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Risk Assessment Model of Chemical Process Based on Interval Type-2 Fuzzy Petri Nets

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Abstract: An interval type-2 fuzzy set and fuzzy Petri net combined risk assessment model for chemical production was proposed to solve the problems of disorganized hierarchy and poorly targeted measures, as well as the requirement for complex equipment associated with chemical production risk assessment. First, four different types of risk databases were established according to the production process of cyclohexane. Considering the intrinsic relationship between the risk factors in the fault database, the interval type-2 fuzzy set was used to improve the semantic transformation accuracy and calculate the confidence in the risk factors. The fuzzy Petri net model was used to simulate the dynamic development of accidents, and the parallel relationship between risk factors was intuitively described. Thereafter, the external relationship between risk factors was analyzed, and the net structure of each layer was divided to build a multilevel model. Finally, the catalyst activation process during cyclohexane production was taken as an example for risk assessment calculation, and the accident risk probability was calculated by multilevel fuzzy reasoning. The results demonstrate that the model is an improvement over traditional methods and can be used for precise prevention and control. Moreover, it can accurately analyze risk probability during chemical production, determine the risk associated with the reaction process, effectively prevent accidents, and provide a reference for risk evaluation and risk classification.

Keywords: cyclohexane; process system; interval type-2 fuzzy sets; fuzzy Petri nets; risk assessment

1. Introduction

Chemical production generally involves many flammable and explosive chemicals, complex and rigorous technical conditions, and technological processes. Due to the complexity of its processes and the use of numerous hazardous chemicals, the accident rate in the chemical industry is significantly high. Major accidents, such as chemical leakage, fire explosions, and chemical poisoning, cause heavy casualties, environmental pollution, property loss, and other catastrophic consequences. Scientific risk assessment can provide guidance on production safety for chemical enterprises. At present, a scientific and reasonable risk index system is needed to evaluate the comprehensive risk elements during chemical production to overcome the lack of an efficient, informative, and accurate risk assessment method for the chemical process [1].

Although traditional risk assessment analysis methods are mature, they present many drawbacks. For example, a traditional hazard and operability study takes the form of expert brainstorming [2]. By first analyzing possible deviations in the chemical installation parameters, the consequences of the deviation are analyzed, and potential safety hazards are identified. However, this analysis has high manpower, material, and financial requirements, which are beyond the capabilities of small factories [3]. In recent years, fuzzy risk assessment has gradually been extended to risk assessment [4,5]. A fuzzy evaluation involves first setting up a fuzzy risk matrix, discussing the possibility of accident occurrence and risk degree at the same scale, introducing the core concept of the analytic hierarchy process (AHP) to determine the influence weight of possibility and risk degree, synthesizing the

evaluation results of different researchers on possibility and risk, and obtaining the risk value by determining the impact weight of possibility and risk and the comprehensive evaluation results [6]. According to the industry characteristics of different fields, domestic and foreign experts have established different risk assessment models. Xiaohua et al. [7] established a new ranking method based on the interval type-2 fuzzy theory, combined the integral method with the interval fuzzy number, and established a risk optimization model. Guanda [8] analyzed the types of water disasters in Chinese coal mines using a multifactor interaction matrix and an ideal point combination. Accordingly, a risk assessment method for water inrush from the coal floor with a variable weight model was developed and successfully applied to coal mines. Zhongan [9] designed safety risk identification, safety risk prediction, and safety information management guidance modules by applying database technology and verified the feasibility of this model through a case study of an oil transmission plant. Petri nets, graphical mathematical modeling tools, are widely used in information modeling and system performance evaluation. Some foreign scholars have proposed security risk assessment methods [10–13] that mainly involve determining the scores of security risk parameters from the subjective opinions of experts. The parameters are then combined with linear relationships to identify the most critical assets according to the scores of the calculated security risk parameters to assist in risk evaluation. A fuzzy Petri net is an upgrade of the traditional Petri net that aims to address the uncertainty and fuzzy nature of risk factors. It retains the advantage of the Petri net for describing the parallel relationships in the complex system, which is suitable for dealing with such systems. Zhou [14] proposed a weighted fuzzy Petri net model with an inhibition arc, considering the rejection factor of risk assessment, and applied it to a hazardous chemical production plant. In addition, research institutions have developed various risk assessment models [15–18] that utilize the strategy of an excessive threshold and determining factors. Accordingly, the relationship between the fuzzy matrices of the determining factors can be established and evolutionary reasoning applied to accident occurrences to assist risk assessment.

