.69	150
3	-260/-160 Raise	241	3.6	0.69	0
4	-150/41217 Raise	110	5.44	0.71	150
5	-260/-160 Raise	244	2.6	0.79	50
6	-360/51105 Raise	320	3.6	0.69	0
7	-360/51105 Raise	320	3.6	0.69	0
8	-260/42314 Raise	234	3.6	0.69	80
9	-260/42319 Gateway	232	4	0.67	50
10	-260/51059 Raise	233	4	0.81	0
11	-150/41228 Raise	140	2.6	0.79	0
12	42036/43311 Raise	250	5.44	0.71	0
13	-150/41228 Raise	110	2.6	0.79	0
14	-260/-150 42319 Face	250	5.44	0.71	50
15	42036/42319 Raise	253	5.44	0.71	0
16	-360/51105 Raise	342	3.6	0.69	0
17	-260/-160 Raise	244	5.44	0.71	125
18	-260/-150 42319 Raise	250	5.44	0.71	0
19	-360/51100 Gateway	356	7	0.67	40
20	-360/51050 Raise	343	11.93	1.45	40
21	-360/42417 Raise	343	5.44	0.71	40
22	-360/42417 Gateway	356	4	0.67	0
23	-360/42417 Raise	356	5.44	0.71	0
24	-150/41230 Raise	130	2.6	0.79	50
25	-260/42319 Raise	248	2.6	0.79	50
26	-460/42505 Raise	303	3.6	0.69	0
27	-360/51107 Raise	311	11.93	1.45	0
28	-460/51510 Drifting road	460	7	0.71	50
29	-460/51510 Drifting road	460	7	0.71	50
30	-360/42418 Raise	328	5.44	0.71	0
31	-360/42418 Raise	315	5.44	0.71	0
32	-360/424170 Raise	360	2.6	0.79	50
33	-460/42506 Drifting road	460	7	0.71	0
34	-460/51507 Drifting road	460	7	1.76	0
35	-460/42506 Raise	445	4.48	3.45	0
36	-460/51507 Gateway	460	5.33	1.76	0
37	-460/-360 Raise	450	7.8	2.63	0
38	-460 Raise	460	7.8	2.63	40
39	-360/260 Raise	331	7	3.25	75
40	-460/42506 Raise	440	7.8	2.63	0
41	-360/-460 Raise	380	4.8	4.62	0
42	-460/42505 Raise	403	7.14	3.19	45
43	-560 Raise	560	7	1.69	45
44	-540/42604 Drifting road	540	7	1.69	0
45	-540/42607 Drifting road	540	7	1.69	0

Table 2. Coal and gas outburst data of Zonguldak hard coal basin (Continued)

