

## Article

# Laboratory Risk Assessment Based on SHELL-HACCP-Cloud Model

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**Abstract:** With the increasing demand and expanding scale of laboratories in colleges and universities, laboratory accidents frequently occur, seriously impacting personal health, schools, society, and the environment. Scientific and effective risk assessment is crucial to prevent accidents. Therefore, in order to effectively reduce the risk of chemical laboratories and minimize the frequency of accidents. This study employs the combination of the SHELL model and HACCP system to analyze the potential sources of hazards in hazardous chemical laboratories and establish a risk assessment index system. Based on the Cloud model, a dynamic risk assessment model for the laboratory is established to quantitatively evaluate the risk level of the evaluation results. In order to ensure the rationality of the assessment results, the subjective and objective weights are combined by the principle of minimizing information entropy. Case analysis proves the scientific validity of the evaluation results of the model, which can assist laboratory managers in formulating emergency plans and risk management mechanisms to reduce or eliminate the occurrence of experimental accidents. This approach ensures the safe and sustainable development of schools and laboratories, which is conducive to the progress of researchers' scientific research results.

**Keywords:** chemical laboratory accidents; dynamic risk assessment; cloud model; risk management



**Citation:** Zhao, X.; Wei, Z.; Gao, Y.; Yin, P. Laboratory Risk Assessment Based on SHELL-HACCP-Cloud Model. *Sustainability* **2023**, *15*, 16590. <https://doi.org/10.3390/su152416590>

Academic Editor: Mario Fagnoli

Received: 25 October 2023

Revised: 22 November 2023

Accepted: 23 November 2023

Published: 6 December 2023



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## 1. Introduction

Laboratories in colleges and research institutions are characterized by a wide variety of dangerous chemicals, high mobility of personnel, and complex equipment, making the potential risks highly likely and difficult to manage. However, there is no national mandatory standard for laboratories. Once a safety accident occurs, it will have irreversible impacts on human health, schools, society, and property. In 2018, an explosion occurred in a laboratory at Beijing Jiaotong University during the treatment of landfill leachate, resulting in the ignition of magnesium powder dust and the tragic loss of three students [1]. In 2021, a laboratory at Nanjing University of Aeronautics and Astronautics experienced magnesium-aluminum powder deflagration, resulting in two deaths and nine injuries [2]. Research shows that the frequency of accidents in chemical laboratories is 65.2%, and the highly explosive nature of hazardous chemicals can trigger various safety hazards, exacerbating the scope and impact of accidents [3]. Therefore, how to ensure the long-term stable operation of the experiment in a safe environment is an important topic of concern for university laboratory safety management personnel and researchers. At the same time, improving the ability of risk management is of great significance for the health and safety of humans, machine, materials, environment, and other factors in university laboratories, and the sustainable development of major laboratories in universities.

In recent years, as an effective method to prevent accidents, risk assessment has been widely used in various fields. To conduct a safety risk assessment, key risk factors affecting laboratory safety should be identified and analyzed. The main methods of risk identification and analysis are the Questionnaire Survey method (QA) [4], Failure Mode and Effect Analysis (FMEA) [5], Failure Analysis Tree (FAT) [6], Fuzzy Bayesian Network (FBN) [7], Bow-Tie technique (BT) [8], Human Factors and Classification System (HFACS) [9] and so on. Among them, methods such as QA, HFACS, FAT, and FMEA need to organize different participants to conduct causal analysis together when applying them and require higher expertise. Due to the complexity of the coupling between laboratory risk factors, common risk analysis methods cannot be directly used in hazardous chemical laboratories. In recent research, the SHELL model is widely used in accident risk analysis of aviation and military industries, which transcends the causal relationship and analyzes the correlation and influence between risk factors from the interaction process between humans and software, hardware, and the environment [10]. Meanwhile, the Hazard Analysis and Critical Point Control (HACCP) system has been widely adopted in the accident risk analysis of food [11] and agriculture [12], which verifies the effectiveness of the HACCP system for critical factor analysis. This shows that SHELL and HACCP have achieved good results in the process of risk analysis.

There are a variety of risk factors in hazardous chemicals laboratories. These factors are interrelated and influence each other. Also, they belong to the decision-making problem of multi-objective attributes, and the decision-making information is ambiguous and complex. The assessment methods for such problems mainly include Analytic Hierarchy Process (AHP) [13], Analytical Network Process (ANP) [14], Fuzzy Comprehensive Evaluation Method (FCEM) [15], FMEA [16], Bayesian Network (BN) [17,18], and Truoket theory [19]. Among them, AHP is a classic multi-objective decision-making method, which is widely used in the evaluation of flood disasters [13], hazardous materials transportation [20], the cement industry [21], and other aspects of evaluation, which illustrate the effectiveness of this method. FCEM is a comprehensive evaluation method based on fuzzy mathematics theory, which has been widely used in seawater desalination projects [22], oil tanker truck driving risk assessments [23], low carbon operation risk assessments of distribution grids [24], landslide sensitivity assessments [25] and so on. However, the AHP often relies on the results of experts' scoring, which is subjective and inaccurate for decision-making on certain issues. Although the FCEM can solve the problem of vagueness, it has some limitations in dealing with randomness.

In order to solve the problems of subjectivity, complexity, and uncertainty in the multi-objective decision-making process, many scholars incorporate fuzzy set theory in risk assessment. The safety of the construction industry is evaluated through the integration of the Interval-Valued Intuitionistic Fuzzy Decision-Making Test and Evaluation Laboratory (IVIF-DEMATEL) and the Interval-Valued Intuitionistic Fuzzy Analysis Network Process (IVIFANP) methods. By considering the interdependence weight between causal factors to determine the level of influencing factors, the method overcomes the subjectivity and uncertainty of relevant decision-making information [14]. A quality function deployment (QFD) method based on the Delphi method and fuzzy logic method is used to improve the safety assessment ability of equipment in the agricultural sector. This effectively reduces the subjective influence of decision-making and increases the consistency of judgment [26]. The authors also proposed an evaluation method integrating Quality Function Deployment (QFD) and Analytic Network Process (ANP) and used Fuzzy Failure Mode and Effects Analysis (FMEA) to improve the accuracy of risk analysis [27]. The study found that the DEMATEL method based on Pythagoras fuzzy set theory (PFDEMATEL) not only improved the accuracy of the evaluation results in complex environments but also visualized the relationship between direct and indirect factors in the construction supply chain system, increasing the intuitiveness of the evaluation method [28]. However, these methods are specific to certain fields, limiting their universal applicability. In the study of laboratory risk assessment, the Petri net model based on Interval Type-2 Fuzzy Sets (IT2FSs) simulates the

dynamic development process of accidents, intuitively illustrating the internal relationship between factors and qualitatively evaluating laboratory risks. This model provides a reference value for risk assessment researchers in other fields [29]. Similarly, the FMEA method based on IT2FSs is used to deal with the uncertainty of evaluation information. This method fully considers the relevant information of the laboratory and improves the accuracy and robustness of the risk assessment results [16]. The grey AHP-TOPSIS model is used to quantitatively evaluate the risk of chemical laboratory, clearly reflecting the risk of chemical laboratory while omitting factors such as personnel and management in the laboratory [30].

