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DOI
10.1016/j.jlp.2021.104553

Publication date
2021

Document Version
Final published version

Published in
Journal of Loss Prevention in the Process Industries

Citation (APA)
Li, X., Zhang, L., Zhang, R., Yang, M., & Li, H. (2021). A semi-quantitative methodology for risk assessment of university chemical laboratory. *Journal of Loss Prevention in the Process Industries*, *72*, Article 104553. https://doi.org/10.1016/j.jlp.2021.104553

Journal of Loss Prevention in the Process Industries 72 (2021) 104553

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

A semi-quantitative methodology for risk assessment of university chemical laboratory

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ARTICLE INFO

Keywords:
University chemical laboratories
C-OWA operator
MEET
Risk assessment

ABSTRACT

University chemical laboratory is a high-risk place for teaching and scientific research due to the presence of various physical and chemical hazards. In recent years, university chemical laboratory accidents occur frequently. This urges the need to enhance university chemical lab safety. A semi-quantitative methodology comprising Matter-Element Extension Theory (MEET) implemented with Combination Ordered Weighted Averaging (C-OWA) operator is proposed to assess the risk of a university chemical laboratory. First, an index-based risk assessment system of university chemical laboratory is built by identifying various risk factors from a system perspective. Then, C-OWA operator is used to calculate the weight of assessment indices, whereas MEET is employed to determine the correlation degree of assessment indices. Finally, the comprehensive risk of university chemical laboratories is assessed, and some safety measures are proposed to reduce the risk of university chemical laboratories. The applicability of the proposed methodology is tested using a practical case. It is observed that the methodology can be a useful tool for risk assessment and management of university chemical laboratories.

1. Introduction

University chemical laboratory is an essential place for experimental teaching and scientific research, but a high-risk place with numerous physical and chemical risk factors, e.g., corrosion, radiation, highly toxic, flammable, and explosive (Ayi and Hon, 2018). Even in an environment with proper safety management and high-level risk control, accidents are unavoidable (Steenbergen et al., 2014; Schröder et al., 2016). Some accidents in university chemical laboratories such as poisoning, suffocation, fire, and explosion may result in casualties, huge property losses and adverse social impacts (Marendaz et al., 2013). Many university chemical laboratory accidents were reported in recent years. In 2008, a research assistant at the University of California, Los Angeles (UCLA) was killed by a laboratory fire accident due to the improper use of dangerous chemical agents (Gibson et al., 2014). In 2012, a student died at the chemical laboratory of Yale University due to the absence of protective equipment for machinery (Gopalaswami and Han, 2020). In 2018, an explosion accident resulting from the violations of laboratory regulations to conduct dangerous experiments occurred in the chemical laboratory of Beijing Jiaotong University, which led to the death of three students participating in the landfill leachate experiment (Yang et al., 2019). Risk assessment is a useful tool for identifying hazards and supporting evidence-based safety management of university chemical laboratories (Li et at., 2019a,b). Since most risk factor in chemical laboratories cannot be measurable and are with missing statistical data, a semi-quantitative methodology is necessary for risk assessment of university chemical laboratories.

At present, considerable works were conducted on the safety and risk issues of university laboratories. Suard (2007) evaluated the feasibility of using the "homogeneous exposure group" (EN 689 Standard) methodology for risk analysis in an academic laboratory. However, since researchers have independent research tendencies, and the strong variability in exposure time, equipment status, personal risk perception, etc., it is difficult to achieve "homogeneous" condition and concluded that the "homogeneous exposure group" methodology is not suitable for the academic environment. Ouédraogo et al. (2011) proposed the Laboratory Assessment and Risk Analysis (LARA) methodology based on the Analytic Hierarchy Process (AHP) and Risk Priority Number (RPN) to determine the critical links of laboratory risk management. Regarding the unsafe behavior of students, Shariff and Norazahar (2012)

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https://doi.org/10.1016/j.jlp.2021.104553
Received 8 May 2020; Received in revised form 9 September 2020; Accepted 17 May 2021
Available online 21 May 2021

established a laboratory risk behavior and improvement system (Lab-ARBAIS). Students' unsafe behaviors in the laboratories by computer databases are collected to warn and restrain students' dangerous behaviors. Laboratory chemical safety is receiving particular attention. Li et al. (2011) proposed establishing a waste management system in university laboratories to avoid pollution accidents caused by improper waste disposal. Leggett (2012) described Lab-HIRA (Hazard Identification and Risk Analysis for the Chemical Research Laboratory) software tool, a three-part process used to assess the risks of any work involving laboratory chemical reactions. Pan and Wu (2019) established an early warning system for hazardous chemicals safety in university laboratories to identify weak links in the safety management of hazardous chemicals. Zhang et al. (2020) used Bayesian network to analyze the dynamic evolution of gas release in university laboratories and to identified the factors affecting the probability of an accident. Pressure vessels are commonly used and highly dangerous equipment in university laboratories. Once an accident occurs, its super-explosive power will detonate various safety hazards in the laboratory, causing the accident to deteriorate and expand further. Liu and Zhang (2011) used AHP and Fuzzy Comprehensive Evaluation (FCE) to evaluate the reliability of pressure vessels system in university laboratories, which provided a scientific basis for the safety management of pressure vessels. The researchers also discussed the safety management of the laboratories. Foster (2003) proposed to create a laboratory safety program in the academic setting by combining elements of Chemical Hygiene Plan, Safety Rules and Policies, Emergency Planning, and Laboratory Inspections. Langerman (2008) proposed to apply the Management of Change methods in the OSHA Process Safety Standard to the laboratory, which has the potential to reduce the risks of the places further. Zakzeski (2009) developed and implemented a comprehensive quality management plan, including HAZOP analysis, to improve the overall safety of the laboratory. Marendaz et al. (2011) published a safety management program, namely MICE (Management, Information, Control and Emergency), which is dedicated to occupational health and safety in the academic environment. In addition, Li et al. (2018) summarized the types of high-risk accidents in chemical laboratories by using a risk matrix diagram and proposed the targeted preventive measures.

Although many studies mention university laboratory safety from different perspectives, two issues remain to be addressed. First, according to the characteristics of disciplines, university laboratories can be roughly divided into chemical, biological, electromechanical, and other categories. Most previous studies regarded university laboratories as a whole to conduct risk research. The studies on risk assessment of the university chemical laboratories can be found infrequently in the literature. Second, due to the complex environment of university chemical laboratories, the ambiguity and uncertainty of risk factors are substantial. Conventional risk assessment methods, e.g., Fuzzy Comprehensive Evaluation (FCE) and Grey Relational Analysis (GRA), cannot accurately assess the risk level of university chemical laboratories. In addition, the weight of risk factors is an essential basis for evaluating its importance. However, the weight calculation methods commonly used, e.g. Analytic Hierarchy Process (AHP) and Entropy Method (EM), have certain limitations. AHP is usually utilized to determine the subjective weight extracted from expert knowledge. EM is used to calculate the weight representing the fundamental relationships among factors based on the statistical data (Biswas et al., 2018; Li et al., 2020).