Because the data for the appellate evaluation method is complex, difficult to fuse, and unified, an interval type-2 fuzzy Petri net risk evaluation model is proposed. The interval type-2 fuzzy set is used to transform the language variables provided by experts into a standard-interval type-2 fuzzy set to unify the data and improve the scientific and accuracy of the evaluation results. Moreover, the errors caused by the subjective factors of experts are reduced by considering the internal relationship between evaluation indices. Compared with the traditional method, a fuzzy Petri net is more suitable for dealing with the uncertainty in the evaluation index. The combination of the two aforementioned methods can effectively address the uncertainty and complexity of the evaluation indicators, clearly divide the hierarchy of risk factors, and generate the final results by establishing fuzzy rule reasoning. Finally, according to the characteristics of the cyclohexane production process, the fault database was established by considering the dangerous points in the process, and the major accident fault database was taken as the final database. Fuzzy reasoning rules are established through the operation process, and the final result is obtained through multilevel reasoning modeling. The risk assessment index system is then constructed to provide a reference for the classification and management of chemical process risk assessment.

2. The Principle Underlying Interval Type-2 Fuzzy Petri Nets

In 1962, Professor C. A. Petri first applied the network structure to simulate the communication system, thus establishing the concept underlying the Petri net method [19]. Petri net is a graphical modeling tool comprising place, transition, and the directed arc. Different types of Petri nets have been developed and applied to various industries, such as a colored Petri net, a random Petri net, and a time Petri net. To solve the inadequacy of traditional Petri nets in dealing with fuzzy indicators, Looney [20] proposed the fuzzy Petri net (FPN) model in 1988 to process, analyze, and model uncertain risk indicators. The

FPN model improves the traditional Petri net method and can effectively deal with the uncertainty of risk factors [21].

2.1. Fuzzy Petri Nets

To realistically consider the actual cyclohexane production process and reduce the operational difficulty, a multilevel network structure was set up, the layer number k of the multilevel fuzzy Petri net was combined with the initial state matrix M, and an improved multilevel fuzzy Petri net was defined as a seven-tuple $FPN = \{P, T, IN, OUT, F, R, M(k)\}$ to meet the computational requirements.

(1) $P = \{P_{1x}, P_{2x}, P_{3x}, P_{4x}\}$, $x = \{1, 2, 3, \cdots, n\}$ represents the limited set of places, namely the risk repositories present in chemical production. The risk places are roughly divided into four types: human factors P_{1x}, system factors P_{2x}, state changes P_{3x}, and accidents P_{4x}. The corner number only represents the four risk types.

(2) $T = \{T_{1x}, T_{2x}, T_{3x}, T_{4x}\}$, $x = \{1, 2, 3, \cdots, m\}$ represents the finite set of transitions, namely the occurrence process of some fuzzy rules.

(3) IN: $P{\rightarrow}T$ is an n × m transition input matrix.

(4) OUT: $T{\rightarrow}P$ is an n by m transition output matrix.

(5) F: Is a diagonal matrix, representing the confidence degree of transition.

(6) R: Is a diagonal matrix, representing the confidence of the place.

(7) $M(k)$: In the state matrix of the risk database, $M(0)$ is the initial state matrix, and k represents the number of layers of multi-level Petri nets, that is, the state matrix after k transitions.