In 1995, Li Deyi et al. proposed a cloud model based on fuzzy mathematics and statistics, integrating uncertainty, fuzziness, and randomness. This model achieved the qualitative and quantitative transformation through specific algorithms [31]. Given the high mobility of laboratory personnel, there exists considerable uncertainty and randomness. The cloud model effectively addresses the challenge of converting qualitative factors into quantitative ones, rendering assessment results more scientific and reliable. The Cloud model is widely used in the risk assessment of rice processing chain [32], fishing capacity assessment of fishing vessels [33], and benefit assessment of the South-to-North Water Diversion East Route Project [34]. However, only limited research based on the Cloud model was applied in the risk assessment of hazardous chemicals laboratory. For the calculation of indicator weights, most studies use a single method such as AHP, Entropy Weight method (EW), Anti-Entropy Weight method (AEW), Important Criterion of Inter-Layer Correlation (CRITLC), etc., or simple linear combinations of two or more methods to derive fixed weights, which cannot be dynamically adjusted when the indicator information is changed, and it will affect the accuracy and reliability of the assessment results.

Based on the above problems and challenges, dynamic risk assessment research on chemical laboratories with hazards is conducted through the integration of SHELL, HACCP, and the cloud model. Firstly, when analyzing the potential hazard sources of hazardous chemical laboratories, the SHELL model and HACCP system are introduced for the first time to determine the key risk factors through combinatorial analysis, leading to the construction of a risk assessment index system for hazardous chemical laboratories. Secondly, the principle of minimum information entropy is introduced by combining the improved AHP method with the AEW method to derive the dynamic comprehensive weight of each index. This integration improves the accuracy of the weight results. Finally, the weighted results are combined with the cloud digital characteristics of the indicators to obtain the final cloud digital characteristics, and the cloud map of risk assessment is drawn. In addition, the model is applied to the chemical laboratory of colleges and universities to determine the key factors affecting the safety of the laboratory and the comprehensive risk level, which proves the feasibility and effectiveness of the method adopted by the model. It can help laboratory managers formulate emergency plans and risk-handling mechanisms to reduce or alleviate the occurrence of laboratory accidents.

## 2. Methodology

### 2.1. SHELL Model

SHELL model was first proposed by Prof. Edward in 1972, which consists of four elements, namely, Software(S), Hardware(H), Environment(E), and Liveware(L), forming a “liveware-centered” security management. Subsequently, Hawkins implemented a graphical representation of the model in 1975 [35], as shown in Figure 1.

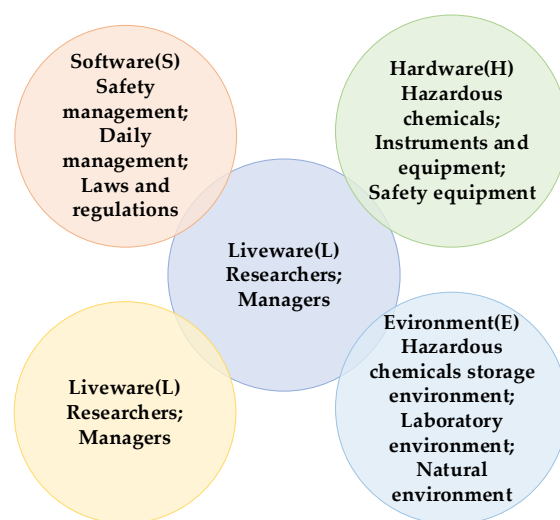


Figure 1. SHELL model.

In order to explore the applicability of the SHELL model in the safety management of chemical laboratories and ensure the well-being of laboratory personnel, this study employs the SHELL model's perspective on "human", "hazardous chemicals and equipment", "environment", and "management". The SHELL model is utilized to analyze potential hazards centered around "human" from the four dimensions: "human", "hazardous materials and equipment", "environment", and "management". This analysis includes 11 typical safety accidents in chemical laboratories from 2015 to 2021, aiming to identify the potential risk factors in the laboratory. At this point, the core of the model is the researchers and managers of the hazardous chemical laboratory, following the concept of the SHELL model, and the meaning of S, H, E, and L in the analysis process is as follows:

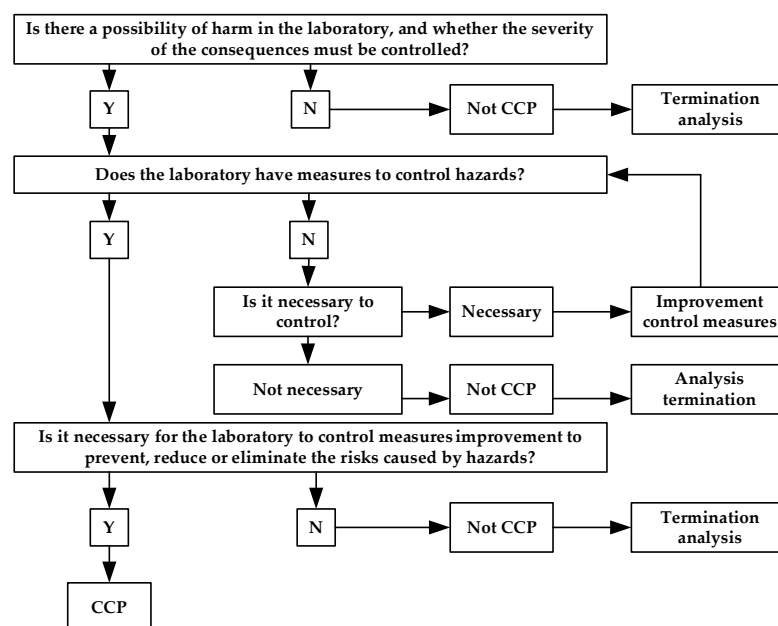
- **Software(S):** management, in which risk mainly comes from mistakes in laboratory management, such as inadequate safety rules and regulations, and lack of safety education and training in the laboratory.
- **Hardware(H):** hazardous chemicals and equipment, the risk mainly comes from two aspects. On the one hand, the unsafe state of hazardous chemicals, such as excessive storage of hazardous chemicals, leakage of substances, etc., and on the other hand, the unsafe state of equipment, such as the aging or damage of the instruments, and defects in the safety management system, etc.
- **Environment(E):** the environment, where the risk mainly comes from three aspects, the first is the working environment, such as aging and short circuits of wires, unreasonable environmental layout, etc. The second is the storage conditions, such as temperature, humidity, pressure, etc. The third is the natural environment, heavy rains, high temperatures, etc.
- **Liveware(L):** the personnel of the laboratory, in which risks mainly originate from researchers and managers, such as violation of operating procedures and lack of safety knowledge, etc.

## 2.2. HACCP Methodology

In the 1960s, Dr. Bauman from Pillsbury, NASA, and the U.S. Army Natick Research Center jointly developed a new food safety supervision and management system, namely Hazard Analysis and Critical Control Points (HACCP) [36]. HACCP is an advanced management system, which is widely used in food safety management. By identifying hazards in the food production process and evaluating the level of hazards, the critical control points and control limits are determined, the monitoring methods and corrective measures are formulated, the document retention system is established, and food quality control is carried out to ensure food safety [37]. At the same time, the HACCP system is

also widely used in medicine, environmental monitoring, and other industries, as it is one of the important means for society to realize scientific management and quality control.

This study adopts the methods in the HACCP system to analyze the daily safety management of hazardous chemical laboratories. By identifying key factors that pose risks, this study effectively reduces or eliminates the possibility of accidents in the laboratory, thus ensuring the safety of laboratory operations. The critical control points in the HACCP system refers to the behavior or states that either cause harm or exhibit weak preventive measures in laboratory management operation. These critical control points are analyzed and confirmed through the decision tree in Figure 2.