For the first issue, this paper fully considers various risk factors of university chemical laboratories from a system perspective. It establishes the index-based risk assessment system for university chemical laboratories to comprehensively assess the risk level of laboratories (Kritzinger, 2006). For the second issue, since Cai proposed the matter-element extension theory (MEET) (Cai et al., 1997; Cai and Yang, 2007), it has been widely used in risk assessment and safety decision-making (Zhang and Yue, 2017). MEET solves the ambiguity and uncertainty of the assessment object by qualitative description and quantitative calculation of the assessment object, suitable for the risk assessment of university chemical laboratories (Gu et al., 2019). The Combination Ordered Weighted Averaging (C-OWA) operator is an improved weight calculation method based on Ordered Weighted Averaging (OWA) operator. It eliminates the subjectivity and extreme value of expert weight assignment by the orderly weighted average operation, making weight more objective and reasonable (Shen, 2018). Moreover, the weight calculated by the C-OWA operator is a relative weight, which can better assess the importance of risk factors. Thus, this work uses the C-OWA operator to calculate the index weight to judge the importance of risk factors, carried out in the risk assessment model of matter-element extension theory.

The purpose of this paper is to develop a novel methodology for risk assessment of university chemical laboratories considering the associated hazards comprehensively. The methodology is comprised of MEET implemented with C-OWA operator. It can be used to assess the operational risk of university chemical laboratories and develop safety management measures.

The rest of this paper is organized as follows: Section 2 presents the proposed methodology; A case study is presented in Section 3 to illustrate the applicability of the proposed methodology; The conclusions of this work are given in Section 4.

2. The proposed methodology

Fig. 1 presents the flowchart of the proposed methodology for risk assessment of university chemical laboratories. The main steps of the methodology include:

- Establishing an index-based risk assessment system;
- Determining weight of assessment indices;
- Calculating the correlation degree of assessment indices;
- Determining the comprehensive risk level; and
- Developing safety management measures.

2.1. Establishing an index-based risk assessment system

Through the literature review and the field investigation, some relevant information of the university chemical laboratory is collected, including management standards, regulations, and historical accidents, etc. The risk factors associated with the operational safety of university chemical laboratories are identified, and an index-based risk assessment system of university chemical laboratory is established by sorting out the internal hierarchical relationship of risk factors. Fig. 2 presents an example of an index-based assessment system, including three-layer constructions for the illustrative purpose. The first-level index represents the target of risk assessment, i.e., the safety or risk status of the system. The second-level indices represent the main aspects of risk factors. The third -level indices denote the primary risk factors.

2.2. Determining the weight of assessment indices

The weight of assessment indices is calculated by using the C-OWA operator. Firstly, relevant experts in laboratory safety and risk research are invited to evaluate the importance of risk factors to acquire the initial decision-making data of assessment indices. Then, the new decision data is acquired by arranging the initial decision data in descending order. Eventually, the relative weight of each assessment index is acquired by the weighted average operation on the new decision data. The specific steps for the C-OWA operator to calculate the assessment index weight are shown as follows:

Step 1: Acquiring decision data.

Some experts working in chemical laboratories are invited to score the importance of risk factors on a 10-point scale to acquire the initial decision data $A = \{a_1, a_2, \ldots, a_n\}$ of the assessment indices. The larger score means the greater importance of the risk factor. The initial

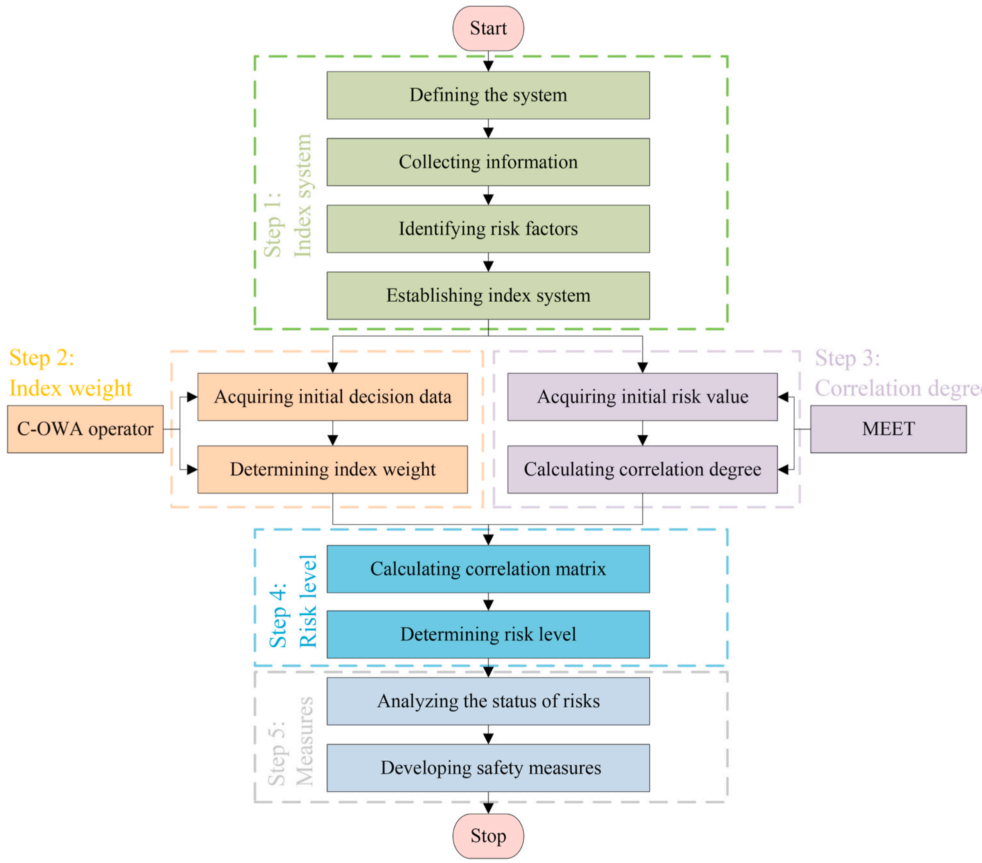

Fig. 1. Flowchart of the proposed methodology.

