Article

Emergency Response Plan for Spontaneous Combustion Based on Case-Based Reasoning

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Abstract: In order to avoid missing the best opportunity for emergency rescue in the event of spontaneous combustion and to prevent accidents from developing further, this paper proposed a method to generate an emergency response plan for spontaneous combustion based on case-based reasoning (CBR). Firstly, we adopted Hadoop big data retrieval technology to establish a case library for spontaneous combustion; then, our team applied CBR technology and introduced the differential determination symbol to calculate case similarity; furthermore, we quickly generated an emergency response plan for spontaneous combustion with the help of the Python program; and finally, we used a case to verify the effectiveness of the method. Overall, the results showed that the emergency response plan generated using this proposed method was consistent with the actual situation of the accident case and, compared with other relevant representative algorithms, the results in this paper were more accurate. In practice, this method may be helpful in providing support for generating emergency response plans for spontaneous combustion.

Keywords: spontaneous combustion; emergency response plan; CBR; similarity

1. Introduction

Spontaneous combustion remains one of the most serious disasters in coal mines because it not only burns coal resources and causes huge economic losses but also produces large amounts of CO, H2S, SO2 and other harmful gases, thereby seriously polluting the air and environment. In addition, it often leads to gas combustion, dust explosion and other accidents, causing serious casualties [1–4]. In China’s key state-owned coal mines, more than 54% of coal mines are at risk of spontaneous combustion and the shortest spontaneous combustion period of coal is less than 3 months [5]. According to incomplete statistics, there were over 4000 spontaneous fire hazards in coal mines in China each year, resulting in over 360 mine disasters. So far, there are still over 800 fire areas formed by spontaneous fires in China, which have sealed and frozen over 200 million tons of coal resources, resulting in a large amount of coal resources that cannot be effectively exploited and utilized. With the increasing depth of mining, combined with the high ground temperatures and high rock temperatures, the problem of spontaneous combustion will become more serious in deep mining than in shallow-zone mining and, thus, more difficult to prevent and control. These factors also make it more difficult to perform emergency rescue in deep mining areas [6].

An emergency response plan is essentially a pre-defined action plan for possible contingencies and the rapid and orderly implementation of emergency actions. From a philosophical point of view focusing on safety, accidents can be prevented, and the most critical means to prevent accidents are to establish a reasonable and effective emergency response plan. The emergency response plan is an essential guide on how to carry out emergency rescue work at an accident site. There are no two identical accidents; since
there is a large diversity of accidents, a fixed single contingency plan cannot meet the actual needs and requires continuous adjustments depending on the circumstances of the accident. At the early stage of an accident, when the location of the incident is unknown and the knowledge and experience of the decision-maker are limited, the rapid formation of emergency response plans in the presence of incomplete information is central to emergency management and acts as an important research topic at this stage.

Many scholars have conducted related research on emergency rescue of spontaneous combustion, which mainly focuses on emergency response systems [7–10], emergency rescue capability [11–14], etc., but less research exists on the generation of emergency response plans for spontaneous combustion.

It is well known that there is an element of uncertainty involved in accidents, i.e., the time and place are uncertain, and rescue experts are generally not the first to reach the scene of an accident. Addressing coal spontaneous combustion accidents quickly and appropriately can effectively avoid the further development of accidents. Once the optimal time for rescue is missed, a coal spontaneous combustion accident will cause a more serious secondary accident, leading to greater difficulty in the rescue and greater danger to both the rescuers and the trapped. The main purpose of this paper is to propose a method to quickly generate an emergency response plan based on previous accident cases, which provides a reference for emergency rescue command, controls the development of the accident and prevents the expansion of the accident.