The FPN model can not only establish an intuitive graphical model by applying fuzzy production rules but also provide a structured mechanism through fuzzy reasoning [22] to divide the evaluation criteria carefully and yield accurate results [23]. During catalyst activation in the cyclohexane production process, for example, the risk pool represents undrained jacket water, and confidence represents the likelihood of the proposition not exhausting jacket water; transition indicates that the state has changed, and confidence represents the likelihood of change. The FPN model is shown in Figure 1. P_1 and P_2 denote the logical relation of the "and" gate, whereas P_2 and P_3 denote the logical relation of the "or" gate.
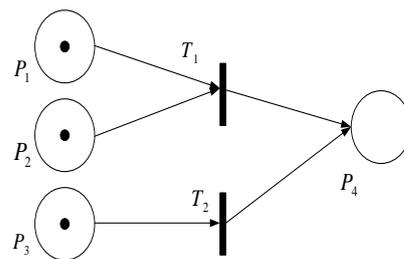

Figure 1. FPN model.

2.2. Interval Type-2 Fuzzy Sets

To define semantic meaning precisely, Professor Zadeh first proposed the fuzzy set concept in 1965 [24]. Based on the uncertainty between semantic individuals, Professor Zadeh then proposed the concept of type-2 fuzzy sets [25] (T2FSs) in 1975. Because of its complex representation and complicated nature, a special case of T2FS is widely used today, namely interval type-2 fuzzy sets (IT2FSs). T2FSs are more accurate and flexible in expressing uncertainty and more effective in solving practical problems than type-1 fuzzy sets [26].

The following are some important IT2FS concepts:

(1) Membership degree function: This is divided into the upper membership function (*UMF*), the lower membership function (*LMF*), and a type-1 fuzzy set formed by the upper

and lower bounds of the membership interval corresponding to any point on the domain. The maximum membership degree of the *LMF* is not 1.

(2) Footprint of uncertainty (*FOU*): All the regions between the *UMF* and the *LMF* constitute the *FOU*.

The principal membership is defined by introducing a multi-valued map $L_x = [a_x, b_x]$, $x \in X$. The corresponding *UMF*, *LMF*, and uncertain coverage domains can be expressed as [27]:

$$\overline{UMF} = \{(x, b_x), x \in X\} \tag{1}$$

$$\underline{LMF} = \{(x, a_x), x \in X\} \tag{2}$$

$$FOU = \cup_{x \in X} X \times L_X = \cup_{x \in X} X \times [a_x, b_x] \tag{3}$$

(3) Interval type-2 fuzzy sets

Definition 1. *IT2FS is described by its membership function and can be expressed as*:

$$\widetilde{A} = \int_{x \in X} \int_{u \in J_X \subseteq [0,1]} 1/(x, u) \tag{4}$$

where x is the first variable and the field is X; $\mu \in [0, 1]$ is the second variable and the field is $J_x \in [0, 1]$, which is termed the first membership of x; and $\mu_A(x, u)$ is called the second membership, and the second membership degree of interval type-2 fuzzy sets $\mu_A(x, u) = 1$.

Definition 2. *IT2FS are represented by the FOU size*:

$$FOU\left(\widetilde{A}\right) = \cup_{\forall \in X} J_X = \{(x, u), u \in J_X \subseteq [0, 1]\} \tag{5}$$

In this equation, the *FOU* size directly corresponds to the uncertainty expressed by the interval type-2 ambiguity.

3. Interval Type-2 Fuzzy Petri Net Risk Assessment Model

A fuzzy Petri net is often used in the fault inference and diagnosis of industrial process systems. Establishing fuzzy Petri nets requires vast basic knowledge and experience. This can be achieved using the fuzzy analytic hierarchy process (AHP), which can transform expert experience into an effective mathematical and thinking system model. Thereafter, an IT2FS is introduced to evaluate the risk factors in multiple dimensions based on the uncertainty between evaluation indices, which improves the evaluation accuracy. Finally, an interval type-2 fuzzy Petri net risk assessment model was established.

The analysis flow based on the basic FPN principle and the cyclohexane process flow is shown in Figure 2.

