DEMATEL and ISM analysis of factors influencing coal spontaneous combustion in longwall gobs

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Abstract

Coal spontaneous combustion in longwall gobs is a major concern in coal mines. In comparison to other hazards, this phenomenon is difficult to detect. Fifteen factors influencing coal spontaneous combustion in longwall gobs were identified from the literature. The logical relationships between these factors were evaluated and quantified by decision-making trial and evaluation laboratory (DEMATEL) and interpretive structural modelling (ISM) methods. A four-level hierarchical structure model was established. The research shows that combining DEMATEL and ISM can reveal the key factors that influence coal spontaneous combustion in longwall gobs and establish the interactions and relationships among these factors. The results can provide the basis for preventing and controlling coal spontaneous combustion in longwall gobs.

Keywords

spontaneous combustion, longwall gob, factor analysis, DEMATEL, ISM

Introduction

Coal spontaneous combustion is a serious threat to safety and production in coal mines. Statistical studies have shown that more than 90% of coal fires in China are caused by spontaneous combustion in longwall gobs and closed areas (Chi, 2008). Coal spontaneous combustion typically occurs in longwall gobs, where residual coal is affected by fresh air flow from a working face. The temperature of the coal can constantly increase, leading to spontaneous combustion under certain conditions of oxidation and heat accumulation (Pan et al., 2013; Wang et al., 2019; Huang et al., 2018; Deng, Ma, and Zhang, 2013). Coal combustion will produce a large amount of toxic gases, and cause gas explosions under certain conditions, thereby threatening the safety of miners and causing serious economic losses and environmental damage (Qi et al., 2015; Kim and Sohn, 2012; Dudzińska and Cygankiewicz, 2015; Onifade, Genc, and Wagner, 2019).

Coal spontaneous combustion in longwall gobs is a complex process that is related to many factors (Krishnaswamy, Agarwal, and Gunn, 1996). An in-depth discussion of these factors can inform risk management and provide a basis for developing an effective safety evaluation system (Zio, 2016; Dekker, Cilliers, and Hofmeyr, 2011; Desveaux et al., 2019; Onifade and Genc, 2018). Many related studies have addressed the risk analysis of coal spontaneous combustion, and several methods for analysing and evaluating the spontaneous combustion of residual coal in longwall gobs have been proposed, including grey correlation analysis, analytic hierarchy process, rough set theory, and matter element extension theory (Genc and Cook, 2015; Wang et al., 2014). However, the factors that affect coal spontaneous combustion in longwall gobs will influence each other, given the complexity of the process This consideration has been neglected in previous studies.

Decision-making trial and evaluation laboratory (DEMATEL) considers the direct and indirect impact relationships between factors to determine key cuases in accidents. DEMATEL is an effective method for analysing complex systems and has been applied in various fields (Tan et al., 2016; Govindan and Chaudhuri, 2016; Park , Kim and Lim, et 2016; Gazibey, and Demirel, 2015). Interpretive structural modelling (ISM) was developed by the Bottelle Institute to analyse complex social system problems. ISM constructs the structure of the system by calculating the reachability matrix among the elements, thereby analysing the direct and indirect relationships among the various factors. ISM has found extensive applications, such as in traffic accidents, address disasters, teaching problems, and enterprises, in recent years (Wang et al., 2018; Huang et al., 2019; Zhou and Lim, 2019; Ma-Jia, and Ding, 2019).

DEMATEL can only discover logical, and not hierarchical, relations among factors. ISM can identify the logical structure of the mutual influences of factors and arrange them in a hierarchy. By combining DEMATEL and ISM, the mutual influence between factors can be analysed and the logical structure between factors established (Chauhan Singh, and Jharkharia, 2018; Zhang and Luo, 2017; Shen et al., 2015). In this study, DEMATEL and ISM are combined to analyse the factors that influence coal spontaneous combustion in longwall gobs and establish a multi-level hierarchical structural model. Then, hierarchical relationships of the influencing factors are determined, and the importance of these factors in coal spontaneous combustion identified.