Based on the above-mentioned findings, this paper proposed the case-based reasoning (CBR) method to rapidly generate an emergency response plan for spontaneous combustion for the first time. CBR is a nature-inspired machine-learning approach that continuously learns from past experiences and saves newly solved problems and corresponding solutions into the case library. This method can effectively utilize accumulated experience in the absence of in-depth knowledge. CBR has been widely applied directly or indirectly to solve complex problems, such as in marine emergency rescue [15], urban water supply networks [16], environmental emergency response decisions [17], marine oil spill emergency responses [18], ontological metro accidents [19], fire emergency decisions in high-rise buildings [20], judicial case recommendations [21], railway emergency response decision-making [22], emergency decision-making system for the South-to-North Water Diversion Project [23], forest fire risk forecasting [24] and in other fields. The application of the CBR method in coal mine safety has mainly focused on hidden danger identification and control [25], coal mine disaster early warning [26], coal and gas outburst accident prevention [27], coal mine water disaster [28] and coal mine gas explosion accidents [29]; however, the application of the CBR method in the generation of an emergency response plan for spontaneous combustion has not yet been explored.

In this paper, we adopted Hadoop big data retrieval technology to establish a case library of coal mine fires, introduced a differential determination symbol to calculate similarity, wrote a program in the Python language based on CBR and quickly generated an emergency response plan of spontaneous combustion. Our research will provide an important reference for the prior disposal of spontaneous combustion and effectively avoiding accident expansion.

2. Case-Based Reasoning Method

CBR involves using past similar cases to solve recently occurring events. A complete “4R” cycle consists of four phases: case retrieval, case reuse, case revise and case retain [19,24].

(1) Retrieval: The most critical stage of CBR is retrieval. The accuracy of similarity is critical to the success of a CBR system. According to the current accident situation, the relevant cases are retrieved according to the settled retrieval rules, and then the most similar case is retrieved based on the similarity between the current and the retrieved case in the case base.

(2) Reuse: Based on the solutions and ideas of the retrieved case, as well as the effectiveness of the final emergency rescue, correct analysis and adaptive adjustment are carried out according to the current situation and applied to the current case to solve the current
emergency problem and achieve better emergency rescue result. (3) Revise: Old solutions to new problem are the essence of CBR, but just as there cannot be two identical leaves in the world, there cannot be two identical events, so old solutions of the retrieved cases need to be revised before applying it to the current accident. Because the social environment and technology are constantly evolving as well as contingencies, the revision requires very specialized knowledge and experience of experts. (4) Retain: cases are added, which are revised by experts, to the case library. Due to practical limitations, it takes a relatively long time to establish a case library, and the number of cases that can be retrieved in the case library also affects the effectiveness of CBR. Continuous learning and accumulation are needed to enrich the case library and improve the accuracy of case retrieval.

The specific solution of CBR is to use past similar cases in the case library to solve the current occurred case. The procedure for solving a new problem based on CBR is shown in Figure 1 [30]:

![Figure 1. The procedure for solving new problem with CBR.](image)

Most studies considered the effect of similarity algorithms on the accuracy of case retrieval. Bannour et al. proposed a two-stage short text case retrieval approach for crisis response similarity computation [31]. However, the semantic similarity approach does not consistently capture the semantics of the text, which may reduce the sensitivity of the similarity computation. Building on the development of online knowledge databases, Li et al. proposed a novel approach to address the limited information and sparse features of short texts by combining Wikipedia with semantic similarity [32]. Chen, M et al. proposed a tree-based semantic similarity computation method to define the relationship between aviation fault parts and fault modes [33]. Yiyang, Z et al. proposed a modified interval similarity computation method to improve the sensitivity of interval similarity computation and introduced structural similarity to reduce the effect of missing attributes on similarity [34]. However, the text parameters in this paper have an obvious impact on accident rescue, different accident locations, smoke conditions, geological conditions and roadway distribution corresponding to different emergency plans, and the text semantic similarity calculation method may detect more irrelevant cases, so it is not applicable to the
method in this paper. In this paper, we set the text parameters as equivalent symbols to compute the similarity, and the results are closer to the real case.

Mathematical research is not limited to “STE” (science, technology and engineering) but should be extended to every subject area [35]. Methods based on pure mathematical theory are relatively rare in case reasoning, possibly because mathematical-based methods require the development of accurate mathematical models and inferential verification of algorithmic stability [36,37].