**Figure 2.** Judgment process of critical control points in laboratory management operation.

### 2.3. Analytical Hierarchical Process

Analytical Hierarchical Process (AHP) is a multi-objective decision analysis method proposed by T.L. Satty, an expert from the University of Pittsburgh in the U.S. It has the advantages of being operational and relatively simple in calculation. It is essentially a subjective assignment method, and its weight calculation results are often affected by experts' decision-making, which affects the reliability of the assessment results. In order to reduce the subjectivity of the AHP method, an improved AHP method is adopted, that is, the IAHP (based on the 3-scalar theory) [38], and its calculation steps are as follows:

#### 1. Constructing a comparison matrix

The 3-scale theory is used to compare the relative importance of each index, which can effectively reduce the influence of experts' subjective knowledge. Therefore, the comparison matrix  $C$  is constructed for  $n$  indexes by using the 3-scale theory.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1j} \\ \vdots & \ddots & \vdots \\ c_{i1} & \cdots & c_{ij} \end{bmatrix} \quad (i, j = 1, 2, \dots, n) \quad (1)$$

where is  $c_{ij}$ :

$$c_{ij} = \begin{cases} 1, & \text{Indicates that } i \text{ is more important than } j \\ 0, & \text{Indicates that } i \text{ is as important as } j \\ -1, & \text{Indicates that } j \text{ is more important than } i \end{cases} \quad (2)$$

#### 2. Constructing the optimal transfer matrix

The optimal transfer matrix  $P$  is

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1j} \\ \vdots & \ddots & \vdots \\ p_{i1} & \cdots & p_{ij} \end{bmatrix} (i, j = 1, 2, \dots, n) \quad (3)$$

where  $p_{ij} = \frac{1}{n} \sum_{n=1}^n (c_{in} + c_{ni})$ ,  $n$  represents the number of indicators and further compute the synthesized judgment matrix  $S$  as:

$$S = \begin{bmatrix} s_{11} & \cdots & s_{1j} \\ \vdots & \ddots & \vdots \\ s_{i1} & \cdots & s_{ij} \end{bmatrix} (i, j = 1, 2, \dots, n) \quad (4)$$

where  $s_{ij} = \exp(p_{ij})$ ,  $n$  represents the number of indicators.

### 3. Calculation the subjective weight

Calculate the weights of  $i$  indicator based on the product square root method with the formula:

$$w_i = \left( \prod_{j=1}^n s_{ij} \right)^{\frac{1}{k}} / \sum_{j=1}^n \left( \prod_{j=1}^n s_{ij} \right)^{\frac{1}{k}} \quad (5)$$

where  $k$  is the number of indices, i.e.,  $k = n$  and then  $W_{IAHP} = (w_1, w_2, \dots, w_n)$  is a vector of subjective weights for  $n$  indicators.

#### 2.4. Anti-Entropy Weight

The entropy weight method is an objective assignment method that mainly utilizes the utility value of information to determine the weight of indicators. The entropy weight function model proves effective in assessing the safety risk of significant events by accurately discerning and categorizing the risk factors influencing laboratory safety through entropy value. However, the entropy weight method's sensitivity to the disorder degree of each index during the calculation process can lead to the generation of extreme weights. In order to avoid this phenomenon, this paper adopts the anti-entropy weight method to calculate the objective weight of each index, and its calculation steps are as follows:

##### 1. Building a standardized matrix

With  $m$  indicators and  $n$  assessment objects, an evaluation matrix  $X_{m \times n}$  can be obtained, which is normalized to reduce the differences in dimensions, order of magnitude, and quality of the data indicators:

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}}, j = 1, 2, \dots, n \quad (6)$$

$$Y = (y_{ij})_{m \times n}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (7)$$

where  $x_{ij}$  is the  $j$ -th indicator value for the  $i$ -th indicator.

##### 2. Calculate the anti-entropy value of the indicator

The anti-entropy value of the  $j$ -th indicator is:

$$e_j = - \sum_{i=1}^m y_{ij} \ln(1 - y_{ij}), j = 1, 2, \dots, n \quad (8)$$

##### 3. Calculation the objective weights

The difference between the entropy of the index and 1 in the evaluation system  $h_j$  is used to determine the utility value of the index:

$$h_j = 1 - e_j, j = 1, 2, \dots, n \quad (9)$$

As the core of the entropy method, the information utility value has a significant impact on the importance of the assessment results. Each indicator is assigned a weight based on the degree of utility of each indicator:

$$W_{AEW} = \frac{h_j}{\sum_{j=1}^n h_j}, j = 1, 2, \dots, n \quad (10)$$

where  $W_{AEW}$  is the objective weight of the indicator.

### 2.5. Minimize Information Entropy

By introducing the principle of minimizing information entropy and integrating subjective weights and objective weights, a dynamic comprehensive weight that changes with the specific situation of the evaluated object is established. The dynamic comprehensive weighting method can dynamically adjust the comprehensive weights according to the value of the indicators in each evaluation target, which overcomes the shortcomings of the traditional evaluation method in assigning fixed weights to the indicators. At the same time, the dynamic comprehensive weighting method can not only reflect the opinions of experts and decision-makers but also make full use of the original information [26]. The dynamic comprehensive weight of each indicator is determined by the following formula:

$$\begin{cases} \min F = \sum_{i=1}^n w_i (\ln w_i - \ln w_{IAHP}) + \sum_{i=1}^n w_i (\ln w_i - \ln w_{AEW}) \\ s.t. \sum_{i=1}^m w_i = 1 (w_i > 0) \end{cases} \quad (11)$$

where  $i = 1, 2, 3, \dots, n$  represents the indicator and the final weight  $w_i = \frac{\sqrt{w_{AHP} w_{AEW}}}{\sum_{i=1}^m \sqrt{w_{AHP} w_{AEW}}}$  is calculated by the Lagrange method.

### 2.6. Cloud Model

Cloud Model is a model based on probability theory and fuzzy set theory that converts qualitative concepts into quantitative representations by means of a specific algorithm [34]. The numerical features in the cloud model are described as  $C[Ex, En, He]$ , where  $Ex$  is the value that best represents the qualitative concepts in the argument space,  $En$  is the acceptable range of the qualitative concepts, and  $He$  is the degree of discretization of the qualitative concepts, presenting the stochastic nature of the qualitative concepts.

#### Determine the Numerical Characteristics of the Rating Set

The benchmark for risk assessment in hazardous chemical laboratories is the delineation of the grade evaluation sets. According to the "Safety management guidelines for chemistry and chemical engineering laboratories (T/CCSAS 005-2019)", "Guidelines of safety assessment for chemistry and chemical engineering laboratories (T/CCSAS 011-2021 [39])" [40], and the standards for university laboratories, we divided the risk level of university chemistry laboratory into five levels, namely, very high risk, high risk, medium risk, low risk, and very low risk, with corresponding intervals of [0.8, 1], [0.6, 0.8], [0.4, 0.6], [0.2, 0.4], and [0, 0.2], and

the domain of the comment set is represented by the equal membership degree of the upper and lower boundary values of the evaluation domain, which is calculated by the formula:

$$\begin{cases} Ex = \frac{c_i^{min} + c_i^{max}}{2}, i = 1, 2, \dots, 5 \\ En = \frac{c_i^{max} - c_i^{min}}{2\sqrt{2\ln 2}}, i = 1, 2, \dots, 5 \\ He = \gamma \end{cases} \quad (12)$$