3.1. Establish Fuzzy Rules and Risk Pools

Here in, the cyclohexane process flow is analyzed, the risk factors in the process are identified, and the risk factors in different risk places are classified to adapt to different evaluation standards and clearly distinguish the categories, establish fuzzy rules according to the causal relationship between risks, and graphically model the fuzzy rules through the FPN model construction principle.
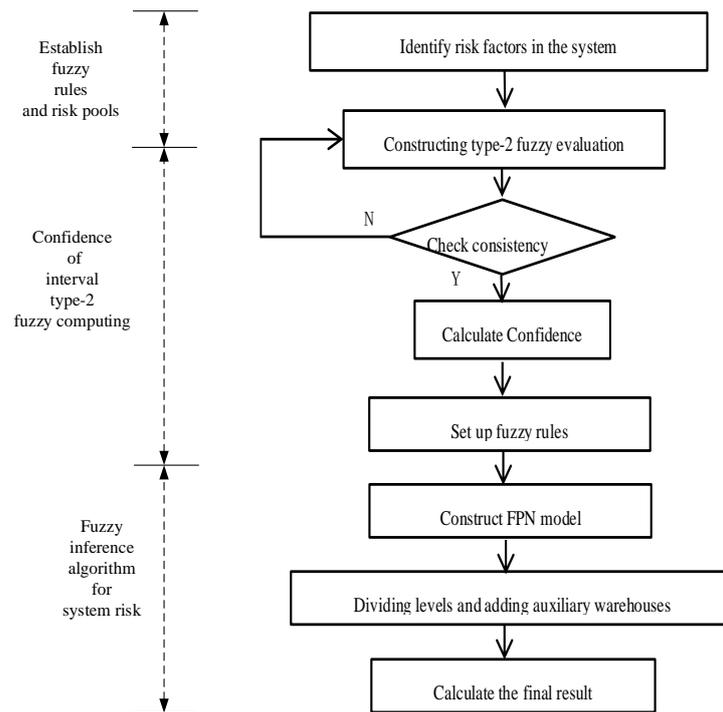
Figure 2. FPN model analysis process.

3.2. Confidence of Interval Type-2 Fuzzy Computing

Step 1: Construct the interval type-2 fuzzy evaluation matrix C and use n experts to evaluate the influence relationship between each indicator. The corresponding T2FS of the language variable interval can be known according to the type-2 fuzzy number scale table of Wang [28], as listed in Table 1.

Table 1. Interval type-2 fuzzy sets corresponding to linguistic variables of influence degree [28].

Influence Degree Language Variables	Interval Type-2 Fuzzy Sets
Absolute strong influence (AS)	(7.00,8.00,9.00,9.00;1.00,1.00), (7.20,8.20,8.80,9.00;0.80,0.80)
1/AS	(0.11,0.11,0.13,0.14;1.00,1.00), (0.11,0.11,0.12,0.14;0.80,0.80)
Very strong influence (VS)	(5.00,6.00,8.00,9.00;1.00,1.00), (5.20,6.20,7.80,8.80;0.80,0.80)
1/VS	(0.11,0.13,0.17,0.20;1.00,1.00), (0.11,0.13,0.16,0.19;0.80,0.80)
Significant influence (FS)	(3.00,4.00,6.00,7.00;1.00,1.00), (3.20,4.20,5.80,6.80;0.80,0.80)
1/FS	(0.14,0.17,0.25,0.33;1.00,1.00), (0.15,0.17,0.24,0.31;0.80,0.80)
Slight influence (SS)	(1.00,2.00,4.00,5.00;1.00,1.00), (1.20,2.20,3.80,4.80;0.80,0.80)
1/SS	(0.25,0.25,0.50,1.00;1.00,1.00), (0.21,0.26,0.45,0.83;0.80,0.80)
Equal influence(E)	(1.00,1.00,1.00,1.00;1.00,1.00), (1.00,1.00,1.00,1.00;0.80,0.80)