Outburst No	Area of Outburst	Mining Depth [m]	Gas Content (m^3/t) [ar]	Moisture Content (%) [ar]	Distance From Fault [m]
46	-460/51506 Raise	444	6.63	3.2	0
47	-260/41305 Raise	228	8.97	3.2	45
48	-360/41419 Raise	328	8.97	1.25	45
49	-540/51506 Drifting road	540	7	0.38	75
50	-360/41406 Gateway	360	7.14	0.38	75
51	-360 Raise	360	8.97	1.25	0
52	-460/42504 Gateway	460	7.14	0.38	0
53	-425/22924 Raise	387	5	1.1	25
54	-425/22924 Raise	402	5	1.1	15
55	-425/22924 Raise	400	5	1.1	10
56	-360/22823 Gateway	360	3.47	1.1	0
57	-360/-300/22823 Raise	345	3.47	1.1	0
58	-360/-300/22823 Raise	325	3.47	1.1	25
59	-425/-369 22944 Raise	405	7	1.4	0
60	-360/22825 Drifting road	360	3.47	1.1	0
61	-414/-358 22945 Raise	401	3.47	1.1	0
62	-425/-360/22923 Raise	398	5.76	2.82	0
63	-425/22926 Raise	402	7	1.4	0
64	-425/22925 Drifting road	420	7	1.4	0
65	-416/22926 Raise	401	7	1.4	0
66	-425/22926 Drifting road	417	7	1.4	0
67	-422/21946 Raise	414	3.47	1.1	0
68	-417/22926 Raise	402	7	1.4	0
69	-417/22923 Raise	396	11.72	1.17	0
70	-425/22929 Drifting road	425	3.47	1.1	0
71	-425/22945 Raise	401	5.76	2.82	20
72	-485/211004 Raise	471	3.47	1.1	25
73	-425/22926 Drifting road	418	7	1.4	75
74	-485/21100 Raise	441	3.47	1.1	15
75	-485/221036 Drifting road	485	11.41	1.15	10
76	-485/221036 Drifting road	485	11.7	2.02	0
77	-485/221009 Drifting road	485	11.41	1.15	20
78	-485/221036 Raise	459	11.41	1.15	10
79	-560/211127 Drifting road	560	11.72	1.17	15
80	-560/211127 Drifting road	560	11.72	1.17	15
81	-485/211004 Drifting road	485	5.76	2.82	15
82	-560/-485 Raise	560	7.6	1.89	15
83	-560/112056355 Drifting road	560	8.88	2.6	15
84	-560/21127 Raise	510	11.72	1.17	15
85	-560/112056355 Raise	548	16.9	1.74	0
86	-560/355 Drifting road	560	16.9	1.74	0
87	-560/112056355 Raise	539	16.9	1.74	0
88	-630/111063405 Drifting road	630	8.88	2.6	0
89	-630/111063405 Drifting road	630	8.88	2.6	0
90	-630/111063405 Drifting road	630	8.88	2.6	0

ar: as received

Determination of cluster numbers and cluster validity

The dendrogram graph of the present study is given in Fig. 5.