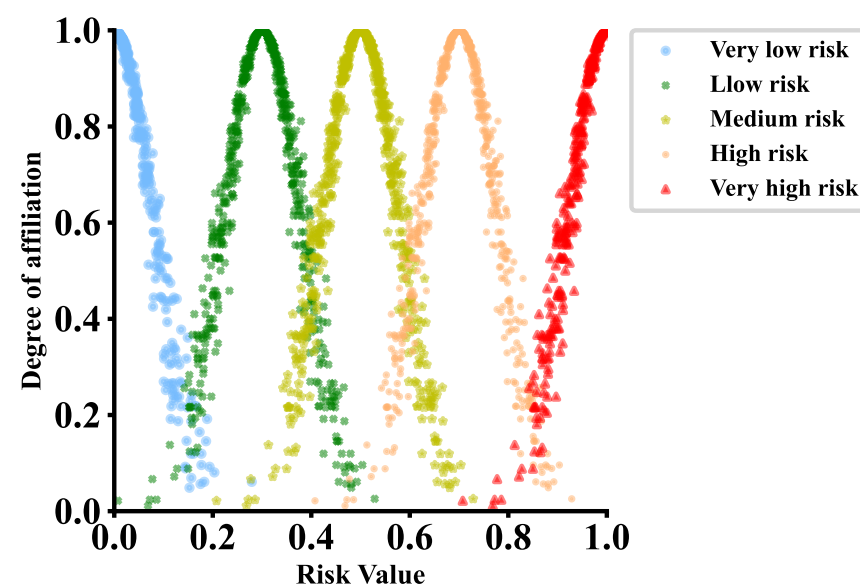
where  $c_i^{min}$  denotes the lower boundary value of the  $i$ th interval and  $c_i^{max}$  denotes the upper boundary value of the  $i$ th interval;  $\gamma > 0$  is a constant, which is taken as 0.01 in this paper.

When the risk level interval is  $[0.8, 1]$ ,  $Ex = (0.8 + 1)/2 = 0.9$ ,  $En = (1 - 0.8)/2\sqrt{2\ln 2} = 0.08$ . Other calculations are similar. The calculation results of digital characteristics of standard cloud corresponding to the evaluation set interval are shown in Table 1. The cloud map is drawn with Python 3.7 software, as shown in Figure 3. Here, the horizontal axis is the index risk value, and the vertical axis is the measure of the degree that the index belongs to a certain level, which is the degree of affiliation. The generation process of the cloud image is as follows:

1. Generate a normal random number  $x_i$  with expectation  $Ex$  and standard deviation  $En$ .
2. Generate a normal random number  $Enn$  with the expectation of  $En$  and standard deviation of  $He$ .
3. Calculate the membership degree,  $y_i = \exp[-(x_i - Ex)^2/2Enn^2]$ .
4. Repeat steps 1–3 until the required number of cloud droplets is generated, where  $(x_i, y_i)$  is a cloud droplet.

**Table 1.** Evaluation of cloud digital features.

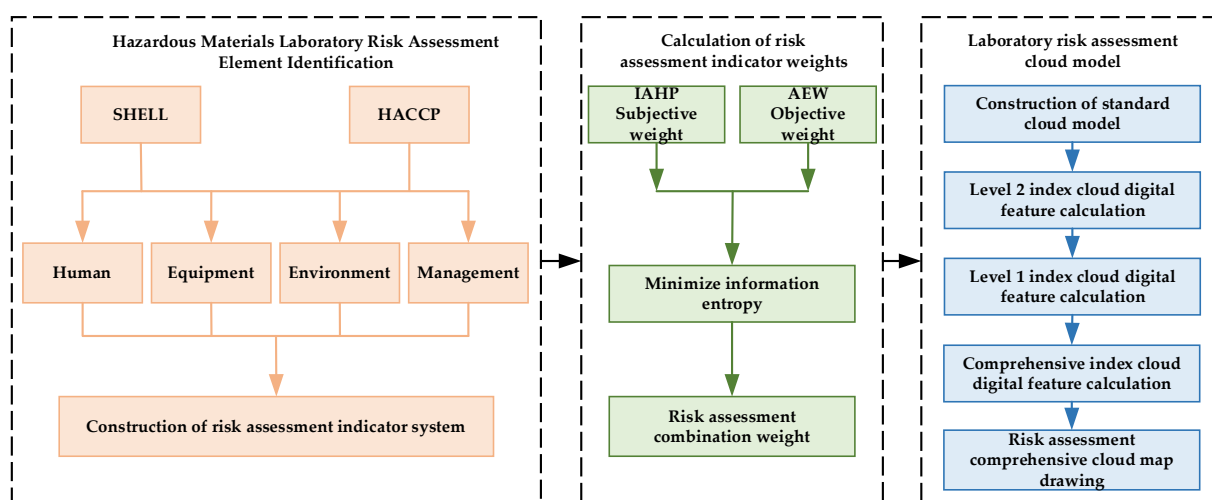
| Risk Level | Interval     | Digital Characteristic |      |      |
|------------|--------------|------------------------|------|------|
|            |              | $Ex$                   | $En$ | $He$ |
| Very high  | $[0.8, 1]$   | 0.9                    | 0.08 | 0.01 |
| High       | $[0.6, 0.8]$ | 0.7                    | 0.08 | 0.01 |
| Medium     | $[0.4, 0.6]$ | 0.5                    | 0.08 | 0.01 |
| Low        | $[0.2, 0.4]$ | 0.3                    | 0.08 | 0.01 |
| Very low   | $[0, 0.2]$   | 0                      | 0.08 | 0.01 |



**Figure 3.** Standard evaluation cloud chart.

### 3. Risk Assessment for Chemical Laboratory in the University

The cloud model can well solve the problem of transforming qualitative factors into quantitative factors, making the evaluation results more scientific and reliable. Before applying the cloud model to risk assessment, it is necessary to establish a reliable and comprehensive risk index system. This can be achieved by combining the SHELL model with the HACCP system, and the reliability of the indicators can be determined in the form of questionnaires. On this basis, the principle of minimizing information entropy is used to combine the IAHP and AEW methods to balance the subjective and objective influence of the weight of risk indicators. At the same time, the variability of risk indicators is taken into account, and the accuracy of evaluation is improved. Finally, a risk assessment model based on the SHELL-HACCP-cloud model was established, as shown in Figure 4.



**Figure 4.** Flow chart of laboratory risk assessment method.

#### 3.1. Constructing an Index System for Risk Assessment of Hazardous Chemical Laboratories

To comprehensively and accurately analyze laboratory risk factors, the SHELL model will be employed to assess risks in “human”, “hazardous chemicals and equipment”, “environment”, and “management”. This analysis, combined with the HACCP system’s examination of key control points, facilitates the identification and analysis of potential risk sources in the daily safety management of hazardous chemical laboratory operations. The hazardous chemicals laboratory risk assessment index system is summarized, as depicted in Figure 5.

In order to assess the reliability of the indicator system obtained through the model analysis, a reliability test of the index system will be conducted. In 1904, reliability was introduced into psychometrics by Spearman, which refers to the degree of consistency or reliability of the test results. The higher the reliability coefficient, the higher the questionnaire’s credibility. Usually, the reliability coefficient ranges from 0 to 1 [41], and its corresponding meaning is shown in Table 2.