Literature review

Spontaneous combustion in longwall gobs is a control problem rather than a choice or decision problem, because the influencing factors constitute a network with complex relationships and interactions (Zwetsloot et al., 2017 Arstad and Aven, 2017). In order for spontaneous combustion to occur, the following conditions are required:

- ➤ The coal must be in a broken state
- ➤ There must be a continuous supply of oxygen
- ➤ The environment must be conducive to accumulation of the heat generated by oxidation
- ➤ The three abovementioned conditions must coexist for long enough for the coal to undergo self-ignition.

In addition, appropriate safety technology can mitigate the risk of coal spontaneous combustion (Onifade and Genc, 2020).

In this study, the factors influencing coal spontaneous combustion in longwall gobs include the following four aspects: coal spontaneous combustion propensity, air leakage in longwall gobs, heat storage and dissipation in longwall gobs, and safety management.

Coal spontaneous combustion propensity

The natural tendency of coal to undergo spontaneous combustion is the inherent factor and is directly related to the danger of spontaneous combustion (Genc and Cook, 2015). The oxygen absorption rate and critical temperature of coal are the external characteristics of spontaneous combustion propensity (Zhai Wang, and Joang, 2019; Shi et al., 2018; Qu, Song, and Tan, 2018; Choudhury, Sarkar, and Ram, 2916; Mohalik, Lester, and Lowndes, 2018).

Air leakage in longwall gobs

The air leakage in longwall gobs, which provides the necessary oxygen supply, depends on the ventilation mode at the working face, as well as the porosity of the gob (degree of fragmentation of the coal (Wang et al., 2018; Chen et al., 2019).

Gas drainage measures in longwall gobs change air leakage patterns, thus complicating the gas flow and increasing the risk of, coal spontaneous combustion. An increase in the coal seam dip angle also has this effect, because it is more difficult to close off the cavity, thereby allowing a large air leakage (Tang et al., 2016).

The roof lithology also affects air leakage in longwall gobs. The porosity of the goaf depends on the roof lithology (Wang et al., 2018).

In the case of a shallow coal seam, communication with the surface via fissures may increase air leakage by admitting atmospheric air (Zhai, Wang, and Kiang, 2019).

In summary, the following factors affect air leakage in longwall gobs (Kong et al., 2017; Su et al., 2022):

- ➤ Ventilation mode at the working face
- ➤ Air flow rate at the working face
- ➤ Gas extraction from the gob
- ➤ Fragmentation of coal in the gob
- ➤ Dip angle of coal seam
- ➤ Roof lithology
- ➤ Depth of coal seam.

Heat storage and dissipation

The ratio of the width of the potential self-ignition area to the advancement speed of the working face determines the length of time that the residual coal is exposed to oxidation conditions. A high ratio indicates a considerable risk of spontaneous combustion. The width of the self-ignition area is related to the air leakage intensity. The surrounding rock temperature affects the timing of coal spontaneous combustion, with a higher temperature indicating a shorter time to self-ignition (Zhang et al., 2019).

Three factors affect the heat storage and dissipation conditions in longwall gobs:

1. The ratio of the width of the self-ignition area to the advancement speed of the working face, which can be called the propulsion speed ratio
2. Surrounding rock temperature
3. Air leakage intensity in the gob.