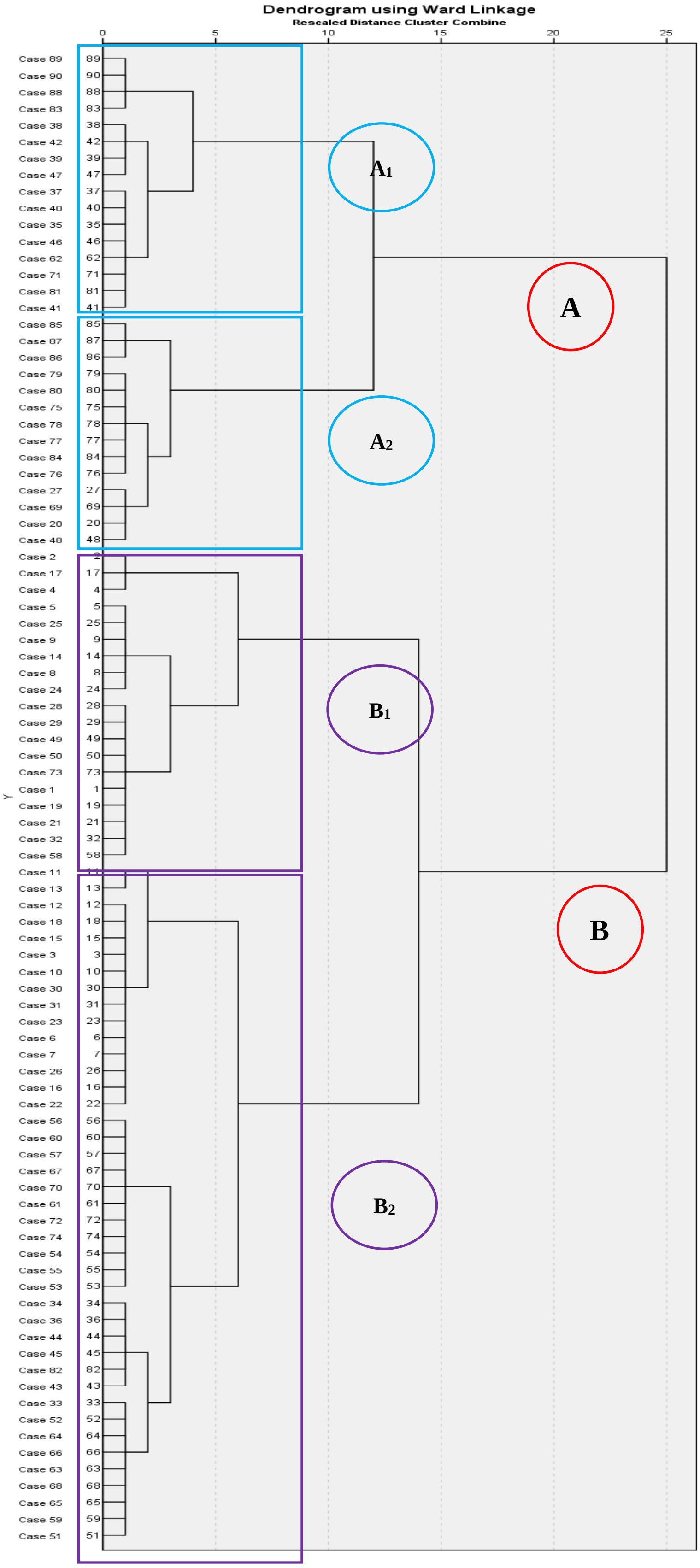

Fig. 5. Dendrogram graph of outburst events

Along the horizontal axis in Fig. 5, it is seen that new cluster formations have emerged which are less distant from each other and include more events. The number of clusters was determined so as not to disturb the homogeneous structure within the cluster and the heterogeneous structure between clusters. According to the hierarchical clustering method, outburst events are collected in two clusters, Cluster A and Cluster B, and their sub-clusters A_1, A_2, B_1, and B_2. Cluster groups formed in the dendrogram graph are summarized in Tab. 3. Multivariate analysis of variance (MANOVA) was performed to test the accuracy of the clusters resulting from the Cluster Analysis, and the results were given in Tab. 4. Hypotheses were constructed as follows:

H_0: The group means vectors are equal in terms of clusters.
H_1: At least one group's mean vector differs from others in terms of clusters.

Table 3. Cluster structure according to the hierarchical clustering method

Cluster A		Cluster B		
Cluster A_1	Cluster A_2	Cluster B_1	Cluster B_2	
Event35	Event20	Event1	Event3	Event51
Event37	Event27	Event2	Event6	Event52
Event38	Event48	Event4	Event7	Event53
Event39	Event69	Event5	Event10	Event54
Event40	Event75	Event8	Event11	Event55
Event41	Event76	Event9	Event12	Event56
Event42	Event77	Event14	Event13	Event57
Event46	Event78	Event17	Event15	Event59
Event47	Event79	Event19	Event16	Event60
Event62	Event80	Event21	Event18	Event61
Event71	Event84	Event24	Event22	Event63
Event81	Event85	Event25	Event23	Event64
Event83	Event86	Event28	Event26	Event65
Event88	Event87	Event29	Event30	Event66
Event89		Event32	Event31	Event67
Event90		Event49	Event33	Event68
		Event50	Event34	Event70
		Event58	Event36	Event72
		Event73	Event43	Event74
			Event44	Event82
			Event45	

Table 4. MANOVA analysis of Cluster A and B

Test Statistic	Value	F	Hypothesis [df]	Error [df]	Sig. [p]
Pillai's Trace	0.770	71.151	4.000	85.000	0.000
Wilks' Lambda	0.230	71.151	4.000	85.000	0.000
Hotelling's Trace	3.348	71.151	4.000	85.000	0.000
Roy's Largest Root	3.348	71.151	4.000	85.000	0.000

Four different multivariate statistical results in terms of sets are significant at 0.05 level ($p < 0.05$). Thus, there is a significant difference between Cluster A, and Cluster B. H_0 hypothesis is rejected, meaning there is no difference between groups. In this way, it is decided that the difference between the groups and the suitability of the cluster structures formed are meaningful.