**Table 2.** The range and meaning of reliability coefficient.

| Mark    | Hidden Meaning                                                           |
|---------|--------------------------------------------------------------------------|
| 0.8–1   | Indicates that the credibility of the indicator system is very good.     |
| 0.7–0.8 | Indicates that the credibility of the indicator system is better.        |
| 0.6–0.7 | Indicates that the indicator system needs to be revised.                 |
| 0–0.6   | Indicates that some items in the indicator system need to be eliminated. |

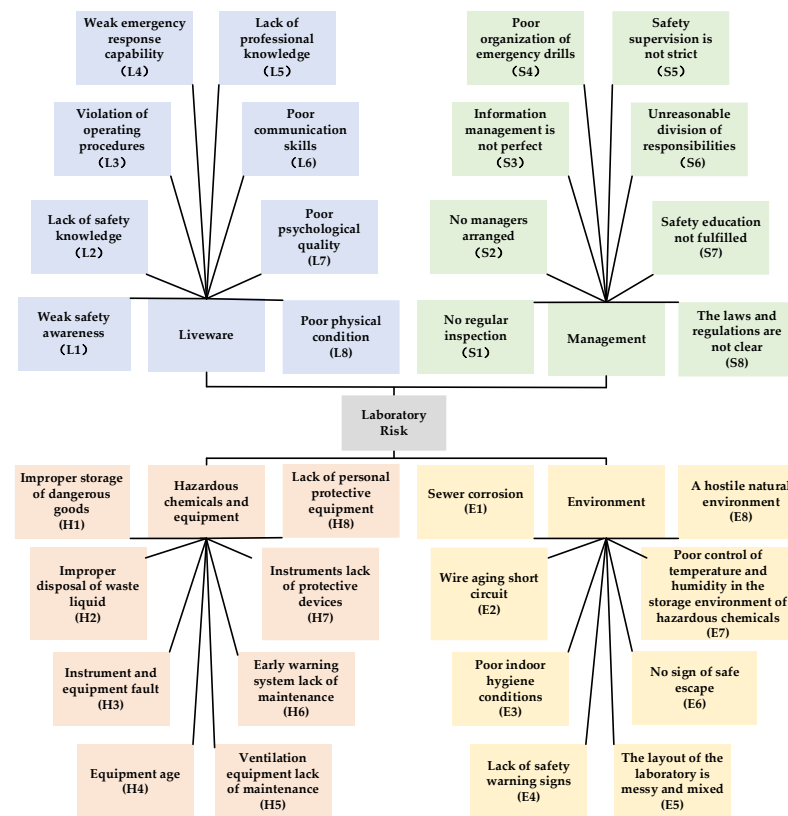


Figure 5. Laboratory risk assessment index system.

A questionnaire comprising 32 questions is designed to transform the index system into a measurable format. Each question was measured on a 5-point Likert scale, assigning a score of 1–5 to “not serious”, “generally serious”, “moderately serious”, “more serious”, and “very serious”, respectively. This questionnaire is distributed to domain experts and laboratory safety managers. Data collected from the questionnaire are analyzed for reliability using Cronbach’s  $\alpha$  reliability test in SPSS25.0 statistical software. The Cronbach’s  $\alpha$  reliability test coefficient is 0.894, signifying the reliability of the questionnaire is very good.

### 3.2. Determination of the Indicator Importance Matrix

Expert  $i$  is invited to analyze the importance of each indicator at each level based on the 3-scaled theory, and an evaluation matrix is given as follows, in which  $L_i$ ,  $H_i$ , and  $E_i$  and  $S_i$  denote the relative importance matrix among level II indicators, and  $A_i$  represent the relative importance matrix among level I indicators.

$$L_i = \begin{bmatrix} 0 & \cdots & -1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 0 \end{bmatrix}_{8 \times 8} \quad H_i = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix}_{8 \times 8} \quad E_i = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix}_{8 \times 8} \quad S_i = \begin{bmatrix} 0 & \cdots & -1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 0 \end{bmatrix}_{8 \times 8} \quad A_i = \begin{bmatrix} 0 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ -1 & \cdots & 0 \end{bmatrix}_{4 \times 4}$$

### 3.3. Determination the Indicator Risk Values

According to the laboratory situation and expertise, the risk scores for the minimum and maximum values of the indicators given by the experts in the interval  $[0, 1]$  are shown in Table 3.

**Table 3.** Laboratory risk score table.

| Expert | Extreme Value | Index |     |       |     |       |     |       |     |
|--------|---------------|-------|-----|-------|-----|-------|-----|-------|-----|
|        |               | $L_1$ | ... | $H_1$ | ... | $E_1$ | ... | $S_1$ | ... |
| 1      | $c_{min}$     | 0.30  | ... | 0.24  | ... | 0.08  | ... | 0.35  | ... |
|        | $c_{max}$     | 0.42  | ... | 0.30  | ... | 0.15  | ... | 0.40  | ... |
| 2      | $c_{min}$     | 0.33  | ... | 0.25  | ... | 0.12  | ... | 0.33  | ... |
|        | $c_{max}$     | 0.44  | ... | 0.30  | ... | 0.18  | ... | 0.39  | ... |
| ⋮      | $c_{min}$     | ...   | ... | ...   | ... | ...   | ... | ...   | ... |
|        | $c_{max}$     | ...   | ... | ...   | ... | ...   | ... | ...   | ... |
| m      | $c_{min}$     | 0.30  | ... | 0.25  | ... | 0.14  | ... | 0.38  | ... |
|        | $c_{max}$     | 0.38  | ... | 0.29  | ... | 0.19  | ... | 0.42  | ... |

### 3.4. Calculation of Weights for Indicator Combinations

According to the matrix  $L_i$ ,  $H_i$ ,  $E_i$ ,  $S_i$  and  $A_i$ , the subjective weights corresponding to indicators II and I are calculated by Equations (3)–(5), the objective weights of the indicators are calculated by Equations (6)–(10) based on the laboratory safety. Formula (11) combines the subjective and objective weights to calculate the dynamic combination weights of the indicators.

### 3.5. Determine the Numerical Characteristics of Evaluation Indicators

Expert  $i$  evaluates the evaluation indicator  $H_i$  ( $i = 1, 2, \dots, 8$ ), the constructed evaluation matrix  $M_{ii}$  ( $i = 1, 2, \dots, 8$ ) as shown below:

$$M = \begin{bmatrix} M_{11} & \cdots & M_{18} \\ \vdots & \ddots & \vdots \\ M_{81} & \cdots & M_{88} \end{bmatrix} \quad (13)$$

For the obtaining evaluation matrix  $M$ , Equation (13) is used to calculate the cloud digital features of the indicator, and the calculation process is the same for the rest of the indicators. Finally, the cloud digital features evaluated by  $m$  experts are combined and calculated to obtain the comprehensive cloud digital features of the index. The equation is as follows:

$$\begin{cases} Ex = (Ex_1En_1 + Ex_2En_2 + \cdots + Ex_mEn_m) / En \\ En = En_1 + En_2 + \cdots + En_m \\ He = (HeEn_1 + HeEn_2 + \cdots + HeEn_m) / En \end{cases} \quad (14)$$

### 3.6. Cloud Mapping for Integrated Risk Assessment

The cloud digital features of level II indicators and their corresponding weights are weighted and calculated to obtain the cloud digital features of level I indicators. Similarly, the cloud digital features of level I indicators and their weights are weighted and calculated to finally obtain the cloud digital features. Python software is utilized to draw the cloud diagram and compare it with the cloud diagram of standard assessment (Figure 4) to determine risk grade. Among them, the weighting operation formula is:

$$\begin{cases} Ex = \sum_{i=1}^n Ex_i \times w_i \\ En = \sqrt{\sum_{i=1}^n En_i^2 \times w_i} \\ He = \sum_{i=1}^n He_i \times w_i \end{cases} \quad (15)$$

#### 4. Case Study

Using the chemical laboratory of a university as an example, following the above risk assessment index system, six experts were invited to give the importance evaluation of the indexes and the risk evaluation value of the laboratory. This process included assigning digital characteristics to the indexes, determining the final risk assessment results, and utilizing Python to create the cloud diagram.

