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Method of Desulfurization Process Selection Based on Improved Fuzzy Comprehensive Evaluation: A Case Study of Papermaking Desulfurization in China

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Abstract: With the increasingly prominent global energy and environmental problems, more and more enterprises have been required to desulfurize the exhausted gases. Different enterprises have different demands for the desulfurization process, thus the choice of desulfurization process methods has become a focus of attention. Since the evaluation of the desulfurization process involves many factors, this paper proposes an improved fuzzy comprehensive evaluation method to evaluate the selection of desulfurization process when the traditional evaluation method is not applicable. Firstly, an evaluation system with two rating indicators was constructed, which considers the subjective and objective weights comprehensively. Secondly using the two hierarchical indicators, an effective desulfurization process method was obtained according to the principle of maximum membership degree. Finally, we took a real papermaking factory as an example to illustrate the detailed implementation processes of this method. The result shows that the model could be used as a comprehensive evaluation tool to select desulfurization scheme or optimize the desulfurization process.

Keywords: entropy weight method; combination weight; improved fuzzy comprehensive evaluation method (IFCE); selection of desulfurization process

1. Introduction

With the rapid development of industry, gas pollution has caused serious environmental problems [1]. From the perspective of environmental benefits, more and more enterprises need to desulfurize the exhaust gas. Different enterprises have different requirements for the desulfurization process, so the choice of the desulfurization process method has become the focus of attention of various enterprises. At present, most of our country's evaluation of the desulfurization process is based on the experience of industry experts, and the selection of the desulfurization process is only determined by economic, technical or the desulfurization effect unilaterally, which leads to the results of evaluation and selection that are not always scientific and well reasonable.

Based on this, in this paper, several desulfurization process methods are evaluated by the improved fuzzy comprehensive evaluation method. Many researchers had studied and improved the fuzzy comprehensive evaluation method. Jingjing You et al. applied the improved fuzzy comprehensive evaluation in the BPR (Bayesian personalized ranking) evaluation system of the manufacturing industry [2]. Concentrations of hydrogen sulfide and amine absorbed in the liquid phase were determined by Usman Shoukat et al. [3]. The loading of hydrogen sulfide was calculated. The effect of solvent type on the absorption of hydrogen sulfide was also discussed. Mengyang Wu et al. applied improved fuzzy comprehensive evaluation to the evaluation of enterprise logistics service quality [4]. Wei Shan et al. found an improved fuzzy support vector machine method for water quality comprehensive evaluation [5]. Meng Wang et al. used improved ANP (analytic network

process) and interval number improved trapezoidal membership function fuzzy comprehensive evaluation model to evaluate and study wind power projects [6]. Ran Zhou et al. based on the fuzzy comprehensive evaluation method, the identification of sedimentary particles was studied [7]. Mehdi Keshavarz Ghorabaeedeng et al. proposed a waspas method for collecting the multi-criteria evaluation area model of green suppliers [8]. Jun Hu et al. took Shangluo District, Yibin City, Sichuan Province as an example, used fuzzy comprehensive evaluation and the analytic hierarchy process to evaluate the seismic disaster risk of the hydraulic fracturing area [9]. Weichao Yang et al. proposed a multi-flood vulnerability assessment method based on the fuzzy comprehensive evaluation method and coordinated development degree model [10]. Zhenhai Zhang et al. used the method of entropy weight to determine objective weight to solve the weight problem in the method of fuzzy comprehensive evaluation [11,12]. Although good results have been achieved, there is still a lack of an improved fuzzy comprehensive evaluation method suitable for the evaluation of desulfurization process. Hongwei Liu et al. applied the entropy weight method to airport operation risk assessment and achieved good results [13]. Anmin Jiang et al. put forward the improved fuzzy comprehensive evaluation method, and applied it to an example [14–22]. Ping L. et al. found a method to evaluate the reliability of manufacturing services in the cloud manufacturing environment [23]. Li Y. et al. applied the fuzzy comprehensive evaluation method to the energy management system of the Internet of Things, and achieved good results [24]. Gong B. et al. put forward a method to evaluate the competitive relationship of cleaner production performance in iron and steel enterprises, and applied this method to comprehensive evaluation information to obtain the performance grade of ISE CP (Iron and Steel Enterprises Cleaner Production) [25]. Besides, Sun et al. [26,27] proposed a Total Environmental Impact Score (TEIS) index to assess the environmental impact of pollutants from iron and steel industry. Taiming Yang et al. established a drought evaluation model based on improved fuzzy comprehensive evaluation [28]. Zhiguo Wang applied the characteristic parameters of NC (Numerical Control) code to the calculation of inverse energy consumption optimization and achieved very good results [29]. Caiqing Zhang et al. studied and analyzed the cost–benefit of the desulfurization system in a power plant [30]. Martin Miltner et al. discussed and studied the selection methods of advanced biogas upgrading [31]. Xu Ying and others have studied the biological desulfurization technology of biogas, and put forward the research progress of several biological desulfurization technologies [32]. Makaruk A. et al. discussed the desulfurization process of biogas purification in detailed [33–39]. Wei G. et al. propose another form of ten similarity measures by considering the function of membership degree, non-membership degree, and indeterminacy membership degree between the q-ROFSs on the basis of the traditional cosine similarity measures and cotangent similarity measures [40].