Case-based reasoning techniques have been improved to accommodate applications in a variety of domains. Zhang, H et al. attempted a strategy of clustering the case database before retrieval to narrow the scope of case retrieval [38]. Shen, L proposed a scenario-based extended CBR approach to introduce risk similarity into the similarity computation for risk response in critical infrastructures [39]. Uysal, F proposed a bootstrap aggregated CBR approach for conceptual cost estimation [40]. Shi, X proposed an ontology-based CBR method for assembly sequence decision-making [41]. Zhan, J proposed an adaptive evaluation system for TBM tunneling based on case-based reasoning [42]. However, these state-of-the-art techniques have specific application domains, and their application in different domains still requires prior validation.

3. Using CBR Method Generate Emergency Response Plan

3.1. Establish a Case Base

To establish a case base, we adopted Hadoop big data and collected relevant cases of spontaneous combustion accidents that were publicly available on websites before May 2023, such as the National Mine Safety Administration, Provincial branches of National Mine Safety Administration, Coal Mine Safety Network, China Academy of Safety Science and Technology and Safety Management Network. Keywords such as “spontaneous combustion”, “spontaneous fire”, “spontaneous fire”, “smoldering fire”, “coal mine fire”, “spontaneous ignition”, “natural ignition” and “natural combustion” were used; the relevant literature on CNKI and Web of Science published before May 2023 were searched; relevant cases were selected; and detailed parameters of the selected cases as well as relevant accident investigation reports were extracted. The above cases formed a library of coal mine fires. Hadoop’s web search is called “Map and Reduce”, and its process is shown in Figure 2.

![Map and Reduce process](image)

**Figure 2.** Map and Reduce process.

3.2. Attribute Parameters and Knowledge Representation of Cases

According to the accident scenarios and influencing factors of spontaneous combustion accidents [43–45], combined with the monitoring data of accident cases [46,47], the knowl-
edge representation and attribute parameters of spontaneous combustion were analyzed and summarized in Table 1.

Table 1. Attribute parameters and knowledge representation of cases.

<table>
<thead>
<tr>
<th>Case Attribute</th>
<th>Attribute Type</th>
<th>Knowledge Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous combustion tendency</td>
<td>Differential determination symbol</td>
<td>Easy spontaneous combustion, spontaneous combustion, nonflammable.</td>
</tr>
<tr>
<td>Locations where the accident happened</td>
<td>Equivalence symbol</td>
<td>Gob roadway, gob, intake airway, return airway, open-off cut, crushed pillar, floating coal, roof falling, junction with old kiln, near the airtight wall, near the stopping line, shaft wall fracture.</td>
</tr>
<tr>
<td>Gas concentration</td>
<td>Definite number or fuzzy interval</td>
<td>Values range from 0 to 1.5%, greater than 1.5%, calculated as 1.5%.</td>
</tr>
<tr>
<td>CO concentration</td>
<td>Definite number or fuzzy interval</td>
<td>Values range from 0 to 1000 ppm, greater than 1000 ppm, calculated as 1000 ppm.</td>
</tr>
<tr>
<td>Air leak condition</td>
<td>Equivalence symbol</td>
<td>Air leakage in gob, air leakage from coal pillar cracks, air leakage from coal wall cracks, air leakage from airtight wall.</td>
</tr>
<tr>
<td>Naked light</td>
<td>Equivalence symbol</td>
<td>Yes, no.</td>
</tr>
<tr>
<td>Smog</td>
<td>Equivalence symbol</td>
<td>Yes, no.</td>
</tr>
<tr>
<td>Gateway arrangement</td>
<td>Equivalence symbol</td>
<td>Two lane, single lane, one and a half lane, Multiple lane.</td>
</tr>
<tr>
<td>Coal-seam thickness</td>
<td>Definite number or fuzzy interval</td>
<td>Values range from 0 to 8 m, greater than 8 m, calculated as 8 m.</td>
</tr>
<tr>
<td>Geological conditions</td>
<td>Equivalence symbol</td>
<td>Simple, moderate, complex.</td>
</tr>
</tbody>
</table>

3.3. Calculate Case Similarity
3.3.1. Calculate Similarity of Case Attributes

As can be seen from Table 1, the case attributes in this paper have the following types: equivalence symbol, differential determination symbol, definite number and fuzzy interval.

Assuming there are two cases, A and B, where A is the accident case and B is the case in the case library, \( a_i \) is the attribute \( i \) with respect to case A, \( b_i \) is the attribute \( i \) with respect to case B, and \( \text{sim}(a_i, b_i) \) is the similarity of attribute \( i \).