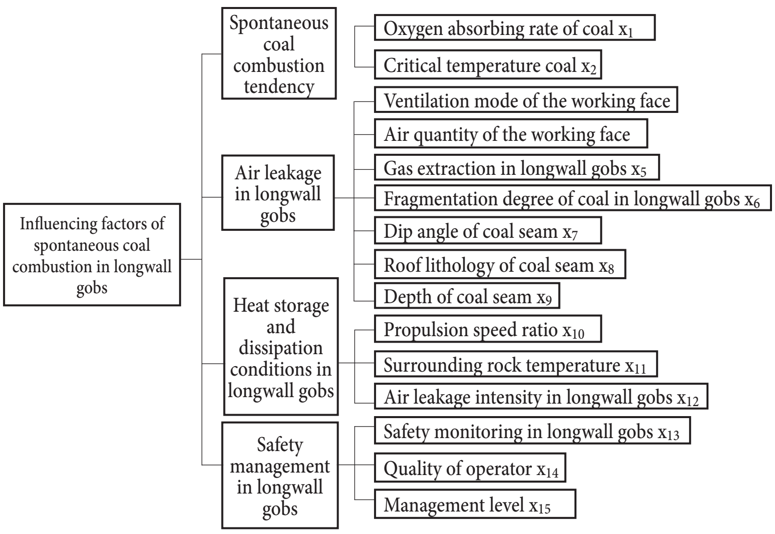

Figure 1—Factors influencing coal spontaneous combustion in longwall gobs

Safety management in longwall gobs

For longwall gobs where people cannot enter, monitoring and predicting the conditions likely to lead to coal spontaneous combustion is crucial. These processes are an effective means of controlling coal spontaneous combustion. In addition, the quality of personnel and the management level must be considered when implementing measures to prevent coal spontaneous combustion in longwall gobs (Guo et al., 2019; Cai, Yang, and Hu, 2019.

As illustrated in Figure 1, 15 factors that influence the coal spontaneous combustion in longwall gobs are identified from four aspects.

The self-ignition hazard in longwall gobs is influenced by many interacting factors simultaneously. These factors can be initially analysed as depicted in Figure 2.

Methodology

The factors influencing coal spontaneous combustion in longwall gobs constitute an interactive network that cannot be accurately analysed using traditional methods. This study uses integrated DEMATEL and ISM. This allows the relative importance of, and interactions between, the various factors to be clearly stated so as to provide specific methods and measures for preventing spontaneous combustion. The basic procedure is outlined in Figure 3.