In summary, on the selection of desulfurization process, although many scholars have studied the evaluation of desulfurization process methods, most of studies only use the traditional fuzzy comprehensive evaluation method for evaluation. There is still a gap of a complete evaluation system to support different application scenarios for scheme selection. For improving this methodology, this paper summarizes the development and application status of desulfurization technology at home and abroad. By using the theory and method of fuzzy comprehensive evaluation, the index of desulfurization process method is analyzed and studied, a reasonable and operable evaluation index system with two rating hierarchical grades is put forward. The subjective and objective weights and evaluation criteria are considered comprehensively. According to the principle of maximum membership degree, the ranking of desulfurization process methods is obtained through the second-level fuzzy comprehensive evaluation of the indicators.

2. Establishment of the Evaluation Index System for the Desulfurization Process

2.1. Desulfurization Process Analysis

As a new energy, biogas is used more and more widely. Our environmental protection standards establish that when using biogas energy, the content of H_2S in biogas should not exceed 20 mg/m^3.

Therefore, before using biogas, we must remove the H_2S. Biogas purification mainly includes desulfurization, dehydration and filtration. Desulfurization refers to the requirement that the mass concentration of H_2S meet the relevant requirements when biogas is used as energy, otherwise it will corrode pipelines and equipment (such as boilers, biogas engines, etc.).

There are three commonly used methods of biogas desulfurization in the industry: Dry desulfurization, wet desulfurization and biological desulfurization. In this paper, three desulfurization methods are briefly summarized after consulting the relevant information. The results are shown in Table 1.

Table 1. Comparison of several desulfurization methods.

Comparison Index	Dry Desulfurization	Wet Desulfurization	Biological Desulfurization
Scope of application	Low biogas flow and concentration	The biogas flow rate is small and the concentration is high	Low flow rate and high concentration of Biogas
Installed power	–	High	30–50% of wet process
Operation cost	High, need to change filler regularly	Moderate	Only a small amount of electricity
Area covered	Very small	More equipment and large area	Moderate
Operation management	Simple operation, unattended	There is lots of equipment, which need special management.	Fully automatic operation, unattended

The common method of dry desulfurization is atmospheric iron oxide desulfurization. Under normal temperature and pressure, biogas passes through the desulfurizer bed, and hydrogen sulfide in biogas contacts with active iron oxide to produce iron sulfide and ferrous sulfide. After regeneration, the desulfurizer containing sulfide contacts with oxygen in the air. When water exists, the sulfide of iron is converted into iron oxide and elemental sulfur. This desulfurization and regeneration process can be carried out many times until most of the voids on the surface of ferric oxide desulfurizer are covered by sulfur or other impurities and lose their activity. Once the desulfurizer loses its activity, it is necessary to discharge the desulfurizer from the tower, spread it on the ground, then spray a small amount of dilute ammonia water on the desulfurizer evenly, and use oxygen in the air for natural regeneration. Wet desulfurization includes direct oxidation, chemical absorption and physical absorption. At present, the main method of desulfurization in China is direct oxidation, which oxidizes hydrogen sulfide into elemental sulfur in the liquid phase. The process is relatively simple, and elemental sulfur can be obtained directly. This method is mainly used to treat gases with lower concentration of hydrogen sulfide and higher concentration of carbon dioxide. The disadvantage of this desulfurization method is that the sulfur capacity of solution absorbing hydrogen sulfide is low, so the solution has a large circulation and a large amount of sulfur recovery, which is suitable for gases with a desulfurization capacity of less than 10 t/d. Biological desulfurization has the advantages of high desulfurization efficiency, integrated management, low comprehensive operation cost, simple maintenance, long service life, reliable operation and low cost of desulfurizer. It can put desulfurization and dehydration in one unit, and the equipment can continuously desulfurize and dehydrate for a long time. The primary desulfurization efficiency is controlled by the pH value. Dry desulfurization is used for secondary desulfurization, which increases the desulfurization rate to 99.8%. Compared with dry desulfurization, the operation cost of biological desulfurization is lower, but because of the complexity of equipment, higher operation level of operation and maintenance is needed.