(1) For equivalence symbol

The calculation of the similarity is based on the Boolean operations, and the formula is:

\[
\text{sim}(a_i, b_i) = \begin{cases} 
0, & a_i \neq b_i \\
1, & a_i = b_i 
\end{cases} 
\]  

(1)

(2) For differential determination symbol

If two attributes are identical, \( \text{sim}(a_i, b_i) = 1 \). In the existing literature, the ordered enumeration attributes were generally used to calculate the similarity of the hierarchy attribute [26]. In this paper, considering the increasing mining depth of coal mines, the similarity of the hierarchy attribute is affected by high temperature, high stress and strong mining exploitation. Therefore, the spontaneous combustion tendency was set as a differential determination symbol. That is, if the two attributes are “easy spontaneous combustion” and “spontaneous combustion”, the similarity can be taken as 0.8, i.e., \( \text{sim}(a_i, b_i) = 0.8 \). If the two attributes are “nonflammable” and “spontaneous combustion”, the similarity can be taken as 0.2, i.e., \( \text{sim}(a_i, b_i) = 0.2 \), or else, \( \text{sim}(a_i, b_i) = 0 \).
(3) For the definite number

The similarity of the definite number can be calculated by the Euclidean distance, which can reflect numerical differences. The calculation formula is:

\[
sim(a_i, b_i) = 1 - \frac{\text{dist}(a_i, b_i)}{z_i} = 1 - \frac{|a_i - b_i|}{\max_i - \min_i}
\]

where \(z_i\) is the value range of the attribute \(i\), \(\max_i\) is the maximum value of the attribute \(i\), and \(\min_i\) is the minimum value of the attribute \(i\).

(4) For definite number and fuzzy interval, the calculation formula is:

\[
sim(a, [b_1, b_2]) = 1 - \frac{\text{dist}(a, [b_1, b_2])}{\max_i - \min_i}
\]

(5) For fuzzy interval and fuzzy interval, the calculation formula is:

\[
\text{dist}(a, [b_1, b_2]) = \left( \int_{b_1}^{b_2} \text{dist}(a, x)dx \right) / (b_2 - b_1) = \begin{cases} 
\frac{(b_2 + b_1 - 2a)}{a \leq b_1} \\
\frac{(b_2 - a)^2 + (b_1 - a)^2}{2(b_2 - b_1)}, b_1 < a < b_2 \\
\frac{2a - b_2 - b_1}{b_2} \end{cases}
\]

(6) If the attribute is missing, that is, if there is no specific value or description for the attribute of the accident case or the case in the case base, then the similarity of the attribute is \(\sim(a_i, b_i) = 0\).

3.3.2. Calculate Case Similarity

Considering that the small number of cases in the case base and some parameters may be incomplete in the case, the nearest neighbor method was used to calculate the overall similarity of the case, and the calculation formula is:

\[
sim(A, B) = \sum_{i=1}^{n} \omega_i \sim(a_i, b_i)
\]

where \(n\) is the number of attributes in the case, \(\sim(a_i, b_i)\) is the similarity of the attribute \(i\), \(\omega_i\) is the weight of the attribute \(i\), given by the experts, and \(\sim(A, B)\) is the overall similarity of the case. The entropy weight method [48], which was founded by German physicist Clausius in 1856, was used to calculate the relevant weight through the expert questionnaire, and the specific calculation process is not repeated. The attribute weights are listed in Table 2.

3.3.3. Candidate Cases

The top three cases in terms of similarity were exported to form candidate cases, and the corresponding emergency response plan formed the available emergency plan. The optimal emergency response plan will be determined by rescue commanders and experts, who will revise and adjust it according to the actual situation. This paper will use prospect
theory to determine the optimal emergency response plan. Due to space issues, it will be described in detail in the subsequent study.

Table 2. Attribute weights of case.