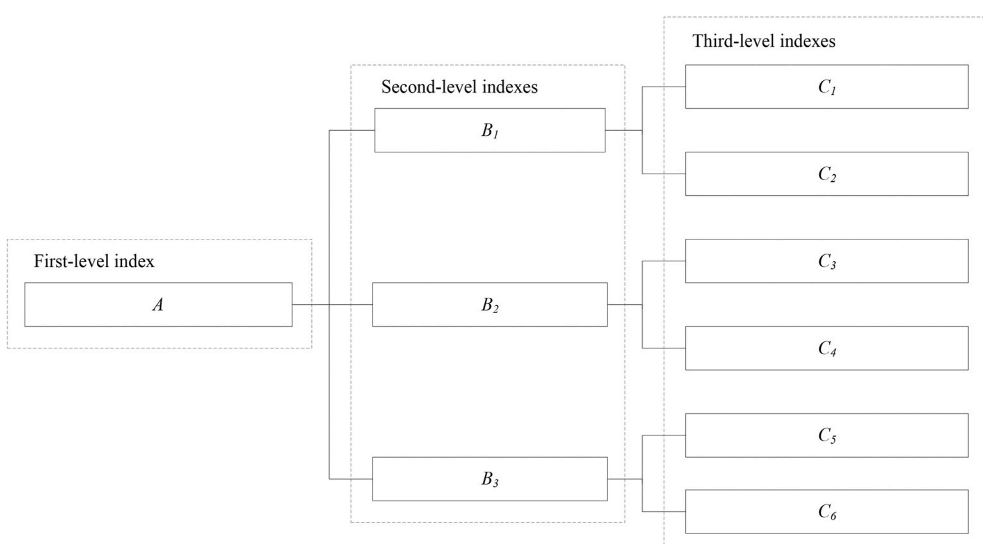

Fig. 2. A simple example of an index-based risk assessment system.

decision data is arranged in descending order to acquire new decision data $B=\{b_1, b_2, \ldots, b_n\}$.

Step 2: Determining the weighted vector.

The weighted vector k_j of the decision data B is calculated by using Eq. (1) (Li et at., 2019a,b).

$$k_j = \frac{C_{n-1}^{j-1}}{\sum_{k=0}^{n-1} C_{n-1}^{k}} = \frac{C_{n-1}^{j-1}}{2^{n-1}}, j = 1, 2, \cdots n \tag{1}$$

where, n represents the number of experts; C_{n-1}^{j-1} represents the combination number of j-1data selected from n-1 data.

Step 3: Calculating the absolute weight.

The absolute weight of the assessment index $\overline{w_i}$ is obtained by weighting the decision data B with the weighted vector k_j, as shown in follows:

$$\overline{w_i} = \sum_{j=1}^{n} k_j \cdot b_j \tag{2}$$

where, i represents the ith risk assessment index.

Step 4: Calculating the relative weight.

According to the absolute weight, the relative weight of assessment index w_i is calculated by using Eq. (3).

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{m} \overline{w_i}}, i = 1, 2 \cdots m \tag{3}$$

2.3. Calculating the correlation degree of assessment index

The correlation degree of assessment index is determined by the matter-element extension theory. A matter-element is ordered triples describing things $N = \{Q, C, R\}$, where Q is the name of the thing, C is the feature set about the thing, and R is the value of the thing. First, the classical domain and the nodal domain are established by classifying the risk level. Then, the risk values of third-level indices are scored according to the range of risk level, and the average value is used as the initial risk value of the index. Thus, the evaluated matter-element is established. Eventually, the correlation degree of the third-level indices is determined. The specific steps of the matter-element extension theory to determine the correlation degree of assessment indicators are shown as follows:

Step 1: Classifying the risk level.

According to "Safety Management Guidelines for Chemistry and Chemical Engineering Laboratories" (China Chemical Safety Association, 2019), and the standards of university laboratories, the risk level is classified into 5 levels to evaluate the risk of university chemical laboratories. They are level I (very low risk), level II (low risk), level III (medium risk), level IV (high risk), and level V (very high risk), as shown in Table 1.

Step 2: Establishing the classical domain.

The classical domain N_j is defined as follows:

$$N_j = (Q_j, C_i, R_{ji}) = \begin{pmatrix} Q_j & C_1 & (a_{j1}, b_{j1}) \\ & C_2 & (a_{j2}, b_{j2}) \\ & \vdots & \vdots \\ & C_m & (a_{jm}, b_{jm}) \end{pmatrix} \tag{4}$$

where Q_j is the jth risk level; C_i is the risk assessment set of third-level indices. R_{ji} is the value range of risk level Q_j; b_{ij} and a_{ij} are the upper and lower limits of risk level.

Step 3: Establishing the nodal domain.

The nodal domain N_d is defined as follows:

$$N_d = (Q, C_i, R_{di}) = \begin{pmatrix} Q & C_1 & (a_{d1}, b_{d1}) \\ & C_2 & (a_{d2}, b_{d2}) \\ & \vdots & \vdots \\ & C_m & (a_{dm}, b_{dm}) \end{pmatrix} \tag{5}$$

where, R_{di} is the value range of the total risk level Q; b_{di} and a_{di} are the upper and lower limits of the total risk level.

Step 4: Establishing the evaluated matter-element.

The evaluated matter element N_i is defined as follows:

$$N_p = (Q_0, C_i, r_i) = \begin{pmatrix} Q_0 & C_1 & r_1 \\ & C_2 & r_2 \\ & \vdots & \vdots \\ & C_m & r_m \end{pmatrix} \tag{6}$$

where, r_i is the initial risk value of the third-level indices.

Step 5: Determining the correlation degree.

The concept of distance is introduced in the matter-element extension theory to determine the correlation degree (Liu and Li, 2019). The distance p (r_i, R_{ji}) between the initial risk value of the third-level index, and the classical domain and the distance p (r_i, R_{di}) between the initial risk value of the third-level index, and the nodal domain can be calculated by using Eqs. (7) and (8) (Xie et al., 2019).

$$\rho(r_i, R_{ji}) = \left| r_i - \frac{a_{ji} + b_{ji}}{2} \right| - \frac{1}{2}(b_{ji} - a_{ji}) \tag{7}$$

$$\rho(r_i, R_{di}) = \left| r_i - \frac{a_{di} + b_{di}}{2} \right| - \frac{1}{2}(b_{di} - a_{di}) \tag{8}$$

Finally, the correlation degree $K_j(C_i)$ of the third-level indices is determined by Eq. (9).

$$K_j(C_i) = \begin{cases} -\rho(r_i, R_{ji}) - 1, \rho(r_i, R_{di}) - \rho(r_i, R_{ji}) = 0 \\ \dfrac{\rho(r_i, R_{ji})}{\rho(r_i, R_{di}) - \rho(r_i, R_{ji})}, \rho(r_i, R_{di}) - \rho(r_i, R_{ji}) \neq 0 \end{cases} \tag{9}$$

2.4. Determining the comprehensive risk level

The risk correlation matrix evaluates the comprehensive risk of university chemical laboratories. First, the risk correlation matrix is calculated from the index weight and the correlation degree. Then, the risk level is determined according to the principle of maximum membership. The specific procedures for calculating the risk correlation matrix and determining the risk level are shown as follows:

The risk correlation matrix of second-level indexes $K(B_i)$ is calculated by using Eq. (10).

$$K(B_i) = \sum_{i=1}^{m} w_i K(C_i) \tag{10}$$

where, w_i represents the third-level index weight. $K(C_i) = (K_j(C_i))$ represents the risk correlation matrix composed of correlation degree of third-level indices.