2.2. Establishment of Evaluation Index System for the Desulfurization Process

There are many factors involved in the evaluation of the desulfurization process. It is necessary to consider all factors and establish a scientific and reasonable evaluation index system, so as to make the evaluation process more comprehensive and reasonable. According to the actual situation of the three desulfurization methods, 12 representative indicators are selected on the basis of hierarchy,

representativeness, scientificity and feasibility, and an evaluation index system of desulfurization process methods is established. The cost criterion layer (p_1–p_3) represents one-time investment, power consumption and operation cost; the environmental criterion layer (p_4–p_8) represents solution circulation, desulfurization efficiency, desulfurization effect, desulfurization organic sulfur and solution side effects; and the process requirement criterion layer (p_9–p_{12}) represents the maximum sulfur content in biogas, the flow limit of biogas, the process control requirements and the initial operation preparation period of the device. Specific indicators are shown in Table 2.

Table 2. Evaluation index system of the desulfurization method.

Target Layer *A*	Criterion Level *C*	Index Level *p*	Index Requirements
Comprehensive evaluation of desulfurization methods	Economic performance C_1	One-time investment p_1	The lower the better
		Power consumption p_2	The lower the better
		Operation cost p_3	The lower the better
	Environmental Standardization C_2	Solution circulation p_4	The smaller the better
		Desulfurization efficiency p_5	The higher, the better
		Effect of desulfurization p_6	The lower the better
		Organic sulfur removal p_7	The lower the better
		Side reaction of solution p_8	The lower the better
	Technological requirements C_3	Maximum sulfur content in biogas p_9	The higher, the better
		Limit of biogas flow p_{10}	The more unlimited the better
		Process Control Requirements p_{11}	The more controllable the better
		Preparatory Period for Initial Operation of Device p_{12}	The sooner the better

3. Research on the Uncertain Evaluation Method

3.1. Comparison of Various Commonly Used Evaluation Methods

Traditional comprehensive evaluation models include: The analytic hierarchy process, fuzzy comprehensive evaluation (FCE), neural network analysis (BP) and data envelope analysis (DEA). Firstly, we simply analyzed the characteristics of these four methods. The results are shown in Table 3.

Table 3. Comparison of commonly used multi-index comprehensive evaluation methods.

Methods	Advantages	Disadvantages
AHP	Combination of qualitative and quantitative. The principle is relatively simple. The reliability of evaluation results is high The error is small.	Quantitative limitation of evaluation object factors. Weight determination is susceptible to subjective factors.
FCE	The model is simple and easy to understand. Quantitative evaluation results of uncertain information include abundant information Strong practicability.	Failure to effectively solve information overlap between indicators The determination of weight is subjective
BP	It has the ability of self-adaptation. Fault tolerance. Realizable input. Arbitrary none of the output question. Linear mapping.	A lot of training books are needed. The accuracy of calculation results is low.
DEA	Data and functional forms. No specific requirements. Information gain. The utilization rate is higher. Objectivity strong evaluation results are clear.	Very sensitive to data. Effective Decision Unit. Less information available.

The Table 3 shows that the analytic hierarchy process is mainly applicable to the complex multi-index comprehensive evaluation with clear overall objectives and difficult to quantify completely; the traditional fuzzy comprehensive evaluation method is applicable to the complex multi-factor and multi-level problems with fixed weights and unclear boundary description; and the neural network evaluation method is mainly used to deal with non-linearity, non-locality and non-convexity. Data envelopment analysis (DEA) is suitable for multi-index comprehensive evaluation of large-scale systems with multiple inputs and multiple outputs.

3.2. Establishment of an Improved Fuzzy Comprehensive Evaluation Model

Considering the factors such as the difficulty of quantifying the index of desulfurization process and the uncertainty of weight, it can be concluded that the traditional comprehensive evaluation methods mentioned above are not suitable for the evaluation of this case. In this paper, 12 representative evaluation indexes were selected according to the actual situation of desulfurization process and the three main aspects of cost, benefit and process requirement. On basis of building a fuzzy comprehensive evaluation model, the traditional fuzzy comprehensive evaluation method was improved, and an improved fuzzy comprehensive evaluation method was put forward to evaluate the comprehensive evaluation of desulfurization process method. A more scientific and reasonable comprehensive evaluation and analysis was made. The element diagram of the improved fuzzy comprehensive evaluation method (IFCE) model is shown in Figure 1.

Figure 1. Establishment process of the improved fuzzy comprehensive evaluation method (IFCE) model.

3.2.1. The Determination of the Commentary Set

Let $V = \{V_1, V_2, V_3, \cdots, V_m\}$ and V is a collection of m comments (or ratings), which is called a set of comments. Comment set is a linguistic description of indicators at all levels and a set of comments given by reviewers on evaluation indicators. This paper adopted the following commentary sets: $V = \{V_1, V_2, V_3, V_4, V_5\}$ = (Excellent, Good, Medium, Qualified, Poor), giving each rating a given score from high to low, respectively. In this paper, a five-point system was adopted, that is to say, the scoring range of V_1 (excellent) is $\{5, 4\}$ V_2 (good) is $\{4, 3\}$, V_3 (medium) is $\{3, 2\}$, V_4 (qualified) is $\{2, 1\}$, V_5 (poor) is $\{1, 0\}$. Finally, the endpoint values $\{5, 4, 3, 2, 1\}$ of each fraction were selected as representative values to assign the evaluation grade.