Risk analysis of outburst events

As a result of the evaluation of outburst events using the SEM method, the risk of outbursts increases with increasing in mining depth, gas content, and moisture content, while the risk of outbursts increases with decreasing distance from the fault (Kursunoglu and Onder, 2019). In this study, the risk degree of the cluster structures obtained by the Cluster Analysis was determined according to this result. Details of the clusters belonging to Cluster A are given in Tab. 5.

Table 5. Variable means of Cluster A_1 and Cluster A_2

Variable	Risk Degree	Cluster A	
		Cluster A_1	Cluster A_2
		Event 35 Event 37 Event 38 Event 39 Event 40 Event 41 Event 42 Event 46 Event 47 Event 62 Event 71 Event 81 Event 83 Event 88 Event 89 Event 90	Event 20 Event 27 Event 48 Event 69 Event 75 Event 76 Event 77 Event 78 Event 79 Event 80 Event 84 Event 85 Event 86 Event 87
Mining Depth	Risk Degree	2	1
Gas Content	Risk Degree	2	1
Moisture Content	Risk Degree	1	2
Distance From Fault	Risk Degree	2	1
Variable Means		MD: 457 m GC: 7.20 m^3/t MC: % 2.90 DFF: 15 m	MD: 469 m GC: 12 m^3/t MC: % 1.39 DFF: 12 m

Considering the increased risk of outbursts under high MD, GC, MC, and low DFF conditions, Cluster A_2 is riskier than Cluster A_1 in terms of all variables except the MC variable. Cluster A_1 is only risky according to the MC variable than Cluster A_2. When a general evaluation is conducted considering the variable means of MD, GC, and DFF, coal seams in Cluster A_2 are risky compared to Cluster A_1. Details of the clusters belonging to Cluster B are given in Tab. 6.

Table 6. Variable means of Cluster B_1 and Cluster B_2

VARIABLE	RISK DEGREE	Cluster B		
		Cluster B_1	Cluster B_2	
		Event 1	Event 3	Event 51
		Event 2	Event 6	Event 52
		Event 4	Event 7	Event 53
		Event 5	Event 10	Event 54
		Event 8	Event 11	Event 55
		Event 9	Event 12	Event 56
		Event 14	Event 13	Event 57
		Event 17	Event 15	Event 59
		Event 19	Event 16	Event 60
		Event 21	Event 18	Event 61
		Event 24	Event 22	Event 63
		Event 25	Event 23	Event 64
		Event 28	Event 26	Event 65
		Event 29	Event 30	Event 66
		Event 32	Event 31	Event 67
		Event 49	Event 33	Event 68
		Event 50	Event 34	Event 70
		Event 58	Event 36	Event 72
		Event 73	Event 43	Event 74
			Event 44	Event 82
			Event 45	
Mining Depth	Risk Degree	2	1	
Gas Content	Risk Degree	1	2	
Moisture Content	Risk Degree	2	1	
Distance From Fault	Risk Degree	2	1	
Variable Means		MD: 317.78 m GC: 5.23 m^3/t MC: % 0.74 DFF: 67.63 m	MD: 374.87 m GC: 5.18 m^3/t MC: % 1.07 DFF: 3.65 m	

When the evaluation is conducted according to variable means of Cluster B_1 and Cluster B_2, Cluster B_1 is risky in terms of GC, and Cluster B_2 is risky in terms of MD, MC, and DFF. Given an overall assessment, the variable means of both clusters are close to each other, but the difference in terms of DFF means is striking. Cluster B_1 has a higher DFF mean than Cluster B_2. The probability of an outburst increases with decreasing DFF. Thus, Cluster B_2 has more risky coal seams than Cluster B_1.

Risk index of clusters

Following the explanations above, a risk index was formed in Tab. 7.