<table>
<thead>
<tr>
<th>Case Attribute</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous combustion tendency</td>
<td>0.1113</td>
</tr>
<tr>
<td>Locations where the accident happened</td>
<td>0.0880</td>
</tr>
<tr>
<td>Gas concentration</td>
<td>0.0681</td>
</tr>
<tr>
<td>CO concentration</td>
<td>0.0824</td>
</tr>
<tr>
<td>Air leak condition</td>
<td>0.1090</td>
</tr>
<tr>
<td>Naked light</td>
<td>0.1057</td>
</tr>
<tr>
<td>Smog</td>
<td>0.0993</td>
</tr>
<tr>
<td>Gateway arrangement</td>
<td>0.1299</td>
</tr>
<tr>
<td>Coal seam thickness</td>
<td>0.1252</td>
</tr>
<tr>
<td>Geological conditions</td>
<td>0.0812</td>
</tr>
</tbody>
</table>

3.3.4. Improve the Case Library

After the current accident was resolved, it was added to the case base as a new case to continuously improve and enrich the case library.

3.4. Program Implementation

The best rescue time for a spontaneous combustion accident is in the early stage of the accident. In the early stage of accident, rapid and effective disposal measurements can effectively prevent the expansion of accidents and minimize accident losses as much as possible. In order to improve the timeliness of emergency rescue, this paper used the Python program to generate emergency response plans based on CBR. The emergency response plan was quickly generated by entering the related parameters of the current accident. Part of the Python program is shown in Figure 3. Because the cases in the case library are in Chinese, this program is mainly applicable to the Chinese case base at present. The emergency response plan can be generated in a few seconds by this program.

```python
def similarity_calculator(an, bn):
    pa = [0.1113, 0.0880, 0.0681, 0.0824, 0.1090, 0.1057, 0.0993, 0.1299, 0.1252, 0.0812]
    sim = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
    try:
        cn[0] = sim[0] = sim[0] = sim[0] = sim[0] = sim[0] = sim[0] = sim[0] = sim[0] = sim[0]
        if sim[2] > sim[2]:
        elif sim[3] > sim[3]:
        else:
            if sim[3] > sim[3]:
            else:
        for i in range(10):
            sim[0] = sim[0] + sim[0]
        return sim
    except
        print("Error in calculating similarity!")
```

Figure 3. Part of the Python program.
4. Case Study

4.1. Accident Case

4.1.1. Accident Overview

On 5 December 2018, during the middle shift, an employee, Lv, who was working in the underground material turnover warehouse, discovered yellow smoke floating outside the closed wall along the track of the 230 fully mechanized top coal caving face (smoke within a range of 0.5 m below the roadway roof) (Shandong Bureau of the National Mine Safety Administration). He immediately reported it to the mine control room, and the person on duty immediately reported it to the deputy mine manager, Feng. Deputy mine manager Feng immediately went down to inspect the situation and found that there was air leakage in the gob area and the residual coal near the mining terminal line ignited spontaneously. After lifting the well, deputy mine manager Feng worked with the mine manager, chief engineer and production mine manager to develop a response plan.

4.1.2. Coal Mine Overview

Tangyang Coal Mine is a low gas mine with no abnormal gas-effusing areas. The main mineable coal seam is coal seam 3, which has a tendency of spontaneous combustion (the spontaneous combustion period is 3–6 months and the shortest spontaneous combustion period is 47 days). The coal dust is explosive (with an explosion index of 35.57%), and the coal seam roof and floor have been identified to have a weak burst potential. The hydrogeological type of the mine is moderate. The mine is equipped with safety monitoring, a personnel positioning system, an emergency adaption system, communication and liaison, a self-saving system, water supply rescue and other safety evacuation systems.

The mining accident area is the second mining area: the main mineable coal seam has three coal seams, the average thickness of the coal seam is 5.11 m, and the coal seam has a spontaneous combustion tendency. In the second mining area, there were a total of 14 working faces, with no abnormal gas-effusing areas. The 230 fully mechanized top-coal caving face is the first mining face in this mining area.

4.2. Case Generation

4.2.1. Extract Accident Attributes

Based on the accident overview and coal mine overview, case attributes were extracted. The floating yellow smoke outside the sealing wall indicated that there was alkane type pyrolysis gas in the gob area, and the gas may have accumulated. Therefore, the gas concentration was defined as 1.5% according to the coal mine safety standard. The accident attributes were listed in Table 3.