##### 4.1. Indicator Importance Matrix

Due to the large data volume, this paper only shows the results of an expert's assessment of the importance of indicators, as follows:

$$\begin{aligned}
 \mathbf{L}_i &= \begin{bmatrix} 0 & -1 & -1 & 0 & -1 & 1 & 0 & -1 \\ 1 & 0 & -1 & -1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & -1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & -1 & 0 & 0 & 1 & 1 & 1 \\ -1 & -1 & -1 & -1 & -1 & 0 & -1 & -1 \\ 0 & -1 & -1 & -1 & -1 & 1 & 0 & -1 \\ 1 & 0 & -1 & 0 & -1 & 1 & 1 & 0 \end{bmatrix} & \mathbf{H}_i &= \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ -1 & -1 & 0 & 1 & 0 & 0 & -1 & 0 \\ -1 & -1 & -1 & 0 & -1 & 0 & -1 & -1 \\ -1 & -1 & 0 & 1 & 0 & 0 & -1 & -1 \\ -1 & -1 & 0 & 0 & 0 & 0 & -1 & 0 \\ -1 & -1 & 1 & 1 & 1 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix} \\
 \mathbf{E}_i &= \begin{bmatrix} 0 & 0 & 1 & 1 & -1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & -1 & 1 \\ -1 & -1 & 0 & -1 & -1 & 0 & -1 & -1 \\ -1 & -1 & 1 & 0 & 0 & 0 & -1 & -1 \\ 1 & -1 & 1 & 0 & 0 & -1 & -1 & -1 \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & -1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 1 & 1 & 1 & -1 & 0 \end{bmatrix} & \mathbf{S}_i &= \begin{bmatrix} 0 & 0 & 1 & -1 & -1 & 0 & -1 & -1 \\ 0 & 0 & 0 & -1 & -1 & -1 & -1 & -1 \\ -1 & 0 & 0 & -1 & 0 & 0 & -1 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & -1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \\
 \mathbf{A}_i &= \begin{bmatrix} 0 & -1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ -1 & -1 & 0 & -1 \\ -1 & -1 & -1 & 0 \end{bmatrix}
 \end{aligned}$$

where  $\mathbf{L}_i$ ,  $\mathbf{H}_i$ ,  $\mathbf{E}_i$ , and  $\mathbf{S}_i$  respectively represent the relative importance evaluation of the sub-indicators of the four indicators of the personnel, hazardous chemicals and equipment, and the environment and management of the laboratory by expert  $i$ .  $\mathbf{A}_i$  denotes the relative importance matrix among the four indicators.

##### 4.2. Indicator Risk Values

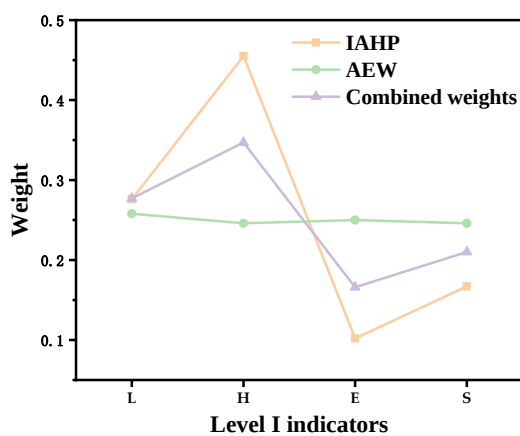
The risk scores of the minimum and maximum values of the indicators given by 6 experts are shown in Table 4.

##### 4.3. Indicator Weights

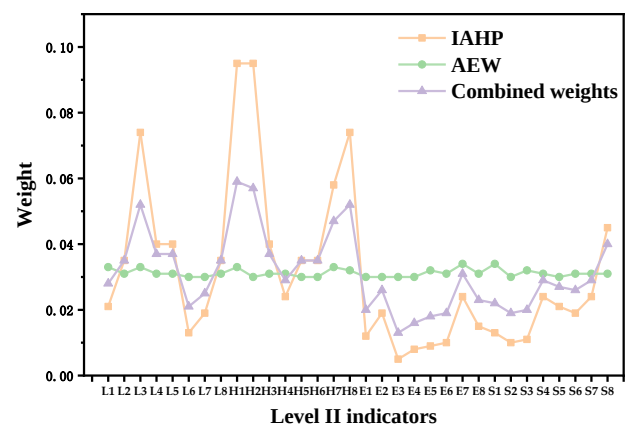
Combined with the index calculation process and the obtained data introduced in Section 3.4, the final weight calculation results are shown in Figure 6a,b. It can be seen that the index weights calculated by IAHP and AEW differ greatly in individual indicators, while the combination weights obtained after minimizing the information entropy are in the middle of the two. The principle of minimum information entropy introduced in this paper can well combine the weight values calculated by subjective and objective methods to improve the reliability of weight calculation and improve the accuracy of risk assessment.