Step 2: Regarding the mutual influence relationship between risk factors, compare each indicator pair by pair and combine the interval type-2 fuzzy set corresponding to the language variable of impact degree. Assuming a total of n experts evaluate n indicators of risk factors, perform the geometric average on the interval type-2 fuzzy evaluation matrix to narrow the gap between different expert evaluations. Notably, $\widetilde{c}_{ij}$ represents the influence degree of indicator *i*, which corresponds to indicator *j*. The equation is as follows:

$$\widetilde{C} = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix} \tag{6}$$

$$\widetilde{c}_{ij} = \left[\widetilde{c}_{ij}^1 \otimes \widetilde{c}_{ij}^2 \otimes \cdots \otimes \widetilde{c}_{ij}^k \right]^{1/n}$$
$$= \sqrt[n]{\widetilde{c}_{ij}^1 \otimes \widetilde{c}_{ij}^2 \otimes \cdots \otimes \widetilde{c}_{ij}^k} \tag{7}$$

$$\sqrt[n]{\widetilde{c}_{ij}} = \left(\sqrt[n]{\widetilde{c}_{ij1}^U}, \sqrt[n]{\widetilde{c}_{ij2}^U}, \sqrt[n]{\widetilde{c}_{ij3}^U}, \sqrt[n]{\widetilde{c}_{ij4}^U}; H_1^U(\widetilde{c}_{ij}), H_2^U(\widetilde{c}_{ij}), \sqrt[n]{\widetilde{c}_{ij1}^L}, \sqrt[n]{\widetilde{c}_{ij2}^L}, \sqrt[n]{\widetilde{c}_{ij3}^L}, \sqrt[n]{\widetilde{c}_{ij4}^L}; H_1^L(\widetilde{c}_{ij}), H_2^L(\widetilde{c}_{ij}) \right) \tag{8}$$

In Equation (7), $\sqrt[n]{\widetilde{c}_{ij}}$ represents the interval type-2 fuzzy set form. $\sqrt[n]{\widetilde{c}_{ij1}^U}, \sqrt[n]{\widetilde{c}_{ij2}^U}, \sqrt[n]{\widetilde{c}_{ij3}^U}, \sqrt[n]{\widetilde{c}_{ij4}^U}$ and $\sqrt[n]{\widetilde{c}_{ij1}^L}, \sqrt[n]{\widetilde{c}_{ij2}^L}, \sqrt[n]{\widetilde{c}_{ij3}^L}, \sqrt[n]{\widetilde{c}_{ij4}^L}$ are the vertices of interval type-2 fuzzy sets. $H_1^U(\widetilde{c}_{ij}), H_2^U(\widetilde{c}_{ij})$ and $H_1^L(\widetilde{c}_{ij}), H_2^L(\widetilde{c}_{ij})$ represent the membership function values corresponding to the corresponding vertices.

Step 3: Perform a consistency test on the evaluation matrix according to the defuzzification method proposed by Bucliey [29]. If the defuzzification evaluation matrix conforms to the consistency test, the corresponding interval type-2 fuzzy judgment matrix can also pass the consistency test. Equation (8) is used to defuzzify the evaluation matrix. The consistency of the interval type-2 fuzzy evaluation matrix is determined by the result of CR = CI/RI. The random indicator (RI)has a fixed value. According to the study by Yu [30], the RI is compared in Table 2. The evaluation matrix passes the consistency test when the consistency ratio meets CR < 0.1.

Table 2. Random index (RI) comparison table.

Matrix Order	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

$$Def(\widetilde{c}_i) = \frac{\left[\frac{(c_{i4}^U - c_{i1}^U) + (H_1(\widetilde{c}_i^U) * c_{i2}^U - c_{i1}^U) + H_2(\widetilde{c}_i^U) * c_{i3}^U - c_{i1}^U)}{4} + c_{i1}^U + \frac{(c_{i4}^L - c_{i1}^L) + (H_1(\widetilde{c}_i^L) * c_{i2}^L - c_{i1}^L) + H_2(\widetilde{c}_i^L) * c_{i3}^L - c_{i1}^L)}{4} + c_{i1}^L \right]}{2} \tag{9}$$