Table 7. Risk index of Zonguldak hard coal basin

	Cluster A		Cluster B	
	Cluster A_2	Cluster A_1	Cluster B_2	Cluster B_1
Risk index	1	2	3	4
Variable Means	MD: 469 m GC: 12 m^3/t MC: % 1.39 DFF: 12 m	MD: 457 m GC: 7.2 m^3/t MC: % 2.9 DFF: 15 m	MD: 374.87 m GC: 5.18 m^3/t MC: % 1.07 DFF: 3.65 m	MD: 317.78 m GC: 5.23 m^3/t MC: % 0.74 DFF: 67.63 m
	MD: 462.80 m GC: 9.72 m^3/t MC: % 2.24 DFF: 14.17 m		MD: 356.80 m GC: 5.20 m^3/t MC: % 0.97 DFF: 23.92 m	

Results and Discussion

The risk index of Cluster A_2 belonging to Cluster A is determined as 1, and the risk index of Cluster A_1 is determined as 2. The risk index of Cluster B_2 constituting Cluster B, which has lower risk seams than Cluster A, was determined as 3. Cluster B_1 risk index was determined as 4. The risk index of coal seams is shown in Tab. 8 in detail. The risk colour of the seams was identified for the risk index. The risk indexes 1, 2, 3, and 4 were represented as red, yellow, green, and blue, respectively.

Table 8. Risk levels of outburst coal seams

Outburst No	Location of Outburst	Cluster	Risk Index
1	-360/42400 Drifting road	B_1	4
2	-360/42417 Drifting road	B_1	4
3	-260/-160 Raise	B_2	3
4	-150/41217 Raise	B_1	4
5	-260/-160 Raise	B_1	4
6	-360/51105 Raise	B_2	3
7	-360/51105 Raise	B_2	3
8	-260/42314 Raise	B_1	4
9	-260/42319 Gateway	B_1	4
10	-260/51059 Raise	B_2	3
11	-150/41228 Raise	B_2	3
12	42036/43311 Raise	B_2	3
13	-150/41228 Raise	B_2	3
14	-260/-150 42319 Face	B_1	4
15	42036/42319 Raise	B_2	3
16	-360/51105 Raise	B_2	3
17	-260/-160 Raise	B_1	4
18	-260/-150 42319 Raise	B_2	3
19	-360/51100 Gateway	B_1	4
20	-360/51050 Raise	A_2	1
21	-360/42417 Raise	B_1	4
22	-360/42417 Gateway	B_2	3
23	-360/42417 Raise	B_2	3
24	-150/41230 Raise	B_1	4
25	-260/42319 Raise	B_1	4
26	-460/42505 Raise	B_2	3
27	-360/51107 Raise	A_2	1
28	-460/51510 Drifting road	B_1	4
29	-460/51510 Drifting road	B_1	4

30	-360/42418 Raise	B_2	3
31	-360/42418 Raise	B_2	3
32	-360/424170 Raise	B_1	4
33	-460/42506 Drifting road	B_2	3
34	-460/51507 Drifting road	B_2	3
35	-460/42506 Raise	A_1	2
36	-460/51507 Gateway	B_2	3
37	-460/-360 Raise	A_1	2
38	-460 Raise	A_1	2
39	-360/260 Raise	A_1	2
40	-460/42506 Raise	A_1	2
41	-360/-460 Raise	A_1	2
42	-460/42505 Raise	A_1	2
43	-560 Raise	B_2	3
44	-540/42604 Drifting road	B_2	3
45	-540/42607 Drifting road	B_2	3

Table 8. Risk levels of outburst coal seams (continued)