3.2.2. Weight Determination of the Evaluation Index

In the fuzzy comprehensive evaluation method, determining the weight is a very important step. The weights are divided into subjective weights and objective weights. In this paper, considering the subjective and objective factors of weight, an improved method is given to determine the subjective weight by analytic hierarchy process, the objective weight by entropy weight method, and the combination weight by subjective weight and objective weight. Entropy weight method is an objective method to determine the weight. When used to determine the weight of the index according to the degree of variation of the index, it can eliminate human subjective interference as far as possible.

Since Shannon put forward the concept of "information entropy" [41], the problem of quantifying information has been solved. Information entropy is a measure of the degree of disorder in a system. It is defined as the probability weighted statistical average of information quantity, that is:

$$H = -\sum_{i=1}^{n} p_i \ln p_i. \tag{1}$$

Among them, p_i is the probability of events; H is the function of p_i, which is an expression of average uncertainty. The information entropy is introduced into the evaluation system to avoid the subjectivity of each factor weight as far as possible.

The basic calculation steps of the entropy weight are as follows:

1. Select n samples of evaluation objects, each of which has m indicators (12 indicators selected in this paper), and construct a judgment matrix:

$$M = (m_{ij}); i = 1, 2, \cdots, n; j = 1, 2, \cdots, m. \tag{2}$$

2. Find out the index ratio of the first object under the first evaluation index:

$$P_{ij} = m_{ij} / \sum_{i=1}^{n} m_{ij}; j = 1, 2, \cdots, m. \tag{3}$$

3. The entropy of the evaluation index is defined as [41]:

$$H_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} p_{ij} \ln P_{ij}; i = 1, 2, \cdots, m. \tag{4}$$

In order to make $\ln P_{ij}$ meaningful, it is stipulated that when $p_{ij} = 0$, $P_{ij} \ln P_{ij} = 0$.

4. Calculate the entropy value of the evaluation index. The entropy value of the first index is:

$$e_f = \frac{1 - H_j}{\sum\limits_{j-1}^{m} \left(1 - H_j\right)}. \tag{5}$$

The objective weights determined by the above steps are: $E = \{e_1, e_2, \cdots, e_m\}$

3.2.3. Weights Determined by the Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a qualitative and quantitative, systematic and hierarchical analysis method. The specific steps are as shown [42]:

Constructing the Judgment Matrix

According to the quantitative criteria, the factors of each level are compared in two or two ways, and the relative importance of the specific digital scale representing factor x_i over factor x_j is used to establish the judgment matrix $A = (a_{ij})_{n \times n}$. The elements a_{ij} of the judgment matrix are determined by the Saaty1–9 scale method. The specific judgment matrix scale and its meaning are shown in Table 4.

Table 4. Scaling and meaning of the judgment matrix.

Scale	Meaning
1	Comparing the two elements, they have the same importance
3	Compared with the two elements, one element is slightly more important than the other
5	Compared with the two elements, one element is obviously more important than the other
7	Compared with two factors, one factor is more important than the other
9	Compared with the two elements, one element is more important than the other
2, 4, 6, 8	The median of the above two adjacent judgments
Reciprocal	$a_{ij} = \frac{1}{a_{ji}}$

Hierarchical Single Ranking and Consistency Test

Hierarchical single ranking refers to the ranking of the importance of the factors at this level relative to the indicators at the upper level. Generally, it is determined by calculating the eigenvalue and eigenvector ω of the judgment matrix. The specific steps are as follows:

1. The judgment matrix $A = \left(a_{ij}\right)_{n \times n}$ is normalized by column: $\overline{a_{ij}} = \frac{a_{ij}}{\sum\limits_{j=1}^{n} a_{ij}}$, where $i, j = (1, 2, \cdots, n)$, the matrix $\overline{A}$ is obtained.

2. Calculate the average value of each row of matrix $\overline{A}$: $\omega i = \frac{1}{n} \sum\limits_{j=1}^{n} \overline{a_{ij}}$, where $i, j = (1, 2, \cdots, n)$, $\omega = [\omega_1, \omega_2, \cdots, \omega_n]^T$ is the eigenvector.

3. Calculate the maximum eigenvalue of the judgment matrix: $\lambda_{\max} = \sum\limits_{i=1}^{n} \frac{(AW)_i}{nW_i}$, in which $(AW)_i$ represents the i component of component AW.