<table>
<thead>
<tr>
<th>Case Attributes</th>
<th>Knowledge Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous combustion tendency</td>
<td>Spontaneous combustion</td>
</tr>
<tr>
<td>Locations where the accident happened</td>
<td>Near the obturating wall</td>
</tr>
<tr>
<td>Gas concentration</td>
<td>1.5%</td>
</tr>
<tr>
<td>CO concentration</td>
<td>/</td>
</tr>
<tr>
<td>Air leak condition</td>
<td>Air leakage in gob area</td>
</tr>
<tr>
<td>Naked light</td>
<td>No</td>
</tr>
<tr>
<td>Smog</td>
<td>Yes</td>
</tr>
<tr>
<td>Gateway arrangement</td>
<td>/</td>
</tr>
<tr>
<td>Coal seam thickness</td>
<td>5.11 m</td>
</tr>
<tr>
<td>Geological conditions</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

4.2.2. Specific Similarity Calculation Steps

Step1: Calculate the similarity of the “spontaneous combustion tendency”. The attribute type of the “spontaneous combustion tendency” is the differential determination symbol, so if the attribute of the case in the case base is “easy spontaneous combustion”, the
similarity is 0.8; if the attribute of the case in the case base is “nonflammable”, the similarity is 0.2; and if the attribute of the case in the case base is “spontaneous combustion”, the similarity is 1.

Step 2: Calculate the similarity of “locations where the accident happened”. The attribute type of “locations where the accident happened” is an equivalence symbol; the similarity is calculated according to Formula (1).

Step 3: Calculate the similarity of “Gas concentration”. The attribute type of “gas concentration” is a definite number; the similarity is calculated according to Formula (2).

Step 4: Calculate the similarity of the “CO concentration”. Due to the attribute being missing, the similarity of this attribute is 0.

Step 5: Calculate the similarity of the “air leak condition”. The attribute type of the “air leak condition” is an equivalence symbol; the similarity is calculated according to Formula (1).

Step 6: Calculate the similarity of “naked light”. The attribute type of “naked light” is an equivalence symbol; the similarity is calculated according to Formula (1).

Step 7: Calculate the similarity of “smog”. The attribute type of “smog” is an equivalence symbol; the similarity is calculated according to Formula (1).

Step 8: Calculate the similarity of “gateway arrangement”. Due to the attribute being missing, the similarity of this attribute is 0.

Step 9: Calculate the similarity of the “coal seam thickness”. The attribute type of the “coal seam thickness” is a definite number; the similarity is calculated according to Formula (2).

Step 10: Calculate the similarity of “geological conditions”. The attribute type of “geological conditions” is an equivalence symbol; the similarity is calculated according to Formula (1).

Step 11: Calculate the similarity of the target case according to Formula (8).

Step 12: Calculate the similarity between the target case and all the cases in the case base according to Step 1 to Step 11. Thus, the top three cases in terms of similarity are selected.

4.2.3. Generate Emergency Response Plan

According to the specific similarity calculation steps, CBR was used to quickly generate an emergency response plan based on the Python program. Considering the incomplete attributes of the case in the case library, incomplete information of the current accident, and the localizability of calculation accuracy due to the computer program, in order to ensure the effectiveness of the emergency response plan, this paper quickly generated the top three emergency response plans in terms of similarity. The case generation results are listed in Table 4.