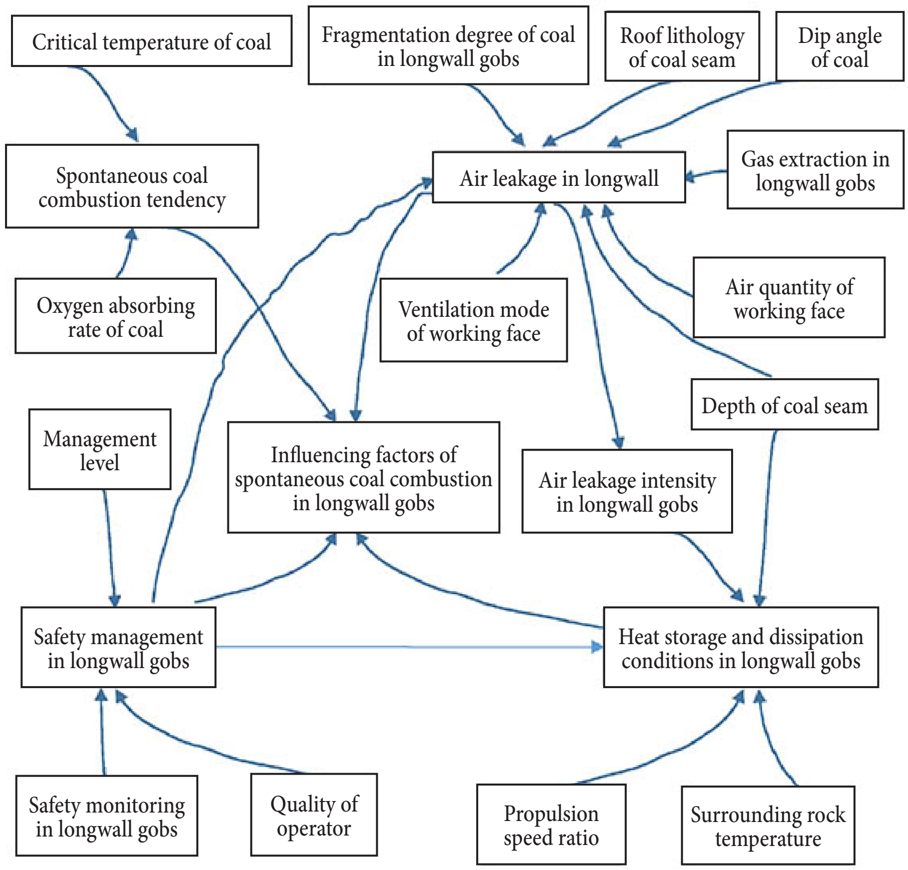

Figure 2—The relationships among the influencing factors

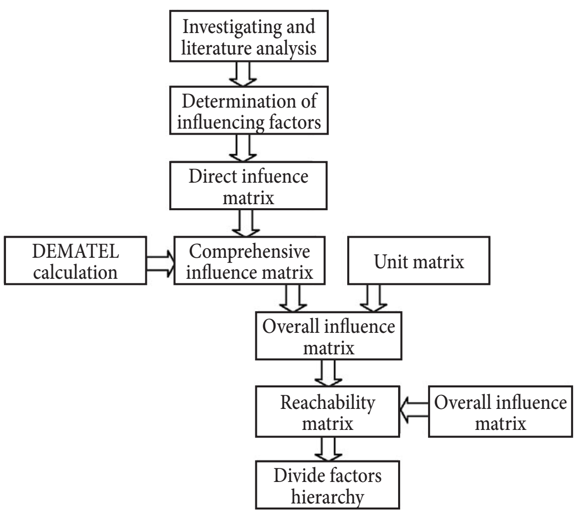

Figure 3—Basic flow of the integrated DEMATEL and ISM methodology

Results and discussion

DEMATEL analysis

In Figure 1, 15 factors that affect coal spontaneous combustion in longwall gobs are determined. Then, expert consultation is used to clarify the relationships among the 15 factors. Four experts from universities and local coal mining enterprises, who have extensive experience in coal spontaneous combustion, were invited to evaluate the relationships between influencing factors. The influence of each factor on the others is ranked into five grades, with each of the factors assigned a specific value, as outlined in Table I.

Table I

Rankings influencing factors.

Influence	None	Weak	Moderate	Strong	Extreme
Rank	0	1	2	3	4

Expert k (k = 1,2,…,m) obtained the direct influence matrix B^k ($B^k = [\beta_{ij}^k]_{n\times n}$), where β_{ij}^k denotes the influence of factor x_i on factor x_j, m denotes the number of experts (m = 4), and n denotes the number of factors (n = 15). Subsequently, the direct influence matrix B($B = [\beta_{ij}]_{n\times n}$) is obtained as follows:

$$B = \begin{bmatrix} 0 & \cdots & \beta_{1n} \\ \vdots & \ddots & \vdots \\ \beta_{n1} & \cdots & 0 \end{bmatrix} = [\beta_{ij}]_{n\times n} \quad [1]$$

where $\beta_{ij} = \frac{1}{m}\sum_{k=1}^{m}\beta_{ij}^k (k = 1,2,\dots,m)$

Table II lists the obtained direct influence matrix.