4. Consistency testing: Consistency testing refers to determining the allowable range of inconsistencies for A. In order to ensure the rationality of weight distribution obtained by using analytic hierarchy process (AHP), the coordination of the importance of each element is checked to avoid conflicting situations. Since λ depends continuously on a_{ij}, the eigenvector ω corresponding to $\lambda_{\max}$ is used as the weight vector of the influence degree of the comparative factors on the upper factors. Therefore, the consistency index CI of judging matrix A should be calculated. $CI = \frac{\lambda_{\max} - n}{n - 1}$. The larger the value of CI, the worse the consistency. The random consistency ratio is defined as CR. The test formula is: $CR = \frac{CI}{RI}$. Among them, RI is the average random consistency index of matrix A. The value of RI is only related to the order of matrix. The value of RI is shown in Table 5.

Table 5. Values of the random consistency index *RI*.

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

When $CR < 0.1$, the judgment matrix has satisfactory consistency and passes the consistency test; otherwise, the judgment matrix needs to be adjusted until it passes the consistency test.

Hierarchical Total Sorting and Consistency Testing

Hierarchical total ranking refers to the importance ranking of all factors in the computing layer for the target layer. This process is carried out from top to bottom layer by layer. If the relative weight of B layer to target layer A is $b_1, b_2, \cdots, b_n$, the consistency index of factor $B_j (j = 1, 2, \cdots, m)$ in upper layer B is CI_j, and the random consistency index is RI_j, then the consistency ratio of total ranking is:

$$CR = \frac{b_1 CI_1 + b_2 CI_2 + \cdots + b_m CI_m}{b_1 RI_1 + b_2 RI_2 + \cdots + b_m RI_m}. \tag{6}$$

Similarly, when *CR* < 0.1, the hierarchical total ranking has satisfactory consistency and passes the consistency test; otherwise, the judgment matrix needs to be adjusted.

The subjective weight obtained by analytic hierarchy process is expressed as: $Z = \{z_1, z_2, \cdots, z_m\}$.

3.2.4. Determination of Comprehensive Weight

Considering that subjective factors of subjective weight have a greater impact on weight, this paper fits the objective weight $E = \{e_1, e_2, \cdots, e_m\}$ of evaluation index determined by information entropy and subjective weight $Z = \{z_1, z_2, \cdots, z_m\}$ determined by analytic hierarchy process, and finally obtains the comprehensive weight vector $W = \{w_1, w_2, \cdots, w_m\}$, seen in [21]:

$$w_i = \frac{e_i z_i}{\sum\limits_{i=1}^{n} e_i, z_i}, i = 1, 2, \cdots, m. \tag{7}$$

3.2.5. Constructing a Fuzzy Evaluation Model

The semi-trapezoidal distribution function was used to standardize the data values of each index. Based on the processed data, a fuzzy evaluation matrix could be established. Firstly, the membership function of each element *p* to *v* was determined, and then the membership degree r_{ij} of each grade of the desulfurization evaluation index was calculated. Its expression is as follows:

$$R = \left(r_{ij}\right)_{m \times g}. \tag{8}$$

In the formula, r_{ij} indicates the degree of subordination of evaluation index p_i to comment set v_j, and *m*, *g* indicates the number of indicators and the hierarchy of indicators. The following formulas can be used to solve the comprehensive index values. The calculation formulas are as follows:

$$C = (w_i)_{1 \times n} \left(r_{ij}\right)_{m \times g} \left(V_j\right)_{v \times 1}. \tag{9}$$

In the formula, V_j represents a quantitative commentary set, which can be used for comprehensive evaluation.

4. Application Case Validation

4.1. Analysis on Desulfurization of Biogas Power Generation Project in a Company

With the normal operation of the 90-ton capacity expansion project of the daily COD (Chemical Oxygen Demand) load of the anaerobic reactor 15mUMAR (Bosch) and the restoration and transformation of EGSB, the biogas production will inevitably increase, and the whole sewage system will produce about 46,000 m^3 biogas per day, which must be recycled. At present, the continuous operation power of the generator is 4500 kw. The excess biogas generated is directly burned into the torch, which wastes a lot of biogas recycling resources. In order to make this "green" energy, economic and effective utilization without wasting and polluting the atmospheric environment, it is necessary to make full use of it. Biogas power generation is an excellent utilization way.

Before biogas is used in power generation, it must be pretreated by dehydration, desulfurization, stabilization, storage, cold-drying and pressurization. At present, two sets of desulfurization units have been built, which adopt biological desulfurization technology. The designed gas handling capacity is 50,000 m^3 biogas per day. At the current H_2S concentration in biogas, the daily treatment capacity is only about 40,000 m^3. The planned expansion of biogas desulfurization equipment is 96,000 − 50,000 m^3/d = 46,000 m^3/d. In order to adapt to the change of H_2S concentration and to meet the urgent need for maintenance and repair of a set of desulfurization equipment for treating 20,000 m^3 per day built in 2008, it is proposed to expand a set of biogas desulfurization equipment for treating 50,000 m^3 per day. However, because of the large flow rate of biogas and the high concentration of

hydrogen sulfide, it belongs to the high sulfur content and large flow biogas desulfurization project, so it is necessary to desulfurize the biogas.