Outburst No	Location of Outburst	Cluster	Risk Index
46	-460/51506 Raise	A_1	2
47	-260/41305 Raise	A_1	2
48	-360/41419 Raise	A_2	1
49	-540/51506 Drifting road	B_1	4
50	-360/41406 Gateway	B_1	4
51	-360 Raise	B_2	3
52	-460/42504 Gateway	B_2	3
53	-425/22924 Raise	B_2	3
54	-425/22924 Raise	B_2	3
55	-425/22924 Raise	B_2	3
56	-360/22823 Gateway	B_2	3
57	-360/-300/22823 Raise	B_2	3
58	-360/-300/22823 Raise	B_1	4
59	-425/-369 22944 Raise	B_2	3
60	-360/22825 Drifting road	B_2	3
61	-414/-358 22945 Raise	B_2	3
62	-425/-360/22923 Raise	A_1	2
63	-425/22926 Raise	B_2	3
64	-425/22925 Drifting road	B_2	3
65	-416/22926 Raise	B_2	3
66	-425/22926 Drifting road	B_2	3
67	-422/21946 Raise	B_2	3
68	-417/22926 Raise	B_2	3
69	-417/22923 Raise	A_2	1
70	-425/22929 Drifting road	B_2	3
71	-425/22945 Raise	A_1	2
72	-485/211004 Raise	B_2	3
73	-425/22926 Drifting road	B_1	4
74	-485/21100 Raise	B_2	3
75	-485/221036 Drifting road	A_2	1
76	-485/221036 Drifting road	A_2	1
77	-485/221009 Drifting road	A_2	1
78	-485/221036 Raise	A_2	1

79	-560/211127 Drifting road	A_2	1
80	-560/211127 Drifting road	A_2	1
81	-485/211004 Drifting road	A_1	2
82	-560/-485 Raise	B_2	3
83	-560/112056355 Drifting road	A_1	2
84	-560/21127 Raise	A_2	1
85	-560/112056355 Raise	A_2	1
86	-560/355 Drifting road	A_2	1
87	-560/112056355 Raise	A_2	1
88	-630/111063405 Drifting road	A_1	2
89	-630/111063405 Drifting road	A_1	2
90	-630/111063405 Drifting road	A_1	2

Outburst events in Zonguldak hard coal basin are divided into two main clusters, Cluster A and Cluster B, based on mining depth, coal seam gas content, moisture content, and distance from fault variables. The effects of these variables' means are expressed below.

Effect of mining depth

When Cluster A and Cluster B are compared in terms of mining depth, Cluster A has an average mining depth of 462.80 m, and Cluster B has a mining depth of 356.80 m (Tab. 7). The possibility of outburst increases with increasing mining depths. This is because the pressure on the coal increases as the depth increases. Increased pressure disrupts the physical structure of the coal and makes it porous. The crushed coal is less resistant to gas pressure and makes outbursts easier. The minimum depth of outburst hazard varies for coals with different degrees of metamorphism. (Bodziony and Lama, 1996; Wang et al., 2014; Zhai et al., 2016).

Effect of gas content

The average coal seam gas content of Cluster A and Cluster is 9.72 m^3/t and 5.20 m^3/t, respectively (Tab. 7). Outburst events occurred in the 5 m^3/t gas content in Ukraine Donetsk hard coal basin. The events in low gas content occur since the coal bed is of a complex tectonic structure and is highly degradable of coal deposits (Saltoğlu, 1975). Before the outburst events in Zonguldak hard coal basin, the coal face shows a very hard structure, even showing strength to make excavation difficult. Therefore, behind such a face, the gas under pressure becomes difficult or impossible to escape. Measurements for gas detection before events occur; low methane contents were generally obtained. In the measurements made after outburst events, methane contents were obtained more than %6-10. As production continues in such an excavation face, the thickness of the part that meets the gas pressure in the coal decreases. Thus, coal cannot withstand gas pressure and breaks down (Saltoğlu, 1975).

Effect of moisture content

The average moisture content of coal seams in Cluster A is higher than in Cluster B (Tab. 7). Variable moisture content averages are higher in first-degree risk seams. A certain increase in moisture content in coal causes a significant increase in thermal conductivity coefficient and heat capacity. This affects the time required for cooking as well as the speed and specific gravity of sorption processes on the surface of the coal. Moisture content in bituminous coals may gradually increase depending on the type of coal (for instance, weather-induced decomposition and weathering). In sub-bituminous coal, while humidity is significantly increased depending on the ambient conditions, the lowest increase in moisture content occurs in bituminous coal and coking coal. Moisture content depends on environmental conditions, in particular ambient temperature and water vapour pressure. Although it is difficult to explain the reasons for the increase in moisture content, Sivek et al., 2010 indicated that moisture content belongs to the interaction of various geological factors, coal composition/structure, sedimentary environment, the porosity of the surrounding rocks, and proximity of tectonic structures.