**Table 4.** Laboratory risk score table by 6 experts.

| Expert        |    | 1    |      | 2    |      | 3    |      | 4    |      | 5    |      | 6    |      |
|---------------|----|------|------|------|------|------|------|------|------|------|------|------|------|
| Extreme Value |    | Min  | Max  | Min  | Max  | Min  | Max  | Min  | Max  | Min  | Max  | Min  | Max  |
| Index         | L1 | 0.30 | 0.42 | 0.33 | 0.44 | 0.32 | 0.40 | 0.35 | 0.39 | 0.34 | 0.40 | 0.30 | 0.38 |
|               | L2 | 0.36 | 0.40 | 0.39 | 0.43 | 0.36 | 0.45 | 0.36 | 0.40 | 0.38 | 0.42 | 0.34 | 0.40 |
|               | L3 | 0.37 | 0.43 | 0.39 | 0.44 | 0.35 | 0.40 | 0.35 | 0.39 | 0.37 | 0.45 | 0.30 | 0.39 |
|               | L4 | 0.40 | 0.46 | 0.36 | 0.43 | 0.34 | 0.39 | 0.36 | 0.41 | 0.43 | 0.45 | 0.39 | 0.42 |
|               | L5 | 0.28 | 0.33 | 0.25 | 0.36 | 0.27 | 0.33 | 0.25 | 0.29 | 0.32 | 0.35 | 0.30 | 0.38 |
|               | L6 | 0.25 | 0.30 | 0.23 | 0.29 | 0.23 | 0.30 | 0.28 | 0.31 | 0.21 | 0.29 | 0.25 | 0.29 |
|               | L7 | 0.18 | 0.22 | 0.20 | 0.25 | 0.24 | 0.30 | 0.20 | 0.24 | 0.23 | 0.30 | 0.22 | 0.30 |
|               | L8 | 0.18 | 0.23 | 0.20 | 0.26 | 0.21 | 0.25 | 0.22 | 0.26 | 0.26 | 0.29 | 0.20 | 0.27 |
|               | H1 | 0.24 | 0.30 | 0.25 | 0.30 | 0.25 | 0.29 | 0.26 | 0.31 | 0.22 | 0.29 | 0.25 | 0.29 |
|               | H2 | 0.30 | 0.40 | 0.35 | 0.41 | 0.29 | 0.39 | 0.33 | 0.38 | 0.29 | 0.33 | 0.32 | 0.36 |
|               | H3 | 0.20 | 0.25 | 0.30 | 0.34 | 0.20 | 0.29 | 0.26 | 0.29 | 0.27 | 0.31 | 0.24 | 0.30 |
|               | H4 | 0.20 | 0.28 | 0.26 | 0.29 | 0.21 | 0.29 | 0.23 | 0.26 | 0.23 | 0.26 | 0.27 | 0.31 |
|               | H5 | 0.25 | 0.35 | 0.30 | 0.38 | 0.28 | 0.33 | 0.30 | 0.34 | 0.33 | 0.37 | 0.24 | 0.30 |
|               | H6 | 0.25 | 0.30 | 0.23 | 0.32 | 0.26 | 0.31 | 0.29 | 0.32 | 0.26 | 0.32 | 0.26 | 0.33 |
|               | H7 | 0.23 | 0.30 | 0.26 | 0.29 | 0.22 | 0.28 | 0.20 | 0.26 | 0.18 | 0.22 | 0.10 | 0.20 |
|               | H8 | 0.29 | 30.5 | 0.29 | 0.34 | 0.28 | 0.33 | 0.30 | 0.36 | 0.19 | 0.28 | 0.25 | 0.30 |
|               | E1 | 0.08 | 0.15 | 0.12 | 0.18 | 0.13 | 0.18 | 0.10 | 0.16 | 0.11 | 0.20 | 0.14 | 0.19 |
|               | E2 | 0.45 | 0.55 | 0.46 | 0.52 | 0.39 | 0.45 | 0.40 | 0.46 | 0.38 | 0.45 | 0.39 | 0.44 |
|               | E3 | 0.28 | 0.35 | 0.33 | 0.38 | 0.32 | 0.36 | 0.31 | 0.36 | 0.30 | 0.38 | 0.30 | 0.40 |
|               | E4 | 0.33 | 0.42 | 0.41 | 0.45 | 0.39 | 0.45 | 0.36 | 0.41 | 0.39 | 0.46 | 0.41 | 0.45 |
|               | E5 | 0.36 | 0.40 | 0.38 | 0.42 | 0.35 | 0.39 | 0.40 | 0.44 | 0.37 | 0.46 | 0.30 | 0.38 |
|               | E6 | 0.26 | 0.30 | 0.25 | 0.29 | 0.28 | 0.32 | 0.25 | 0.32 | 0.28 | 0.35 | 0.25 | 0.29 |
|               | E7 | 0.22 | 0.28 | 0.25 | 0.29 | 0.24 | 0.27 | 0.23 | 0.30 | 0.25 | 0.31 | 0.26 | 0.32 |
|               | E8 | 0.10 | 0.15 | 0.14 | 0.18 | 0.09 | 0.13 | 0.15 | 0.20 | 0.10 | 0.18 | 0.16 | 0.22 |
|               | S1 | 0.35 | 0.40 | 0.33 | 0.39 | 0.32 | 0.36 | 0.38 | 0.42 | 0.30 | 0.37 | 0.38 | 0.42 |
|               | S2 | 0.20 | 0.25 | 0.22 | 0.26 | 0.19 | 0.23 | 0.22 | 0.28 | 0.19 | 0.26 | 0.24 | 0.29 |
|               | S3 | 0.30 | 0.36 | 0.32 | 0.38 | 0.32 | 0.36 | 0.33 | 0.37 | 0.33 | 0.39 | 0.37 | 0.40 |
|               | S4 | 0.36 | 0.40 | 0.38 | 0.42 | 0.41 | 0.46 | 0.40 | 0.45 | 0.39 | 0.46 | 0.39 | 0.45 |
|               | S5 | 0.34 | 0.42 | 0.38 | 0.45 | 0.33 | 0.37 | 0.33 | 0.41 | 0.36 | 0.42 | 0.36 | 0.42 |
|               | S6 | 0.50 | 0.60 | 0.50 | 0.58 | 0.48 | 0.58 | 0.55 | 0.59 | 0.45 | 0.56 | 0.47 | 0.55 |
|               | S7 | 0.23 | 0.29 | 0.22 | 0.29 | 0.22 | 0.30 | 0.25 | 0.31 | 0.21 | 0.27 | 0.27 | 0.31 |
|               | S8 | 0.36 | 0.45 | 0.33 | 0.42 | 0.38 | 0.42 | 0.33 | 0.39 | 0.37 | 0.40 | 0.33 | 0.40 |



(a)



(b)

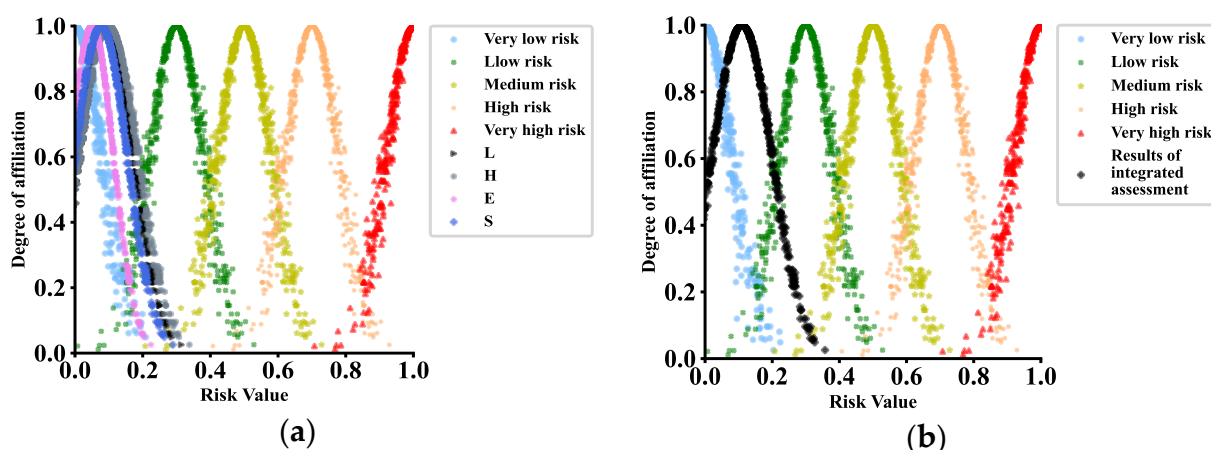
**Figure 6.** Weight of indicators. (a) Represents the weight of level I index; (b) represents the weight of level II index.