After desulfurization treatment, the biogas can be used to generate electricity to the grid, which can eliminate the pollution of hydrogen sulfide gas, save most of the electricity cost of sewage treatment plants and create remarkable economic benefits. Biogas power generation is a good model for pollution reduction and recycling in paper industry. It is a typical demonstration of cleaner production and circular economy development. It is a demonstration project of energy saving and emission reduction. It can realize win–win of social, environmental and economic benefits.

4.2. Information Collection of Desulfurization Process Schemes Classification and Indicators Evaluation of Each Process Schemes in the Company

According to the factors such as comprehensive desulfurization efficiency and investment, the company makes a preliminary analysis of three commonly used desulfurization methods. Among them, dry desulfurization is only suitable for gas desulfurization with small gas flow and low concentration of hydrogen sulfide. It is not suitable for the company's desulfurization standard, but wet desulfurization and biological desulfurization have their own characteristics. Considering the company's own needs and conditions, the combined desulfurization method of wet desulfurization and biological desulfurization was proposed. The company plans to formulate three desulfurization schemes: Biological desulfurization, conventional wet desulfurization and wet + biochemical (DDS). Table 6 provides an evaluation of the evaluation indicators for each alternative.

Table 6. Evaluation of evaluation indicators for each alternative.

Index Level	Biological Desulfurization	Normal Wet Desulfurization	Wet + Biochemical (DDS)
One-time investment p_1	1	0.25	0.25
Power consumption p_2	0.25	1	0.5
Operation cost p_3	0.75	1	0.375
Solution circulation p_4	0.33	1	0.55
Desulfurization efficiency p_5	0.78	0.55	1
Effect of desulfurization p_6	0.89	0.55	1
Organic sulfur removal p_7	0	0.4	1
Side reaction of solution p_8	0.25	1	0.25
Maximum sulfur content in biogas p_9	0.5	1	1
Limit of biogas flow p_{10}	0	1	1
Process control requirements p_{11}	1	0.75	0.75
Preparatory period for initial operation of device p_{12}	1	0.33	0.33

Since the linear cross-type membership function can better describe the fuzziness of the evaluation index grade interval, the linear cross-type membership function was adopted. The unqualified threshold and excellent threshold of solution circulation and desulfurization efficiency were 0.5 and 0.9 respectively. According to the requirement of desulfurization method, the unqualified threshold *a* and excellent threshold *b* are determined, and [*a*, *b*] is divided into corresponding grade intervals. Every $u < a$ belongs to v_5 completely and $u > b$ belongs to v_1 completely. The membership function value of the point, which can best express the characteristics of this grade is 1. The boundary intersection is the most ambiguous, and its membership degree is 0.5. Based on data of Table 6, the sensitivity radar map to all indicators of the three desulfurization processes was plotted by comparison of Biological desulfurization, Normal Wet Desulfurization and Wet + Biochemical (DDS), as shown in Figure 2.
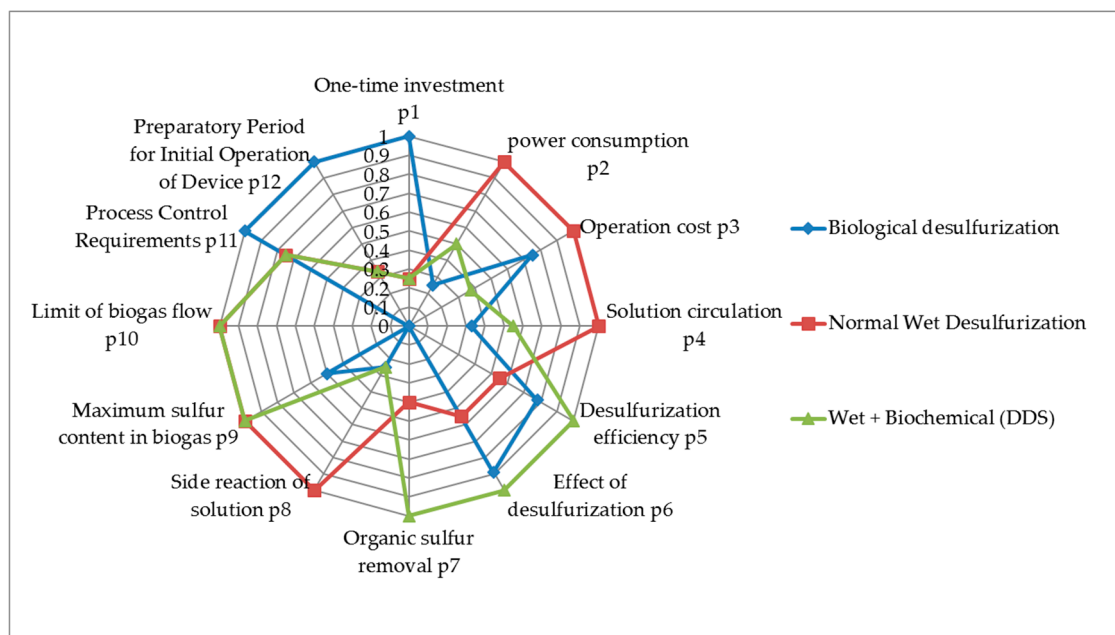
Figure 2. Sensitivity radar charts of indicator layers.