The direct influence matrix reflects only the direct relationships among the factors. However, these relationships are complicated. The direct and indirect relationships among these factors must be

Table II

Direct influence matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
x_1	0	1.25	0	0	0	0	0	0	0	2.5	0	0	0.75	0.25	0.5
x_2	1	0	0	0	0	0	0	0	0	1.75	0	0	2	0.5	1
x_3	0	0	0	3.25	2.5	1.5	0	0	0	3	0	3	0.75	1	0.5
x_4	0	0	0	0	1.5	0	0	0	0	2.25	0	3.25	2.25	0.5	0.25
x_5	0	0	0	0	0	1.25	0	0	0	2	0	2.75	2.75	1.25	0.5
x_6	0.75	1.25	0	0	0	0	0	0	0	2.75	0	2.5	1.75	0.25	0.25
x_7	0.25	0	1.5	2.75	0.75	2	0	0	0	1.75	0	1.5	0.25	1	1.25
x_8	0.5	0.25	1.25	1	0.75	2.25	2	0	0	1.25	1.5	2.75	2.5	0.75	1
x_9	1.5	1.25	0.75	0.5	0.5	2	0	0.75	0	1.25	2.75	0.5	1	0.75	1
x_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.75
x_{11}	0	0	0	0	0	0	0	0.5	0	1.75	0	0	1	0.5	0.75
x_{12}	1	0	0	0	0	0	0	0	0	2.25	0	0	1.5	0	1
x_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1
x_{14}	0.25	0.25	1.25	1.5	1.25	1	0	0	0	2.25	0	2.5	2.75	0	1.75
x_{15}	0.5	0.25	1.75	2.25	2	1.75	0.5	0.75	1	2.25	1	1.75	2	2.25	0

Table III

Comprehensive influence matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
x_1	0.007	0.073	0.007	0.010	0.009	0.008	0.002	0.002	0.003	0.166	0.003	0.015	0.071	0.026	0.048
x_2	0.062	0.008	0.012	0.017	0.016	0.014	0.003	0.004	0.005	0.137	0.006	0.025	0.146	0.047	0.081
x_3	0.025	0.013	0.016	0.206	0.177	0.114	0.003	0.004	0.005	0.300	0.006	0.276	0.168	0.094	0.087
x_4	0.016	0.004	0.009	0.013	0.097	0.017	0.002	0.003	0.003	0.188	0.004	0.217	0.185	0.049	0.054
x_5	0.019	0.010	0.014	0.020	0.019	0.086	0.002	0.003	0.004	0.184	0.005	0.197	0.216	0.091	0.072
x_6	0.058	0.076	0.007	0.011	0.010	0.009	0.002	0.002	0.003	0.206	0.003	0.156	0.144	0.029	0.050
x_7	0.038	0.017	0.105	0.199	0.095	0.148	0.004	0.006	0.007	0.238	0.008	0.201	0.131	0.098	0.123
x_8	0.060	0.035	0.101	0.119	0.094	0.176	0.117	0.009	0.007	0.238	0.094	0.271	0.267	0.096	0.133
x_9	0.109	0.092	0.064	0.066	0.065	0.147	0.009	0.052	0.006	0.206	0.167	0.114	0.166	0.085	0.115
x_{10}	0.003	0.002	0.006	0.008	0.008	0.007	0.002	0.002	0.003	0.014	0.003	0.011	0.040	0.009	0.048
x_{11}	0.006	0.004	0.012	0.016	0.015	0.016	0.005	0.031	0.004	0.128	0.007	0.027	0.088	0.043	0.063
x_{12}	0.061	0.007	0.009	0.013	0.013	0.011	0.003	0.004	0.004	0.158	0.005	0.018	0.111	0.016	0.076
x_{13}	0.005	0.003	0.010	0.014	0.013	0.012	0.002	0.003	0.004	0.025	0.005	0.021	0.023	0.040	0.066
x_{14}	0.039	0.027	0.090	0.126	0.115	0.093	0.005	0.007	0.009	0.251	0.011	0.234	0.260	0.048	0.155
x_{15}	0.064	0.039	0.130	0.188	0.175	0.159	0.036	0.051	0.061	0.315	0.075	0.252	0.276	0.184	0.091

considered. A comprehensive impact matrix can reflect the direct and indirect relationships of the factors (Zio, 2016). This matrix can be calculated using Equations. ([2] and [3].

$$C = \frac{1}{\max\limits_{1\le i\le n} \sum_{j=1}^{n} \beta_{ij}} B \quad [2]$$

$$T = C + C^2 + \ldots + C^n \quad [3]$$

where C is the normalized direct impact matrix, and $T(T = \lfloor t_{ij} \rfloor_{n\times n})$ is the comprehensive influence matrix, n = 15.