The risk correlation matrix of first-level index $K(C)$ is calculated by using Eq. (11).

$$K(A) = \sum_i w'_i K(B_i) \tag{11}$$

where, w' i represents the weight of secondary index.

According to the principle of maximum membership, if $K_j(A)$=max $K(A)$, $\{j = 1, 2, \ldots, 5\}$, then the risk level of the index is judged to be jth level.

2.5. Developing safety measures

Safety measures are essential elements in risk management. The evaluated risk level can reflect the importance of the risk from exposure to the hazard. Based on risk assessment outcomes, the risk level of evaluation indices can help to determine which hazard should be controlled prior in risk management of chemical laboratory. Some useful safety measures can then be developed to prevent the occurrence possibility or mitigate the impact of the accident from exposure to the

Table 1

Risk level of university chemical laboratories.

Risk level	Value range	Degree of risk
Level I	(0, 2]	Very low risk
Level II	(2, 4]	Low risk
Level III	(4, 6]	Medium risk
Level IV	(6, 8]	High risk
Level V	(8, 10]	Very high risk

identified hazards in chemical laboratory, and this can improve the safety of university chemical laboratories. Eventually, the risk can be reassessed after considering the implementation of safety measures to verify their effectiveness.

3. Case study

The proposed method was applied to risk assessment of chemical laboratories in a university of western China. Fig. 3 presents the flowchart for implementing the case study.

3.1. Risk assessment system of university chemical laboratories

The risk factors of the university chemical laboratory are adequately identified from a system perspective by using the information collected through on-site investigation, which include hazards, failures or deviations existing in chemical laboratory. Thus, an index-based risk assessment system of university chemical laboratories is established, as shown in Fig. 4. It is a generic index-based risk assessment system and can also be applied to other university chemical laboratories.

This index-based risk assessment system consists of three levels of indexes. The first-level index is the comprehensive risk status of the university chemical laboratory, which is the target of risk assessment. The second-level indices are comprised of 5 risk factors, i.e., unsafe behavior of lab users, the unsafe state of instrument and equipment, improper storage, use and disposal of chemicals, adverse environmental factors and management flaws, the main factors affecting the operational safety of university chemical laboratories. The third-level indices are specific aspects of the second-level indices and represent the primary risk factors. A total of 34 basic risk factors are identified as the third-level assessment indices. Lab users are the main body of laboratory work. Their unsafe behavior may directly affect the operational safety of a laboratory. The unsafe behavior of lab users mainly includes risk factors such as violation of operating regulations, careless operation, lack of safety knowledge and weak security awareness. These risk factors are used as the third-level indices in the branch of a second-level index, i.e., unsafe behavior of lab users. The unsafe state of instrument and equipment includes 5 third-level indices. The safe operation of instruments and equipment is important for laboratories to carry out daily teaching and scientific research. If instruments and equipment are into unsafe state, such as aging and failure, it will increase the chemical laboratory's operational risk. Due to the specific experiment requirement, it is usually needed to use and store some chemicals in laboratory. Considering the wide variety and complex nature of chemicals, their storage, use, and disposal may pose a threat to the safety of laboratory. The improper storage, use and disposal of chemicals include 8 third-level indices, as shown in Fig. 4. The adverse environmental factors may also contribute to the high operation risk of university chemical laboratory, and this work identified a total of 9 risk factors associated with the environment, including excessive circuit load, defective ventilation system and inadequate fire protection facilities. These adverse environmental factors are usually hidden and indiscoverable. The flaws in laboratory management may increase the operational risk of laboratory. There are 8 third-level indices in the branch of management flaws, such as inadequate safety supervision, education, and training.

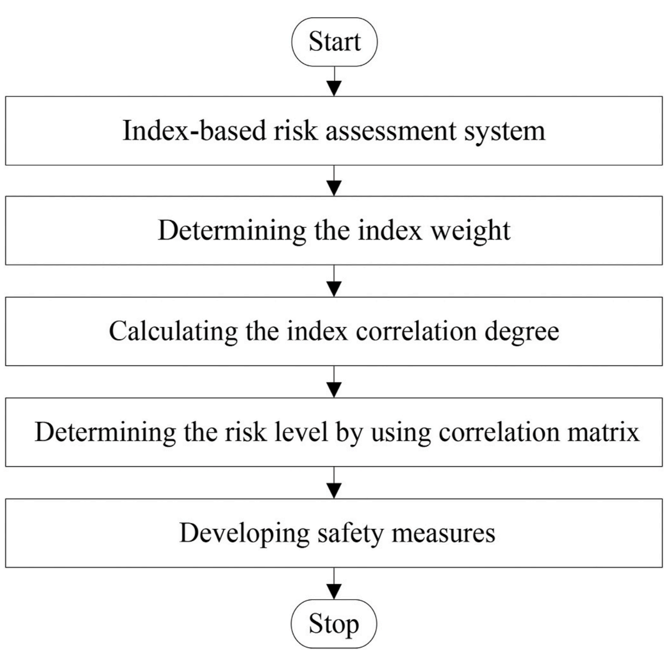

Fig. 3. The implementation steps of the case study.

3.2. Determining the index weight by C-OWA operator

According to the C-OWA operator, five relevant experts from the field of laboratory safety, as listed in Table 2, were invited to score the importance of each assessment index on a 10-point scale. This weighting technique considers the ambiguity and uncertainty in expert judgments.

Table 3 presents the expert's scores on the importance of each index, in which the higher score means higher importance. Thus, the initial decision data of the assessment index is obtained. Then, the new decision data can be obtained by sorting the initial decision data in descending order.

Fig. 5 presents the weight of the risk assessment index calculated by Eqs. (1)–(3). As can be observed that the second-level index B_3 (Improper storage, use, and disposal of chemicals) has a relatively large weight, indicating it is with the highest importance. It is also observed that the weight of the three-level index C_1 (Violation of operating regulations) has the largest weight, indicating the importance of standardizing experimental operations.