The chart shows that the one-time investment, process control requirements and equipment initial operation preparation of biological desulfurization method are weaker than the other two desulfurization methods. The power consumption, operation cost, solution circulation and solution side reaction of the conventional wet desulfurization methods are weaker than those of the other two schemes. The indices of DDS (Desulfurization & Decarburization Solution Activities) method are generally better than those of the first two schemes, but it is not the best method for individual indices. Therefore, these three desulfurization methods have their own advantages and disadvantages, which needs to be further compared to determine the optimal desulfurization method.

4.3. Weight Determination of Rating Indicators

According to the data of a small and micro enterprise in the past ten years given in the table, the fuzzy relation matrix is constructed, and the entropy values of 12 indexes are calculated by formula (2)–(4):

$$(0.79, 0.87, 0.94, 0.91, 0.97, 0.97, 0.58, 0.79, 0.96, 0.66, 0.99, 0.86).$$

The objective weight is calculated by formula (5):

$$E = (0.12, 0.08, 0.04, 0.05, 0.01, 0.02, 0.25, 0.12, 0.02, 0.20, 0.01, 0.08).$$

The main content of the analytic hierarchy process is to construct a judgment matrix. In this paper, combining expert opinions and relevant data, the importance of each element is analyzed by the nine-point scale method, and the judgment matrix of each level of the evaluation index is established as follows:

$$G = \begin{Bmatrix} 1 & 2 & 2 & 3 & 0.25 & 0.2 & 0.33 & 4 & 0.5 & 0.5 & 5 & 6 \\ 0.5 & 1 & 0.5 & 2 & 0.17 & 0.14 & 0.2 & 2 & 0.33 & 0.33 & 4 & 5 \\ 0.5 & 2 & 1 & 2 & 0.25 & 0.2 & 0.33 & 2 & 0.5 & 0.5 & 3 & 4 \\ 0.33 & 0.5 & 0.5 & 1 & 0.17 & 0.14 & 0.2 & 2 & 0.25 & 0.25 & 2 & 3 \\ 4 & 6 & 4 & 6 & 1 & 0.5 & 2 & 7 & 2 & 2 & 8 & 8 \\ 5 & 7 & 5 & 7 & 2 & 1 & 2 & 7 & 2 & 2 & 8 & 8 \\ 3 & 5 & 3 & 5 & 0.5 & 0.5 & 1 & 6 & 2 & 2 & 7 & 8 \\ 0.25 & 0.5 & 0.5 & 0.5 & 0.14 & 0.14 & 0.17 & 1 & 0.2 & 0.2 & 2 & 2 \\ 2 & 3 & 2 & 4 & 0.5 & 0.5 & 0.5 & 5 & 1 & 2 & 5 & 5 \\ 5 & 3 & 2 & 4 & 0.5 & 0.5 & 0.5 & 5 & 0.5 & 1 & 5 & 5 \\ 0.2 & 0.25 & 0.33 & 0.5 & 0.12 & 0.12 & 0.14 & 0.5 & 0.2 & 0.2 & 1 & 2 \\ 0.17 & 0.2 & 0.25 & 0.33 & 0.12 & 0.12 & 0.12 & 0.5 & 0.2 & 0.2 & 0.5 & 1 \end{Bmatrix}.$$

The maximum eigenvalue of matrix G is 17.29, and the consistency ratio $CR = \frac{\lambda_{max} - 12}{1.54 \times (12-1)} = 0.058 < 0.1$ of matrix meets the consistency requirement. Therefore, the eigenvector of matrix G is the weight:

$$Z = (0.07, 0.04, 0.05, 0.03, 0.18, 0.22, 0.15, 0.02, 0.11, 0.10, 0.02, 0.01).$$

Finally, according to formula (7), the comprehensive weight is calculated as follows:

$$W = (0.10, 0.04, 0.02, 0.02, 0.03, 0.05, 0.44, 0.03, 0.03, 0.23, 0.01, 0.01).$$

4.4. Comprehensive Evaluation Value of Desulfurization Process Schemes

From the evaluation value of alternatives and the threshold range of membership function, the fuzzy evaluation matrix of alternatives can be calculated.