<table>
<thead>
<tr>
<th>Case No</th>
<th>Similarity</th>
<th>Emergency Response Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>0.57</td>
<td>(1) Monitor the gas composition and concentration near the airtight wall; (2) repair the sealing wall with yellow mud paste; (3) build an explosion-proof wall outside the obturating wall and take measurements to prevent the accumulation of gas and the explosion; (4) build a permanent sealing wall outside the sealed upper and lower auxiliary alleys to reduce air leakage in the fire area; (5) grout the new obturating wall of the upper auxiliary lane; (6) constantly inject nitrogen into the fire area to extinguish the fire.</td>
</tr>
<tr>
<td>3</td>
<td>0.56</td>
<td>(1) Monitor the gas composition and concentration near the airtight wall and the gob area, monitor temperature changes; (2) mine shutdown, centralize reinforcement of the airtight wall in the gob area and apply white mortar to seal the joints and leaks; (3) seal the connection of the gob areas with other mines; (4) inject grout into the airtight wall to extinguish the fire, and replenish grout into other airtight walls.</td>
</tr>
<tr>
<td>57</td>
<td>0.51</td>
<td>(1) Close working face; (2) take timely measurements to prevent and control the further expansion of the fire, determine the location of the fire; (3) inject carbon dioxide and nitrogen to extinguish the fire.</td>
</tr>
</tbody>
</table>
The case with the highest similarity is case 56, followed by case 3 and case 57. Case 56 is the 12·5 accident at Chaohua Mine. A spontaneous fire occurred in the gob area of Chaohua Mine when the coal mine opened the airtight wall without monitoring the gas concentration and temperature changes near the stopping face. The situation of gas accumulation was fully considered, and emergency response measurements were conducted in a timely manner, without causing the expansion of the accident.

Case 3 is the 4·20 accident at Liutungou Mine. Coal spontaneous combustion occurred in the gob area of Liutungou Mine, and CO gas was found gushing out at the close mouth of the ventilation roadway in the working face, which exceeded the specified safe concentration. Due to the untimely implementation of emergency response measurements, the fire in the gob area spread towards the main roadway, leading to the shutdown of the entire mine.

Case 57 is the 6·28 accident at Liyang Coal. The coal seam spontaneous combustion accident occurred at Liyang Coal. The monitoring system showed that the CO concentration in the return airway reached 19 ppm, and the CO concentration in the cracks between the supports reached 100 ppm. The emergency response measurements were taken without causing the expansion of the accident.

5. Discussion

5.1. Compliance of Results

The accident case used in this paper is the 12·7 spontaneous combustion and pyrolysis gas explosion accident of Tangyang Coal Mine. In the early stage of the accident, improper emergency response measurements were taken because the gas composition and concentration in the gob area were not analyzed. The airtight wall was built without detecting and treating the gas accumulation in a timely manner, which was the indirect cause of the accident, resulting in a gas explosion and leading to the expansion of the accident.

From the results of CBR, it can be seen that the overall similarity of cases was low, mainly because there were missing attributes in the accident case. In fact, in the early stage of an accident, it is difficult to obtain all the information about the accident.

The results were consistent with the prevention and control measurements of the accident recorded in the investigation report. By applying the emergency response plan generated using CBR to the accident cases, case 56 and case 3 can eliminate the main indirect causes of accidents and avoid their expansion. In practice, taking into account the actual situation of the mine and the differences in time and space between cases, it is necessary to refer to the opinions of rescue command and experts and make adaptive adjustments according to local conditions.

The CBR method proposed in this paper considerably saves time, buys additional time for emergency rescue and improves the timeliness of emergency rescue for spontaneous combustion in coal mines.

5.2. Compare Analysis with Different Methods

Similarity calculation is the core content of CBR, which is related to the accuracy of the results. Many scholars have made related improvements and carried out research on the similarity calculation method of CBR; this paper compared and analyzed different similarity calculation methods in the literature, and the results are listed in Table 5.

From the comparison analysis in Table 5, it can be seen that the results of the proposed method in this paper were basically consistent with the results of the calculation methods used in the existing literature, and were closest to the research findings of Liu et al. and Chen et al. [15,26]. Liu et al. [15] used a strict difference determination symbol to calculate the similarity of hierarchy attributes, that is, for those with a hierarchy difference of 1, the similarity is 0.5, and for others, the similarity is 0, and if the two attributes are “nonflammable” and “spontaneous combustion”, the overall similarity of the case will relatively high. Chen et al. [26] adopted the ordered enumeration attributes; using this method, if the two attributes are “nonflammable” and “easy spontaneous combustion”, the
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overall similarity of the case will be relatively high. Khan et al. [30] and Kim et al. [49] used
deterministic symbols to calculate the similarity and ignored the certain similarity between
relatively close hierarchy, which resulted in smaller calculation results and the possibility
of missing cases.

Table 5. Compare analysis with different methods.