Effect of distance from the fault

There is a relationship between outbursts and geologically disturbed regions. In irregular stress distribution areas, shear causes the charcoal microstructure to be extremely thin, making it soft and weak. In the tectonically deformed regions, coal loses its layered structure and transforms into micro-structurally altered forms. Outbursts generally occur in this tectonically modified coal zone around the fault. This modified coal has low strength, fine particles, and a large surface area. They exhibit high gas absorption capacity and desorption rate (Cao et al., 2001). When Cluster A and Cluster B were compared in terms of DFF, the average DFF of Cluster A (14.17 m) is lower than Cluster B (23.92 m) in Tab. 7. Cluster A is the first-degree risky group due to the proximity of the fault regions of coal seams.

Conclusions

Cluster Analysis is a simple and convenient method to classify a range of complex data using certain variables. It is used to make data meaningful, analyze, present meaningful results, and interpret the results obtained. Due to this property, it is feasible and applicable to create clusters based on different variables. The Cluster Analysis method was applied to make the risk indexing of coal seams in this study. For this purpose, four effective factors, such as mining depth, coal seam gas content, moisture content, and distance from the fault, were evaluated. Coal and gas outbursts occurring in Zonguldak hard coal basin were divided into two clusters, Cluster A and Cluster B. As a result of MANOVA analysis, four different multivariate statistical results were found to be significant at 0.05 level. In interpreting the clusters, high mining depth, gas content, moisture content, and low fault distance conditions were considered. When Cluster A and Cluster B variables were analyzed in terms of these conditions, it was determined that coal seams forming Cluster A are first-degree risky for all variables and Cluster B is second-degree risky. Cluster A and Cluster B were divided into two subsets, Cluster A_1-A_2 and Cluster B_1-B_2, according to the dendrogram graph obtained from the Cluster Analysis. Cluster A_1 is riskier than Cluster A_2 only in terms of moisture content variables. When a general evaluation is made, Cluster A_2 is found to be first-degree risky, according to Cluster A_1. The average mining depth, gas content, and moisture content of Cluster B_1 and Cluster B_2 are close to each other. Distance from fault means of both clusters is quite different. The average fault distance of the coal seams in Cluster B_2 is lower than in Cluster B_1. Therefore, Cluster B_2 is first-degree risky, according to Cluster B_1. The risk index was established according to these risk levels of the clusters. The risk index value of the clusters was determined as 1, 2, 3, and 4 for Cluster A_2, A_1, B_2, and B_1, respectively.

Using the Cluster Analysis, 90 coal and gas outburst accidents in Zonguldak hard coal basin were converted into smaller and more meaningful clusters that will support occupational safety experts to make decisions more accurately. According to the study results, high mining depth, gas content, moisture content, and low fault distance should be considered as the primary criteria for the outburst prevention impact, which can be utilized to direct the coal mining sector. Prior to coal seam mining, it is essential to assess the danger of an outburst. The method that is being suggested primarily evaluates the entire risk at the beginning of mining, which is an essential component for designing outburst management and prevention. As a result, when gas drainage is utilized to control outbursts, gas pressure might be considered the primary measurement standard. To enhance coal mine safety production, the gas drainage system should be improved with a focus on enhancing the effect of gas pressure reduction. To prevent outburst events, it is necessary to reduce the effect of the gas pressure or increase the force that tries to keep the face and prevents its disintegration. Gas pressure can be relieved by protective seam excavation. The gas load can be reduced by excavating a seam located at the roof or floor side of the outburst risky seam. Control drilling should be applied to create a relief area in case of progress with a narrow excavation face, such as a gateway.

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