Table III presents the obtained comprehensive influence matrix, with the influencing degree, influenced degree, centrality, and causality of each factor. For factor i , the influencing degree is denoted as f_i , the influenced degree as e_i , the centrality as m_i, and the causality as n_i. These are calculated as follows:

$$f_i = \sum_{j=1}^{n} t_{ij} (i = 1,2,\ldots,\mathrm{n}) \qquad e_i = \sum_{j=1}^{n} t_{ji} (i = 1,2,\ldots,\mathrm{n}), \quad [4]$$

$$m_i = f_i + e_i (i = 1,2,\ldots,n) \quad n_i = f_i - e_i (i = 1,2,\ldots,n) \quad [5]$$

The results are presented in Table IV.

ISM analysis

The comprehensive influence matrix excludes the effects of an individual factor on itself. Therefore, a unit matrix E must be added to obtain the overall influence matrix H ($\mathrm{H} = \lfloor h_{ij} \rfloor_{n\times n}$), as expressed in Equation [6].

$$\mathrm{H} = \mathrm{E} + \mathrm{T} \quad [6]$$

Table V summarizes the obtained overall influence matrix.

On the basis of Equation [6], the reachability matrix $\mathrm{U}(\mathrm{U} = \lfloor u_{ij} \rfloor_{n\times n})$ is constructed by Equation [7].

$$u_{\mathrm{ij}} = \begin{cases} 1 & (h_{\mathrm{ij}} \ge \lambda) \\ 0 & (h_{\mathrm{ij}} < \lambda) \end{cases} \quad (i = 1,2,\ldots,n; j = 1,2,\ldots,n) \quad [7]$$

where λ is the threshold set in accordance with the actual situation.

On the basis of many test results, expert advice, and practical requirements, λ is set to 0.15 in the present study, and then U is constructed as listed in Table VI.

Table IV

Calculation results through the DEMATEL method

Factor	f_i	e_i	M_i	N_i	Factor	f_i	e_i	M_i	N_i
x_1	0.4434	0.5619	1.0052	−0.1185	x_9	1.4429	0.1174	1.5602	1.3255
x_2	0.5688	0.4018	0.9706	0.1670	x_{10}	0.1636	2.7020	2.8656	−2.5385
x_3	1.4702	0.5716	2.0418	0.8985	x_{11}	0.4536	0.3897	0.8434	0.0639
x_4	0.8466	0.9968	1.8434	−0.1502	x_{12}	0.5048	1.9953	2.5001	−1.4905
x_5	0.9201	0.8919	1.8121	0.0282	x_{13}	0.2337	2.2467	2.4804	−2.0130
x_6	0.7593	0.9890	1.7482	−0.2297	x_{14}	1.2003	0.9262	2.1265	0.2741
x_7	1.3925	0.1910	1.5835	1.2014	x_{15}	2.0488	1.0836	3.1324	0.9652
x_8	1.7909	0.1744	1.9653	1.6165					