#### 4.4. Results and Discussion

Combined with the expert evaluation results, the cloud digital characteristics of the indicators are calculated by Equations (12) and (14). Equation (15) is used to weight the level II indicators to obtain the cloud digital features of the level I indicators:

$$C_L[0.094, 0.080, 0.003], C_H[0.009, 0.086, 0.004], C_E[0.050, 0.063, 0.002], C_S[0.079, 0.077, 0.002].$$

Drawing a comprehensive cloud diagram as in Figure 7a, it can be seen that the risk level is ranked as H-L-S-E, indicating a relatively high potential risk associated with hazardous chemicals and equipment. This is attributed to the inherent toxic, hazardous, and flammable properties of the chemicals, posing unpredictable hazards with even slight negligence. Moreover, the aging failure of the experimental equipment has a great impact on the normal operation of the equipment, because ensuring the fluency of the experiment is also the key to preventing accidents. The results are consistent with those of Li Xiangong [42], who analyzed the laboratory accidents by correlation rules, affirming the validity of the model. Therefore, we believe that in the daily management process of the laboratory, there should be a strong emphasis on managing hazardous chemicals and equipment to prevent compromising the laboratory's safety. In addition, Figure 6b shows that among the factors, such as hazardous chemicals and equipment, H1 (unreasonable storage of hazardous chemicals) has the largest weight among all indicators and is the most influential risk factor. This suggests a certain degree of inadequate understanding among laboratory personnel regarding drug storage rules, coupled with the substantial risks associated with dangerous chemicals, posing a significant impact on laboratory safety. Another influential factor is L3 (violation of operating procedures), which is the direct cause of chemical accidents. Some researchers, either pressured by work and study or aiming for efficiency, tend to neglect operational norms. Any negligence in the process of chemical experiments may bring serious losses. It is of great significance to strictly abide by the experimental design and corresponding operational norms in the process of the experiment.



**Figure 7.** Laboratory risk assessment cloud map. (a) Represents the risk assessment cloud chart of each index of L-H-E-S; (b) presents the risk level for the current laboratory risk assessment cloud map.

Similarly, Equation (15) is used to calculate the cloud digital features for comprehensive risk assessment of hazardous chemical laboratories:  $C[0.086, 0.079, 0.003]$ . A composite cloud was similarly plotted, as shown in Figure 7b. The observation shows that the risk level of this laboratory (Diamond Mark) lies between the cloud ranges of very low and low-risk criteria cloud ranges, indicating that the current laboratory risk is low. In this study, the fuzzy comprehensive evaluation method was also used to obtain the evaluation results of this laboratory as  $[0, 0, 0.023, 0.284, 0.018]$ . According to the principle of maximum affiliation, the assessment result is 0.284, which corresponds to the risk level of low risk. It

can be seen that the calculation results of the two methods are basically consistent, proving the feasibility and effectiveness of the method proposed in this research.

Compared with other multi-decision risk assessment studies across various design fields [14,16,26–30], the method proposed in this paper has the following advantages: Firstly, this study integrates the SHELL model and HACCP system for the first time for the identification and analysis of laboratory influencing factors. It eliminates redundant factors to establish an index system including S, H, E, and L aspects of risk assessment. The reliability of the index is clarified through the form of a questionnaire, which not only improves the reliability but also enhances the robustness of risk assessment. Secondly, this study integrates IAHP and AEW to calculate the comprehensive weight of the index by minimizing the information entropy. On the one hand, it balances the subjectivity and objectivity of the obtained data. On the other hand, it fully considers the variability of the data and realizes the adjustment of the weight, which is more in line with the dynamic and complex environmental characteristics of the laboratory. Finally, the final cloud map drawing results revealed that the comprehensive evaluation results obtained by the cloud model are consistent with the fuzzy comprehensive evaluation method. On the one hand, it proves the feasibility and effectiveness of the proposed method. On the other hand, the cloud model also reflects the uncertainty and fuzziness in the evaluation process and can intuitively present the key factors affecting safety and classification to managers. In summary, the advantage of the model proposed in this study is that it can capture the variability of relevant data, and at the same time deal with the subjectivity and ambiguity of experts in relevant evaluations.

#### 4.5. Implications

The IAHP-AEW-Cloud model proposed in this paper provides some different theoretical references and practical significance for laboratory risk management. In terms of theoretical reference, SHELL and HACCP are integrated for the first time to analyze laboratory risk factors, and a laboratory risk assessment index system including human, hazardous chemicals and equipment, the environment, and management is constructed. This system not only provides a solid foundation for other laboratory assessment or research fields but also allows for a comprehensive analysis and understanding of current environmental risk factors, laying the groundwork for the establishment of new index models. In addition, the research results demonstrate the application of the minimum information entropy principle to combine the subjective and objective weights of IAHP and AEW, which effectively solves the problem of unbalanced subjective and objective weights of indicators and the influence of dynamic change factors. It provides a new idea for the safety assessment of a dynamic complex environment. In practice, the utilization of the cloud model in the risk analysis method and risk index system proposed in this paper visually represents the randomness and fuzziness of risk occurrence through cloud maps. It intuitively communicates the key factors influencing the laboratory and the ranking of risk levels to managers. On the one hand, it can encourage managers to quickly grasp the cause of the accident or potential risks, and improve the ability to prevent accidents or respond to emergencies. Moreover, the ranking of risks provides a reference for risk management decision-making and facilitates the orderly execution of activities to reduce the occurrence or further expansion of laboratory accidents, effectively ensuring the safety and sustainable development of laboratories.

#### 5. Conclusions

In recent years, the frequency of laboratory accidents has increased, and the serious consequences have always reminded us to strengthen the risk management capabilities of laboratories. In order to effectively reduce the risk in laboratories, protect the safety of laboratory personnel and property, and minimize the environmental impact of chemical substances, this study introduced the combination of the SHELL model and HACCP system into the risk analysis with respect to four aspects of human, hazardous chemicals

and equipment, the environment, and management. A risk assessment system for chemical laboratories with hazards was constructed, which included 4 level I indicators and 32 level II indicators.

Then, a risk assessment method based on the combination of the IAHP-AEW-Cloud model was proposed. By incorporating the principle of minimum information entropy and combining the subjective and objective weights calculated by IAHP and AEW, this method not only balances the subjectivity and objectivity of the index but also dynamically adjusts the evaluation results according to the changes of the index. This dynamic adjustment effectively increases the accuracy and rationality of the index weight calculation. Moreover, the utilization of cloud digital characteristics and cloud images of the indicator represents the risk assessment results, effectively presenting the uncertainty and ambiguity associated with the occurrence of risks and making the evaluation results more intuitive.

Finally, the model was applied to the hazardous chemicals laboratory in colleges and universities to verify the effectiveness and feasibility of the method. The model can provide ideas and methods for risk analysis and evaluation of university laboratories. This model can assist laboratory managers in formulating emergency plans and risk management mechanisms, reducing the occurrence, and mitigating the severity of laboratory accidents. As a result, it effectively alleviates the losses caused by accidents and ensures the continued and sustainable operation of the laboratory.

Building on the findings of this study, there is still some subjectivity in our index system, and some index analysis may not be thorough enough, the laboratory risk index system will undergo further analysis and refinement to enhance the accuracy of risk assessment. At the same time, this method is only based on the construction of hazardous chemicals laboratories, which may have certain limitations for the risk assessment application of various laboratories in universities and needs further adjustment. Future research endeavors will focus on conducting emergency management studies specific to hazardous chemicals laboratories. The results of risk assessments will be integrated with early warning systems, emergency decision-making processes, and mitigation measures. This holistic approach aims to ensure laboratories' safety consistently and effectively, offering ongoing safety assurances. Ultimately, it seeks to diminish threats to human health, society, and the environment.

**Author Contributions:** Conceptualization, X.Z. and Z.W.; methodology, X.Z.; software, X.Z.; validation, X.Z., Z.W. and P.Y.; formal analysis, Y.G.; investigation, X.Z., Z.W., Y.G. and P.Y.; data curation, X.Z. and Y.G.; writing—original draft preparation, X.Z.; writing—review and editing, X.Z. and Y.G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Natural Science Foundation of China (grant number 12274017).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** While not publicly available due to confidentiality, the data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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