3.3. Calculating the index correlation degree by MEET

According to the matter-element extension theory, since 5 risk levels are used to evaluate the risk of university chemical laboratories, Eqs. (4) and (5) establish 5 classical domains and a nodal domain. Taking third-level indices in the branch of the second-level index B_1 (unsafe behavior of lab users) as an example, the classical domains are as follows:

$$N_{\mathrm{I}} = \begin{pmatrix} Q_{\mathrm{I}} & C_1 & (0,2) \\ & C_2 & (0,2) \\ & C_3 & (0,2) \\ & C_4 & (0,2) \end{pmatrix},$$

$$N_{\mathrm{II}} = \begin{pmatrix} Q_{\mathrm{II}} & C_1 & (2,4) \\ & C_2 & (2,4) \\ & C_3 & (2,4) \\ & C_4 & (2,4) \end{pmatrix},$$

$$N_{\mathrm{III}} = \begin{pmatrix} Q_{\mathrm{III}} & C_1 & (4,6) \\ & C_2 & (4,6) \\ & C_3 & (4,6) \\ & C_4 & (4,6) \end{pmatrix},$$

$$N_{\mathrm{IV}} = \begin{pmatrix} Q_{\mathrm{IV}} & C_1 & (6,8) \\ & C_2 & (6,8) \\ & C_3 & (6,8) \\ & C_4 & (6,8) \end{pmatrix},$$

and

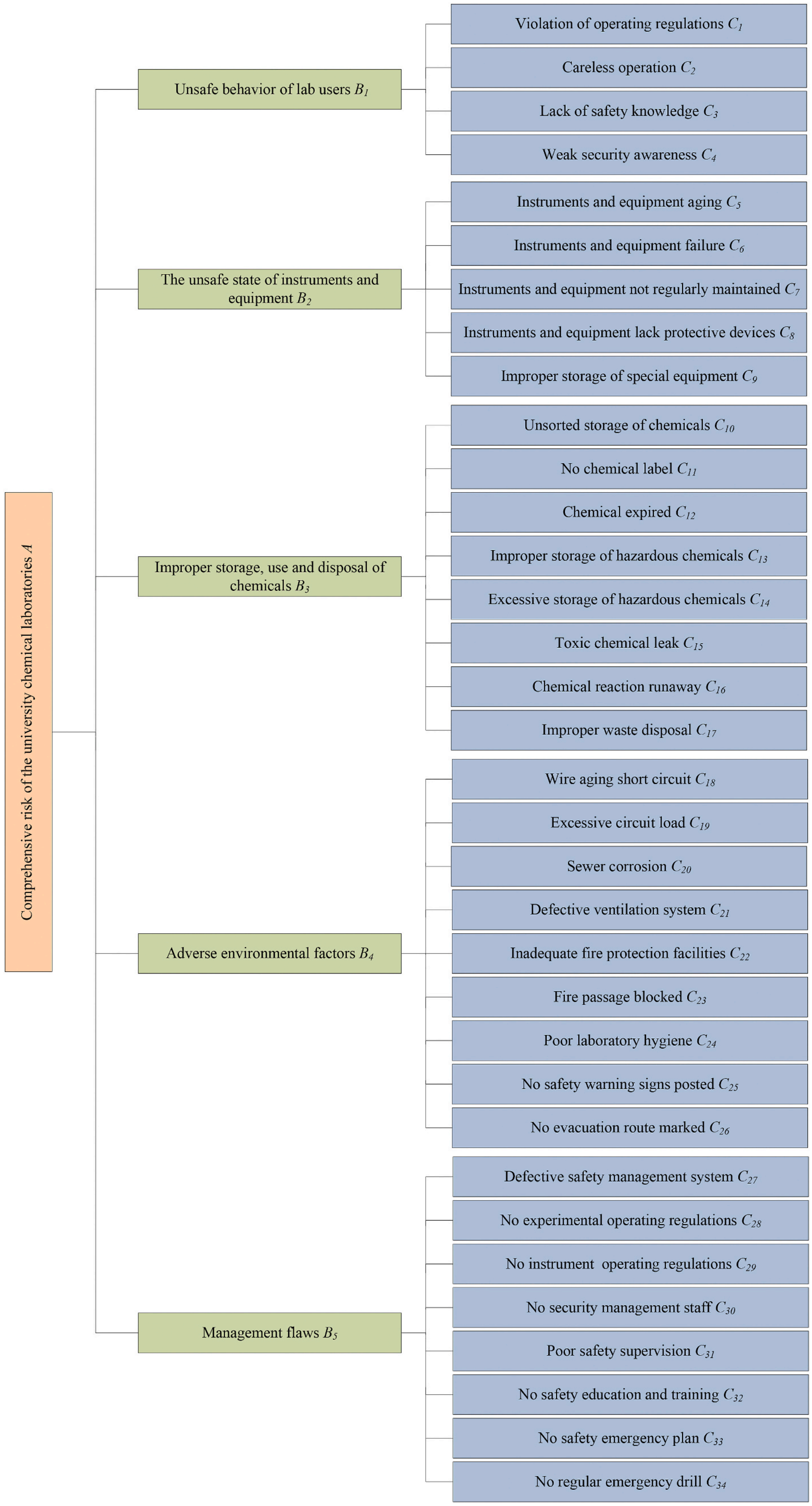

Fig. 4. Index-based risk assessment system for university chemical laboratories.

Table 2
Expert information.

No.	Professional position	Service time (years)	Educational level
Expert 1	Professor (Chemical engineering)	32	Doctor
Expert 2	Professor (Safety engineering)	25	Doctor
Expert 3	Laboratory safety supervisor	18	Doctor
Expert 4	Laboratory safety manager	12	Master
Expert 5	Laboratory safety manager	10	Master

Table 3
Index importance scores.

Index	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
B_1	8.0	8.5	8.5	8.0	8.0
B_2	8.5	9.0	9.0	8.5	8.5
B_3	9.0	9.5	9.0	9.5	9.5
…	…	…	…	…	…
C_{33}	8.5	8.0	8.0	8.5	8.5
C_{33}	7.5	8.0	8.0	7.5	8.0
C_{34}	9.0	8.5	7.5	7.5	8.0

$$N_V = \begin{pmatrix} Q_V & C_1 & (8,10) \\ & C_2 & (8,10) \\ & C_3 & (8,10) \\ & C_4 & (8,10) \end{pmatrix}.$$

The nodal domain is as below:

$$N_d = \begin{pmatrix} Q & C_1 & (0,10) \\ & C_2 & (0,10) \\ & C_3 & (0,10) \\ & C_4 & (0,10) \end{pmatrix}.$$

Five experts score the risk of the third-level indices, and the initial risk value of the index is obtained after taking the average. Fig. 6 presents the initial risk value of the third-level indices. As can be observed that the initial risk value of C_{19} (Excessive circuit load) is the largest and the initial risk value of C_{26} (No evacuation route marked) is the smallest, indicating that the circuit load of the laboratories is too large. Thus, it should plan and use circuits reasonably to avoid accidents caused by excessive circuit load. Based on the initial risk values of the third-level indices, Eq. (6) established the evaluated matter-element:

$$N_p = \begin{pmatrix} Q_0 & C_1 & 6.2 \\ & C_2 & 3.8 \\ & C_3 & 3.4 \\ & C_4 & 4.7 \end{pmatrix}.$$