<table>
<thead>
<tr>
<th>Case Attributes</th>
<th>Proposed Method</th>
<th>Khan et al. [30] and Kim et al. [49]</th>
<th>Liu et al. [15]</th>
<th>Chen et al. [26]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous combustion tendency</td>
<td>1 1 0 0.8</td>
<td>1 1 0 0.8</td>
<td>1 1 0 0.8</td>
<td>1 1 0 0.8</td>
</tr>
<tr>
<td>Locations where the accident happened</td>
<td>1 1 0 0.8</td>
<td>1 1 0 0.8</td>
<td>1 1 0 0.8</td>
<td>1 1 0 0.8</td>
</tr>
<tr>
<td>Gas concentration</td>
<td>0.13 0.04 0</td>
<td>0.13 0.04 0</td>
<td>0.13 0.04 0</td>
<td>0.13 0.04 0</td>
</tr>
<tr>
<td>CO concentration</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Air leak condition</td>
<td>0 1 1 0</td>
<td>0 1 1 0</td>
<td>0 1 1 0</td>
<td>0 1 1 0</td>
</tr>
<tr>
<td>Naked light</td>
<td>1 0 1 0</td>
<td>1 0 1 0</td>
<td>1 0 1 0</td>
<td>1 0 1 0</td>
</tr>
<tr>
<td>Smog</td>
<td>1 1 0 0</td>
<td>1 1 0 0</td>
<td>1 1 0 0</td>
<td>1 1 0 0</td>
</tr>
<tr>
<td>Gateway arrangement</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Coal seam thickness</td>
<td>0.639 0.518 0.999</td>
<td>0.639 0.518 0.999</td>
<td>0.639 0.518 0.999</td>
<td>0.639 0.518 0.999</td>
</tr>
<tr>
<td>Geological conditions</td>
<td>1 1 1 1</td>
<td>1 1 1 1</td>
<td>1 1 1 1</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>Overall similarity</td>
<td>0.57 0.56 0.51</td>
<td>0.57 0.56 0.51</td>
<td>0.57 0.56 0.56</td>
<td>0.42 0.48 0.45</td>
</tr>
</tbody>
</table>

Notes: the numbers 56, 3 and 57 in the table represent the top three case numbers in terms of similarity with the accident case.

In this paper, a differential determination symbol was used to calculate the similarity
of the spontaneous combustion tendency, which may enrich and refine the attributes and
make the CBR results more accurate.

6. Conclusions

In this study, we proposed a method to quickly generate an emergency response
plan to respond to spontaneous combustion based on CBR, and used a case to verify the
effectiveness of the proposed method. The main work and research results are as follows:

(1) The research results showed that the emergency response plan for spontaneous com-
bustion generated by CBR was consistent with the actual results. Compared with
other representative methods, the differential determination symbol used in this paper
improved the reliability of CBR results.

(2) Due to the incompleteness of the emergency and the inconvenience of collecting
information, some cases missed attributes, and affected by the accuracy of computer
calculations, the accuracy of similarity needs to be improved in the future. The case
library established in this paper is in Chinese, so the Python program is currently only
applicable to the Chinese case library.

(3) The emergency response plan generated using CBR cannot replace experts’ opinion;
how to make quick and correct decisions in situations of incomplete information
remains a key focus of emergency management. In the future, we plan to apply
improved prospect theory to conduct research on emergency decision-making.

(4) The method proposed in this paper applied big data techniques to the construction of a
coil spontaneous combustion case base for the first time and introduced a differential
determination symbol parameter type to compute the case similarity and improve
the accuracy of case retrieval. The proposed method effectively solves the problem
of generating emergency response plans for coal spontaneous combustion under
incomplete information and provides a certain theoretical basis for preventing coal
spontaneous combustion.

(5) The proposed method is applicable not only to the generation of emergency response
plans for coal spontaneous combustion in shallow and deep mines but also to the
generation of emergency response plans for exogenous fires in coal mines. It can also be extended to additional disasters in coal mines by adjusting the accident scenario parameters and building a library of relevant cases, which is promising for a wide range of applications.

In future work, we will sufficiently consider the complexity of accident scene situations, optimize the accident parameters and improve the sensitivity of case retrieval. We will also establish a library of English cases so that the method can be applied to English case retrieval. The problem of decision-making in emergency response plans will also be an essential research topic to follow.

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