Table V

Overall influence matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
x_1	1.007	0.073	0.007	0.010	0.009	0.008	0.002	0.002	0.003	0.166	0.003	0.015	0.071	0.026	0.048
x_2	0.062	1.008	0.012	0.017	0.016	0.014	0.003	0.004	0.005	0.137	0.006	0.025	0.146	0.047	0.081
x_3	0.025	0.013	1.016	0.206	0.177	0.114	0.003	0.004	0.005	0.300	0.006	0.276	0.168	0.094	0.087
x_4	0.016	0.004	0.009	1.013	0.097	0.017	0.002	0.003	0.003	0.188	0.004	0.217	0.185	0.049	0.054
x_5	0.019	0.010	0.014	0.020	1.019	0.086	0.002	0.003	0.004	0.184	0.005	0.197	0.216	0.091	0.072
x_6	0.058	0.076	0.007	0.011	0.010	1.009	0.002	0.002	0.003	0.206	0.003	0.156	0.144	0.029	0.050
x_7	0.038	0.017	0.105	0.199	0.095	0.148	1.004	0.006	0.007	0.238	0.008	0.201	0.131	0.098	0.123
x_8	0.060	0.035	0.101	0.119	0.094	0.176	0.117	1.009	0.007	0.238	0.094	0.271	0.267	0.096	0.133
x_9	0.109	0.092	0.064	0.066	0.065	0.147	0.009	0.052	1.006	0.206	0.167	0.114	0.166	0.085	0.115
x_{10}	0.003	0.002	0.006	0.008	0.008	0.007	0.002	0.002	0.003	1.014	0.003	0.011	0.040	0.009	0.048
x_{11}	0.006	0.004	0.012	0.016	0.015	0.016	0.005	0.031	0.004	0.128	1.007	0.027	0.088	0.043	0.063
x_{12}	0.061	0.007	0.009	0.013	0.013	0.011	0.003	0.004	0.004	0.158	0.005	1.018	0.111	0.016	0.076
x_{13}	0.005	0.003	0.010	0.014	0.013	0.012	0.002	0.003	0.004	0.025	0.005	0.021	1.023	0.040	0.066
x_{14}	0.039	0.027	0.090	0.126	0.115	0.093	0.005	0.007	0.009	0.251	0.011	0.234	0.260	1.048	0.155
x_{15}	0.064	0.039	0.130	0.188	0.175	0.159	0.036	0.051	0.061	0.315	0.075	0.252	0.276	0.184	1.091

Table VI

Reachability matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
x_1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
x_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
x_3	0	0	1	1	1	0	0	0	0	1	0	1	1	0	0
x_4	0	0	0	1	0	0	0	0	0	1	0	1	1	0	0
x_5	0	0	0	0	1	0	0	0	0	1	0	1	1	0	0
x_6	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0
x_7	0	0	0	1	0	0	1	0	0	1	0	1	0	0	0
x_8	0	0	0	0	0	1	0	1	0	1	0	1	1	0	0
x_9	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0
x_{10}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
x_{11}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
x_{12}	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
x_{13}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
x_{14}	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0
x_{15}	0	0	0	1	1	1	0	0	0	1	0	1	1	1	1