The following shows the specific process of determining the correlation degree of the evaluated matter-element. Taking C_1 as an example, the initial risk value of C_1 is 6.2. Firstly, the distance between the initial

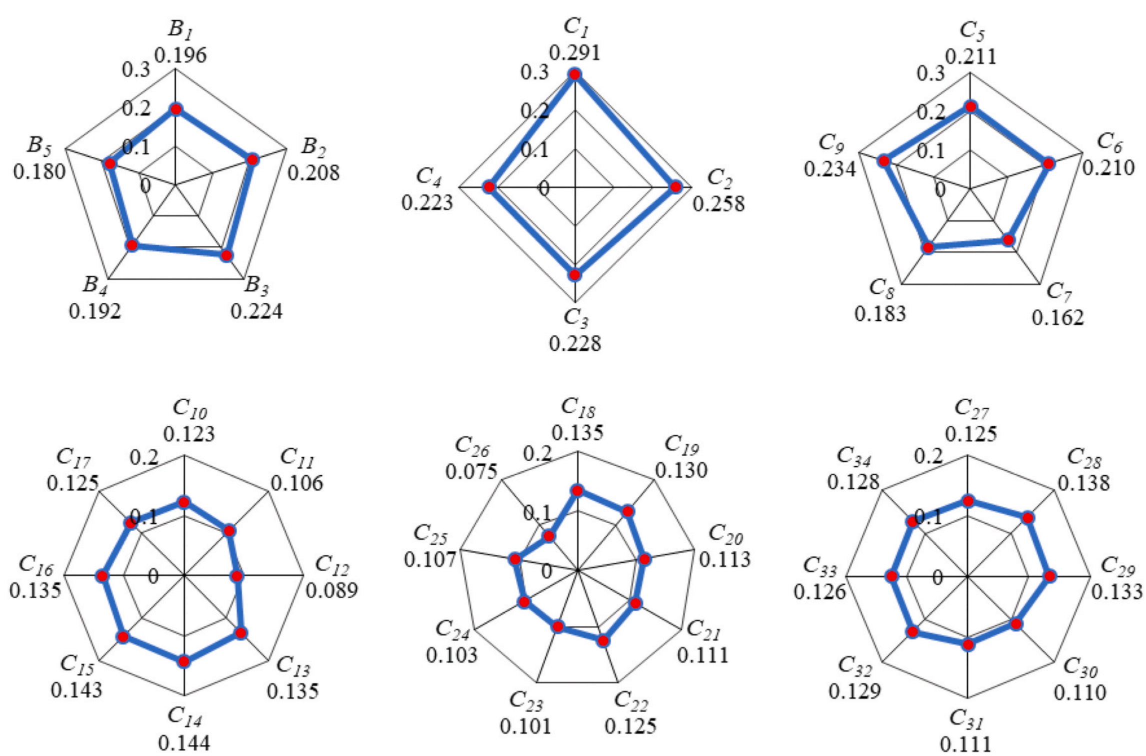

Fig. 5. Risk assessment index weight.

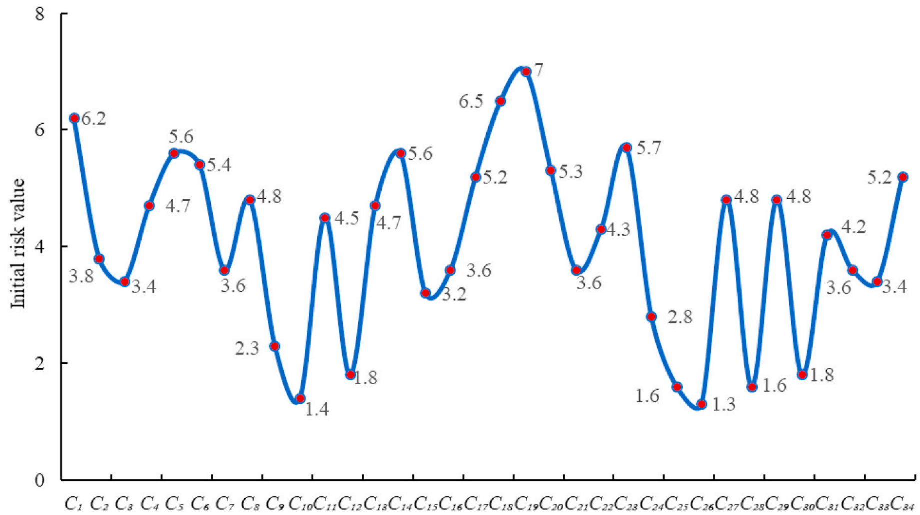

Fig. 6. Third-level index initial risk value.

Table 4
Third-level index correlation degree.

Index	Level I	Level II	Level III	Level IV	Level V
C_1	−0.525	−0.367	−0.050	0.056	−0.321
C_2	−0.321	0.056	−0.050	−0.367	−0.525
C_3	−0.292	0.214	−0.150	−0.433	−0.575
C_4	−0.365	−0.130	0.175	−0.217	−0.413
C_5	−0.450	−0.267	0.100	−0.083	−0.353
C_6	−0.425	−0.233	0.150	−0.115	−0.361
C_7	−0.308	0.125	−0.100	−0.400	−0.550
C_8	−0.368	−0.143	0.200	−0.200	−0.400
C_9	−0.115	0.150	−0.425	−0.617	−0.713
C_{10}	0.750	−0.300	−0.650	−0.767	−0.825
C_{11}	−0.357	−0.100	0.125	−0.250	−0.438
C_{12}	0.125	−0.100	−0.550	−0.700	−0.775
C_{13}	−0.365	−0.130	0.175	−0.217	−0.413
C_{14}	−0.450	−0.267	0.100	−0.083	−0.353
C_{15}	−0.273	0.333	−0.200	−0.467	−0.600
C_{16}	−0.308	0.125	−0.100	−0.400	−0.550
C_{17}	−0.400	−0.200	0.200	−0.143	−0.368
C_{18}	−0.563	−0.417	−0.125	0.167	−0.300
C_{19}	−0.625	−0.500	−0.250	0.500	−0.250
C_{20}	−0.413	−0.217	0.175	−0.130	−0.365
C_{21}	−0.308	0.125	−0.100	−0.400	−0.550
C_{22}	−0.348	−0.065	0.075	−0.283	−0.463
C_{23}	−0.463	−0.283	0.075	−0.065	−0.348
C_{24}	−0.222	0.400	−0.300	−0.533	−0.650
C_{25}	0.333	−0.200	−0.600	−0.733	−0.800
C_{26}	1.167	−0.350	−0.675	−0.783	−0.838
C_{27}	−0.368	−0.143	0.200	−0.200	−0.400
C_{28}	0.333	−0.200	−0.600	−0.733	−0.800
C_{29}	−0.368	−0.143	0.200	−0.200	−0.400
C_{30}	0.125	−0.100	−0.550	−0.700	−0.775
C_{31}	−0.344	−0.045	0.050	−0.300	−0.475
C_{32}	−0.308	0.125	−0.100	−0.400	−0.550
C_{33}	−0.292	0.214	−0.150	−0.433	−0.575
C_{34}	−0.400	−0.200	0.200	−0.143	−0.368

risk value of C_1 and the classical domains is calculated by using Eq. (7). The distance is calculated as below:

$\rho(r_1, R_{11}) = 4.2$,
$\rho(r_1, R_{21}) = 2.2$,
$\rho(r_1, R_{31}) = 0.2$,
$\rho(r_1, R_{41}) = -0.2$,
and
$\rho(r_1, R_{51}) = 1.8$.