Step 4: Equation (9) was used to calculate the geometric mean value of the influence relationship between each risk factor. $\widetilde{r}_i$ represents the geometric mean of the risk factors for each row, and *i* represents the number of rows. $\otimes$ represents the multiplication of two interval type-2 fuzzy sets.

$$\widetilde{r}_i = \left[\widetilde{c}_{i1} \otimes \widetilde{c}_{i2} \otimes \widetilde{c}_{i3} \otimes \widetilde{c}_{i4} \otimes \widetilde{c}_{i5} \otimes \widetilde{c}_{i6} \otimes \widetilde{c}_{i7} \right]^{1/7} \tag{10}$$

Step 5: Normalize the influence relationship of each risk factor and calculate the fuzzy weight $\widetilde{w}_i$. $\oplus$ represents the addition of two interval type-2 fuzzy sets.

$$\widetilde{w}_i = \widetilde{r}_i \otimes \left[\widetilde{r}_1 \oplus \widetilde{r}_2 \oplus \widetilde{r}_3 \oplus \widetilde{r}_4 \oplus \widetilde{r}_5 \oplus \widetilde{r}_6 \oplus \widetilde{r}_7 \right]^{-1} \tag{11}$$

Step 6: Equation (8) is used to defuzzify the fuzzy confidence and obtain the proposition and transition confidence, which can be used for the initial risk matrix and later for the transition confidence of fuzzy Petri nets.

3.3. Fuzzy Inference Algorithm for System Risk

For the multilevel fuzzy Petri net structure, the chemical risk assessment system is transformed into the fuzzy Petri net model. A fuzzy Petri net can not only better simulate and solve the complex net structure and the time sequence of accidents in the chemical system but also deal with the uncertainty of risk factors in the system. The transition input matrix IN and transition output matrix *OUT* can be obtained by graphically modeling fuzzy Petri nets. k represents the number of layers in the FPN model from left to right. If k = 0, the initial risk matrix $M(0)$ and the transition confidence level *F* can be determined

through expert evaluation and an interval type-2 fuzzy AHP. Notably, confidence refers to the weight of risk factors in the chemical evaluation.

Step 1: Calculate the first level and let $k = 0$; if the proposition is true and the confidence is $IN^T M(0)$, the output matrix after the transition is $OUT \bullet F$. $\bullet$ denotes matrix multiplication.

Step 2: The second level of computing is the next state after the transition. $\oplus$ represents the maximum output value of two elements after comparison.

$$M(1) = M(0) \oplus [OUT \bullet F] \left[IN^T M(k) \right] \tag{12}$$

Step 3: The calculation only commences when $M(k + 1) = M(k)$, which can be summarized by the following equation:

$$M(k + 1) = M(k) \oplus [OUT \bullet F] \left[IN^T M(k) \right] \tag{13}$$

This method is applied to matrix calculation, which is calculated in the direction from the initial risk matrix to the completion of k changes. To ensure the hierarchy of the net is complete, repeated changes are made to the cross-layer, which are represented by dotted lines when cross-layer changes are present [31].

4. Illustrative Example

To test the scientific merit, rationality, and applicability of the interval type-2 fuzzy Petri net risk assessment model proposed in this study, catalyst activation during cyclohexane production is taken as the research object; four different types of risk databases, namely human factors, system factors, protection failure, and major accidents, are established as the research objects, and a longitudinal comparative analysis is conducted. The effectiveness of the model was verified by comparing the actual situation with the experimental data, and the chemical process risk was evaluated. From the specific evaluation results, effective suggestions and measures have been proposed for the cyclohexane process.