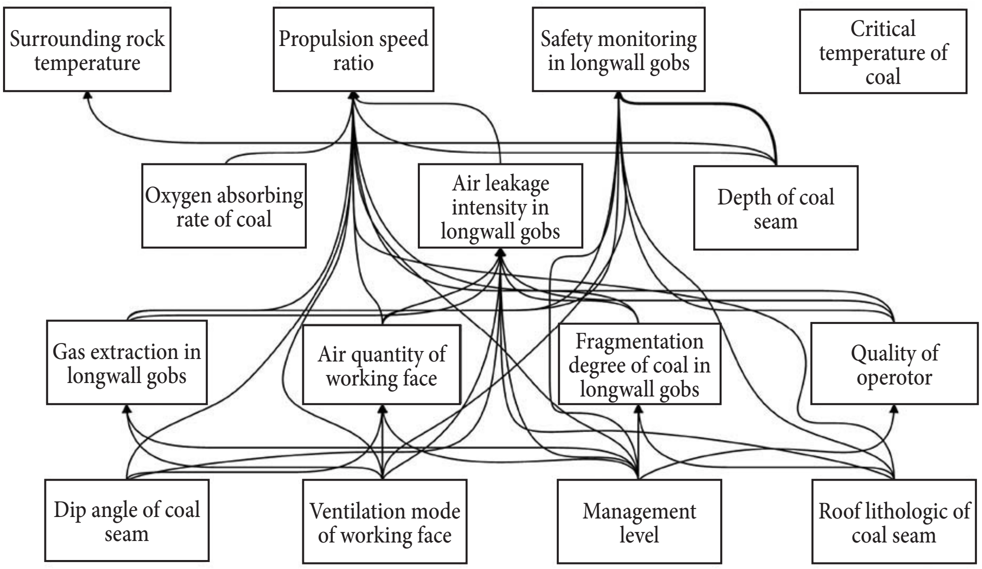

Figure 4 – Hierarchical model of the factors influencing coal spontaneous combustion in longwall gobs

Subsequently, the reachable set R_i and antecedent set S_i of factor *i* are determined in accordance with Equation [8], and the top-level factors for the reachability matrix are obtained using Equation [9].

$$R_i = \{a_j | a_j \in A, k_{ij} \neq 0\} \qquad S_i = \{a_j | a_j \in A, k_{ji} \neq 0\} \qquad (i = 1,2,\ldots,n) \quad [8]$$

$$R_i = R_i \cap S_i \,(i = 1,2,\ldots,n) \quad [9]$$

Results

The top factor is removed from the reachability matrix. Then, we continue to find the top-level factors of the residual matrix and remove them from the matrix until all the factors are screened. The order in which the factors are removed constitutes the hierarchy. The collections of the top-, second-, third-, and lowermost-layer factors correspond to $\{X_2, X_{10}, X_{11}, X_{13}\}$, $\{X_1, X_9, X_{12}\}$, $\{X_4, X_5, X_6, X_{14}\}$, and $\{X_3, X_7, X_8, X_{15}\}$. The hierarchy of the factors is displayed in Figure 4.

Discussion

The four direct causes of the spontaneous combustion of coal in longwall gobs are the temperature of the surrounding rock, the advancement speed of the working face, safety monitoring of the gob, and the critical temperature of the coal.

The intrinsic propensity of a coal to undergo spontaneous combustion can be assessed using methods such as the Wits-Ehac index and CJI index (Onifade and Genc, 2020; Gao et al., 2021). In this study, the critical temperature and oxygen absorption rate of the coal were used to determine the spontaneous combustion propensity (Wang et al., 2014). These factors have minimal impact on external factors, which are both the direct and fundamental causes of coal spontaneous combustion.

The dip angle of the coal seam, ventilation mode at the working face, management of the longwall gas extraction area, and lithology of the coal seam roof are closely related to other factors, indicating that these four factors have a complex relationship with other factors and are brittle factors of coal spontaneous combustion.

Coal spontaneous combustion in longwall gobs is governed by a complex network of nonlinear correlations among the factors causing spontaneous combustion.

Conclusions

In this study, the mechanisms of coal spontaneous combustion in longwall gobs were analysed, and 15 factors influencong the phenomenon were identified on the basis of relevant literature. The relationships among these factors were analysed in detail through the DEMATEL–ISM method. This method integrated the DEMATEL and ISM to elucidate the logical relationships among the factors and determine their relative importance. The direct and primary causes and the key factors that lead to spontaneous combustion were identified through this method. The results clearly indicate the relationships among the factors that cause coal spontaneous combustion in longwall gobs. The results can also constitute a basis for preventing accidents caused by spontaneous combustion.

Author contributions

Conceptualization, Liang Zhou; Data curation, Liang Zhou; formal analysis, Liang Zhou, Jian Wang, Mingyun Tang, and Jinwei Qiu; funding acquisition, Guanglong Dai; methodology, Jian Wang; resources, Liang Zhou, Jinwei Qiu; Writing – original draft, Liang Zhou.

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Conflicts of interest

The authors declare no conflict of interest.

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