$$R_1 = \begin{Bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & \frac{1}{4} & \frac{3}{4} & 0 & 0 \\ 0 & 0 & \frac{1}{4} & \frac{3}{4} & 0 \\ \frac{13}{20} & \frac{7}{20} & 0 & 0 & 0 \\ 0 & \frac{9}{10} & \frac{1}{10} & 0 & 0 \\ \frac{11}{20} & \frac{9}{20} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{3}{4} & \frac{1}{4} \\ 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{Bmatrix} R_2 = \begin{Bmatrix} 0 & \frac{1}{4} & \frac{3}{4} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & 0 & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{4} & \frac{3}{4} & 0 & 0 \\ 0 & \frac{7}{20} & \frac{13}{20} & 0 & 0 \end{Bmatrix} R_3 = \begin{Bmatrix} 0 & \frac{1}{4} & \frac{3}{4} & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & \frac{3}{4} & \frac{1}{4} \\ 0 & \frac{3}{4} & \frac{1}{4} & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{3}{4} & \frac{1}{4} \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & \frac{7}{20} & \frac{13}{20} & 0 & 0 \end{Bmatrix}$$

By using ordinary matrix multiplication, the fuzzy evaluation set is obtained:

$$B_1 = W \cdot R_1 = (0.28, 0.05, 0.06, 0.36, 0.12),$$
$$B_2 = W \cdot R_2 = (0.26, 0.47, 0.11, 0.06, 0.11),$$
$$B_3 = W \cdot R_3 = (0.76, 0.01, 0.17, 0.05, 0.02).$$

In order to get the specific value of comprehensive evaluation of various schemes and facilitate the intuitive comparison between different schemes, the IFCE was adopted in this study. According to the established evaluation set $V = (5, 4, 3, 2, 1)$, five of them were excellent and one was poor, so we could get:

$$C_1 = B_1 \cdot V^T = 2.62, \qquad C_2 = B_2 \cdot V^T = 3.74, \qquad C_3 = B_3 \cdot V^T = 4.38.$$

4.5. Comparing and Analyzing Each Process Plan

By comparing the evaluation values of the three schemes, we could see that scheme 3 should be chosen to achieve the best desulfurization effect. Compared with the conventional wet desulfurization and biological desulfurization, the DDS method had considerable advantages in the desulfurization effect and desulfurization efficiency. In addition, the DDS method was superior to conventional biological desulfurization in the one-time investment and initial operation cycle of equipment, and is superior to conventional wet desulfurization in the power consumption and solution side reaction. Through calculation and analysis, it can be seen that the wet process plus biochemical desulfurization method is effective and feasible, and is superior to the other two methods.

5. Conclusions and Prospect

This paper comprehensively considered the influence of human subjective judgment and objectivity on the calculation and determination of each weight more scientifically and reasonably. Finally, the subjective weight was determined by the analytic hierarchy process, and the objective weight was determined by the entropy weight method. The comprehensive weight was determined by combining the two methods.

According to the actual situation of the enterprise, this paper determined the corresponding secondary evaluation index, using the theory and method of fuzzy comprehensive evaluation, gave the improved fuzzy comprehensive evaluation model based on the theory of fuzzy mathematics. According to the above theoretical model, the important indexes of the three desulfurization schemes given by the enterprise were analyzed and studied. According to the principle of maximum membership degree, the comprehensive ranking of desulfurization schemes was obtained through the fuzzy comprehensive evaluation of the indicators.

The two-level fuzzy comprehensive evaluation model of desulfurization scheme quantified the qualitative indicators by the scientific method and evaluated and calculated them together with the quantitative indicators. It had strong operability, comprehensive and objective evaluation work, and the results obtained by the model had great credibility. The model could be used as a practical tool to optimize the desulfurization scheme or the desulfurization manufacturer in the desulfurization process.

In order to further improve the evaluation level of desulfurization process, the following suggestions are proposed:

(1) In the process of desulfurization process evaluation, some secondary indicators belong to the first-level indicators of cost and environment. Such indicators should be considered comprehensively, and the weights of secondary indicators should be allocated to the weights of cross-first-level indicators, so as to achieve more accurate evaluation results.

(2) In the evaluation of the desulfurization process, we should not only select the lowest investment or the lowest bid evaluation scheme, but also make a comprehensive quantitative evaluation of technology and investment. We should also analyze the environmental benefits and operation economic benefits after putting into operation according to the "Measures for the Operation and Management of Desulfurization Electricity Prices and Desulfurization Facilities for Coal-fired Generating Units (Trial)", taking into account the initial investment and operation cost comprehensively, so as to ensure the investment benefits maximization.

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