Then, the distance between the initial risk value of C_1 and the nodal domain is calculated by using Eq. (8):

$$\rho(r_1,\ R_{d1}) = -3.8$$

Eventually, the correlation degree of the index concerning each risk level is determined according to Eq. (9). The correlation degree is as follows:

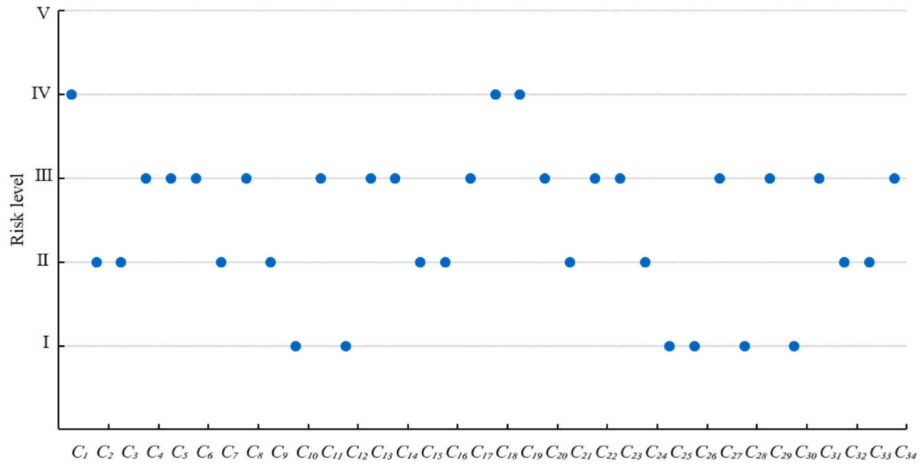

Fig. 7. Risk level of third-level indices.

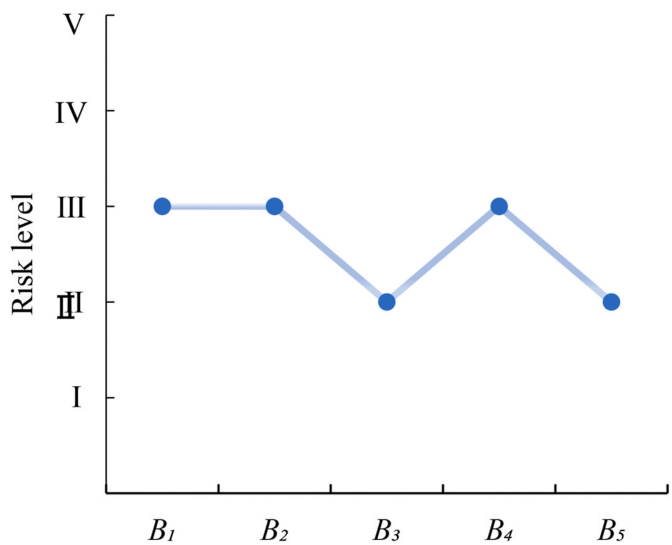

Fig. 8. Risk level of second-level indices.

Table 5
The primary risk factors for the laboratory.

Risk problems	Causations
Some lab users violate operation regulations.	• Lack of safety knowledge. • Weak security awareness. • Inadequate safety education and training.
Most instruments and equipment face are getting into aging and failure.	• Long service life. • No regularly maintained.
Some instruments and equipment that are easy to cause mechanical injury lack of protection devices.	• Original design flaws. • The lab is not equipped with protective devices.
Excessive storage of hazardous chemicals. Most experimental waste is directly poured into the sewer, causing serious corrosion of sewer system.	• Not comply with lab's regulations and guidelines regarding the storage, use and disposal of chemicals.
Wire aging seriously.	• Long use time. • Failure to replace aged wires in time.
Multiple high-power equipment uses the same wiring board, resulting in excessive circuit load.	• A special socket is used for the high-power devices

$$K_{\mathrm{I}}(C_1) = \frac{\rho(r_1, R_{11})}{\rho(r_1, R_{d1}) - \rho(r_1, R_{11})} = \frac{4.2}{-3.8 - 4.2} = -0.525,$$

$$K_{\mathrm{II}}(C_1) = \frac{\rho(r_1, R_{21})}{\rho(r_1, R_{d1}) - \rho(r_1, R_{21})} = \frac{2.2}{-3.8 - 2.2} = -0.367,$$

$$K_{\mathrm{III}}(C_1) = \frac{\rho(r_1, R_{31})}{\rho(r_1, R_{d1}) - \rho(r_1, R_{31})} = \frac{0.2}{-3.8 - 0.2} = -0.050,$$

$$K_{\mathrm{IV}}(C_1) = \frac{\rho(r_1, R_{41})}{\rho(r_1, R_{d1}) - \rho(r_1, R_{41})} = \frac{-0.2}{-3.8 - (-0.2)} = -0.056,$$

and

$$K_{\mathrm{V}}(C_1) = \frac{\rho(r_1, R_{51})}{\rho(r_1, R_{d1}) - \rho(r_1, R_{51})} = \frac{1.8}{-3.8 - 1.8} = -0.321.$$

Similarly, the correlation degree of the remaining third-level indices can be determined. Table 4 presents the correlation degree of the third-level indices for each risk level. Moreover, the risk level of the third-level indices is determined by the correlation degree, which reflects the degree of membership of the index for each risk level.

3.4. Determining risk level of university chemical laboratory

The comprehensive risk assessment of the university chemical laboratories from a system perspective can help to fully understand the safety status of the laboratory, thereby taking adequate safety measures to ensure the operational safety of laboratories. Fig. 7 presents the risk level of third-level indices. As can be observed that the number of third-level indices with risk levels I, II, III, IV is 6, 10, 15 and 3, respectively accounting for 17.65%, 29.41%, 44.12% and 8.82% of the total number of third-level indices. Furthermore, the third-level indices with the risk level of IV are C_1 (Violation of operating regulations), C_{18} (Wire aging short circuit), and C_{19} (Excessive circuit load), which are in the "high risk". According to the on-site investigation, it is found that the wires of the university's chemical laboratories are seriously aging and that multiple high-power instruments and equipment use the same wiring board, which could easily cause electric shock and fire accidents. In addition, the lab users of the university's chemical laboratories frequently violated the operation regulations, increasing the possibility of accidents.