4.1. Cyclohexane Process

Cyclohexane is an important organic raw material [32]. Benzene is hydrogenated to cyclohexane through the addition reaction under specific temperature and pressure conditions in the presence of a catalyst (Pt, Pd, Ni, etc.). Cyclohexane is an important organic chemical raw material that is mainly used as a solvent, diluent, and extraction agent for some coatings. Because of its low toxicity, it can be used for degreasing and depainting instead of benzene. It can also be used as an analytical reagent, including as a chromatographic analysis reference material and photoresist solvent. Although extracting cyclohexane from the gasoline fraction of naphthenic crude oil is facile, producing cyclohexane with a purity of more than 99.9% is very difficult due to difficulties associated with the process and strict standard requirements. Benzene hydrogenation is often performed in industrial production to obtain cyclohexane, which can be divided into liquid phase and gas phase methods. A foreign catalytic distillation company studied benzene hydrogenation to produce cyclohexane, and the simplified process flow is shown in Figure 3. The experimental data are based on the production process data. The process is as follows: benzene enters the top of the distillation tower reactor, hydrogen enters the bottom of the distillation tower, the catalyst is added in the reaction tower, and benzene is hydrogenated to cyclohexane in the tower. The reboiler at the bottom provides heat by circulating materials to maintain the reaction balance. Benzene reacts with hydrogen in the tower through the catalyst, and the released heat results in steam entering the top condenser to condense the excess material. Gas is then separated through the receiving reactor to obtain cyclohexane as the product. The advantages of this process are increased safety, low by-product generation, and low operating costs.
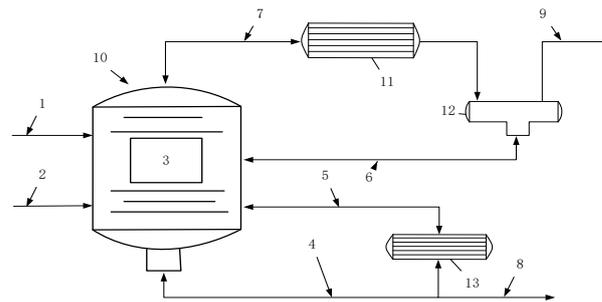
Figure 3. Process flow of cyclohexane. 1—C$_6$H$_6$; 2—H$_2$; 3—Catalyst bed; 4—Tower bottom circulation pipeline; 5—Tower bottom circulation pipeline; 6—Return line; 7—Top of tower; 8—Discharge pipe; 9—Gas discharge pipe; 10—Distillation tower reactor; 11—Condenser; 12—Receiving and separator; 13—Reboiler.

4.2. Case Calculation Process

Human factors, system factors, and the state change risk database are considered during the intermediate calculation process, and the accident risk database is the final result. For the example of the human factor risk database, seven total risk factors are considered. Five experts are selected to evaluate the impact indicators among the risks. The experts determine the relevant project materials and conduct field investigations to fully apprise themselves of the situation surrounding the project. They then deliver scores according to the language set: {AS,VS,FS,SS,E} = {absolute strong influence, very strong influence, strong influence, slightly strong influence, completely equal}. The scoring is listed in Table 3. {SS,SS,E,1/FS,1/FS} presents the five experts' evaluation of P_{11} on P_{12}: {influence slightly strong, influence slightly strong, completely equal, influence weak, influence weak}. $P_{11} \times P_{12}$ in Table 3 refers to the influence of P_{11} on P_{12}, whereas $P_{12} \times P_{11}$ represents the converse. Notably, the causal relationship between risk factors will vary. P_{1x} is the human factor risk databases, and P_{2x} is the system factor risk databases. Due to the relatively small impact on the four risk databases, the impact on the risk databases was not considered, and only the mutual influence of hazards within the risk databases was considered.

First, the geometric average of the appeal evaluation matrix was calculated using Equation (6). Taking the second column of Table 3 as an example to calculate for Equation (6), and so on, yields the following:

$$\widetilde{c}_{12} = [SS \otimes SS \otimes ES \otimes 1/FS \otimes 1/FS]^{1/5}$$

$$= \begin{bmatrix} ((1.0, 2.0, 4.0, 5.0; 1, 1), (1.2, 2.2, 3.8, 4.8; 0.8, 0.8)) \\ \otimes ((1.0, 2.0, 4.0, 5.0; 1, 1), (1.2, 2.2, 3.8, 4.8; 0.8, 0.8)) \\ \otimes (1, 1, 1, 1; 1, 1), (1, 1, 1, 1; 1, 1) \\ \otimes (0.14, 0.17, 0.25, 0.33; 1, 1), (0.15, 0.17, 0.24, 0.31; 0.8, 0.8) \\ \otimes (0.14, 0.17, 0.25, 0.33; 1, 1), (0.15, 0.17, 0.24, 0.31; 0.8, 0.8) \end{bmatrix}^{1/5} \quad (14)$$