The risk correlation matrixes of second-level indices are calculated by Eq. (10), and are shown as follows:

$$K(B_1) = (-0.384, \ -0.073, \ -0.023, \ -0.226, \ -0.452),$$
$$K(B_2) = (-0.328, \ -0.076, \ -0.027, \ -0.287, \ -0.479),$$
$$K(B_3) = (-0.179, \ -0.073, \ -0.095, \ -0.363, \ -0.530),$$
$$K(B_4) = (-0.228, \ -0.175, \ -0.170, \ -0.206, \ -0.484),$$

and

$$K(B_5) = (0.201, \ -0.063, \ -0.092, \ -0.388, \ -0.542).$$

Fig. 8 presents the risk level of second-level indices. It can be observed that the risk level of B_3 (Improper storage, use, and disposal of chemicals) and B_5 (Management flaws) is in level II, which are in the "low risk" state, while the risk level of the B_1 (Unsafe behavior of experimenters), B_2 (The unsafe state of instruments and equipment) and B_4 (Adverse environmental factors) is in level III, which are in the "medium risk" state. It shows that B_1, B_2 and B_4 are the weaknesses of risk management and control in the chemical laboratories of this university.

The risk correlation matrix of first-level index is calculated by Eq. (11):

$$K(A) = (-0.191, \ -0.091, \ -0.081, \ -0.295, \ -0.497).$$

It is observed that the university's chemical laboratory's comprehensive risk level is in level III, which is in the "medium risk" state. Table 5 presents the main risk problems and reasons for the laboratory under the investigation. By comparing the laboratory's risk factors identified in the present work with the risk factors reported in Gopalaswami and Han (2020), it is concluded that the risk assessment outcomes are consistent with the laboratory's actual situation of the laboratory, indicating that the proposed methodology is applicable and practical.

3.5. Risk management of university chemical laboratory

Based on risk assessment outcomes, some safety measures are proposed to manage and control the risk of the university chemical laboratories. Firstly, due to some lab users violate operating regulations, safety education and training are essential to standardize their operation. It can increase the safety knowledge and awareness of lab users and avoid unsafe behaviors, thereby reducing the possibility of injuries and accidents caused during the experimental operation. Then, as the long service life, most instruments and equipment in the laboratory face problems such as aging or failure. Regular maintenance inspections can discover and solve their potential failures in time, which is crucial to the safe operation of instruments and equipment.

Moreover, due to the design flaws, some instruments and equipment that may be easy to cause mechanical injury lack protection devices, shall be equipped with protective devices to protect lab users from mechanical injury. Regarding the storage, use and disposal of chemicals, the laboratory stores excessive amounts of hazardous chemicals, and most of the experimental waste is directly poured into the sewer, which seriously affected the laboratory safety. The risks involved in chemicals could be reduced by strictly complying with regulations and guidelines for the storage, use and disposal of chemicals, including the storage specifications and use records of hazardous chemicals, and the reasonable disposal of waste based on the characteristics of experimental waste. Besides, the electrical safety in laboratory should be paid special attention. Due to long use time, laboratory's wires are seriously aging, and multiple high-power equipment use the same wiring board, resulting in the excessive circuit load. These failures increase the electrical risk in the laboratory. Through timely replacing aging wires and the high power-equipment with a special socket, the electrical risk can be controlled. In most cases, laboratory's safety may be threatened by the combined effects of these risk factors. University chemical laboratory safety should arouse the attention of both safety managers and lab users. The efficient risk management requires the joint participation of them.

We reassessed the risks of the university's chemical laboratory after implementing these safety measures for a period of time. The reassessment results show that the laboratory risk has been mitigated and is now in the "low level" state. The third-level indices C_1 (Violation of operating regulations), C_{18} (Wire aging short circuit), and C_{19} (Excessive circuit load), were previously in the "high risk" state, are now in the "medium risk" state.

4. Conclusions

This paper builds a semi-quantitative methodology for risk assessment of university chemical laboratories by combining C-OWA operator and MEET, which is implemented in the framework of an index-based risk assessment system. C-OWA operator handles the subjectivity and extreme value of the weight assignment. The ambiguity and uncertainty of risk factors in the university chemical laboratory are addressed by MEET. A case study on risk assessment of university chemical laboratories in western China illustrates the proposed methodology.

In the case study, an index-based risk assessment system is established, comprising of 5 s-level indices, i.e., unsafe behavior of experimenters, the unsafe state of instruments and equipment, improper storage, use and disposal of chemicals, adverse environmental factors and management flaws. There are 34 third-level indices in the branch of second-level indices, which are the primary risk factors associated with the university chemical laboratory. The weight calculation finds that B_3 (Improper storage, use, and disposal of chemicals) and C_1 (Violation of operating regulations) have the higher weights, indicating that they are of higher importance than others. The risk assessment results present that the comprehensive risk level of the laboratory is in III, which is "moderate risk" state. Furthermore, the third-level indices C_1 (Violation of operating regulations), C_{18} (Wire aging short circuit), and C_{19} (Excessive circuit load) have a risk level of IV and are in the "high risk" state. Therefore, the increased effort should be to strengthen safety education and training of lab users to enhance their safety awareness and standardize experimental operations, and the electrical safety in laboratory should be paid more attention. Based on assessment results, some pertinent safety measures are discussed. After implementing safety measures, the laboratory risk is reassessed. The new observations reflect that risks of the laboratory have been effectively mitigated, demonstrating the effectiveness of these safety measures.

In summary, the uniqueness of this study is that it adequately considers the risk factors in university chemical laboratory from a system perspective and builds a novel methodology for risk assessment of university chemical laboratories. The methodology can find the safety weaknesses in university chemical laboratory and develop the targeted measures to reduce its operational risk. This methodology can be applied to risk assessment of other university laboratories. Besides, considering the dynamics of risk factors of university chemical laboratory, future work can be planned to carry out continuous risk monitoring of university chemical laboratory.

Acknowledgment

The authors gratefully acknowledge the financial support provided by the Project funded by Major theoretical and practical research project of Social Science in Shaanxi Province, China (2020Z188), Special Scientific Research Project of Education Department of Shaanxi Province, China (20JK0729), Fundamental Research Funds for the Central Universities (20CX02315A), and the Opening Fund of National Engineering Laboratory of Offshore Geophysical and Exploration Equipment.

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