$$= ((0.46, 0.64, 1.00, 1.22; 1, 1), (0.50, 0.68, 0.93, 1.17; 0.8, 0.8))$$

After obtaining the evaluation matrix, perform deblurring to obtain the evaluation matrix $Def(\widetilde{c}_{12}) = 0.79$. The evaluation matrix C_{ij} is obtained after deblurring all matrix elements. The specific evaluation matrix is as follows:

$$C_{ij} = \begin{bmatrix} 0.95 & 0.79 & 0.22 & 2.20 & 2.93 & 2.90 & 3.61 \\ 0.57 & 0.95 & 0.17 & 0.30 & 0.81 & 0.21 & 0.21 \\ 2.75 & 1.29 & 0.95 & 4.55 & 2.73 & 1.29 & 1.97 \\ 0.18 & 0.34 & 0.27 & 0.95 & 2.52 & 0.81 & 0.54 \\ 1.61 & 4.55 & 0.16 & 0.86 & 0.95 & 0.53 & 3.47 \\ 0.25 & 0.48 & 0.98 & 0.42 & 2.64 & 0.95 & 1.20 \\ 0.93 & 0.37 & 0.17 & 0.97 & 0.91 & 0.23 & 0.95 \end{bmatrix} \quad (15)$$

Table 3. Expert evaluation of the relationship between the indicators of the program.

	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{21}	P_{22}	P_{23}
P_{11}	E,E,E,E,E	SS,SS,E, 1/FS,1/FS	E,1/AS,1/VS, 1/FS,1/FS	E,SS,FS,FS,E	SS,FS,SS, VS,E	1/FS,FS,FS, VS,VS	SS,E,FS, AS,VS			
P_{12}	E,1/SS,1/SS, E,1/SS	E,E,E,E,E	1/VS,1/FS,1/VS, 1/FS,1/FS	1/FS,1/FS,1/FS, 1/AS,SS	1/VS,SS, 1/VS,SS/SS	1/VS,1/FS,1/FS, 1/FS,1/SS	1/SS,1/SS,1/ FS,1/SS,E			
P_{13}	SS,SS,FS,FS,E	1/SS,1/SS, FS,E,FS	E,E,E,E,E	FS,SS,FS, FS,VS	ES,FS,AS, FS,E	1/SS,1/SS,FS, FS,E	SS,E,E, FS,SS			
P_{14}	1/FS,1/SS,1/ AS,1/FS,1/AS	E,1/FS,1/FS,E,1/VS	1/AS,1/VS,1/ AS,1/FS,FS	E,E,E,E,E	E,VS,VS, ES,SS	1/FS,E,E, 1/SS,FS	1/FS,1/SS,1/ SS,1/SS,SS			
P_{15}	AS,1/VS,VS, AS,1/FS	FS,SS,VS,FS,FS	1/AS,1/FS,1/FS, 1/FS,1/AS	VS,1/SS,E,E,1/FS	E,E,E,E,E	SS,SS,1/FS, 1/FS,1/VS	FS,SS,SS,SS, FS			
P_{16}	1/FS,E,1/FS, 1/FS,1/VS	SS,SS,1/VS, 1/FS,1/VS	FS,FS,1/FS, ES,1/FS	SS,SS,1/AS, 1/VS,1/VS	E,FS,FS, E,VS	E,E,E,E,E	1/SS,E,VS, 1/VS,AS			
P_{17}	1/SS,1/SS, FS,E,E	1/SS,1/SS,1/AS, 1/VS,1/SS	1/SS,1/AS,1/AS, 1/FS,1/VS	FS,FS,1/SS, 1/FS,1/SS	SS,E,1/SS, SS,1/FS	1/FS,1/FS,E, 1/VS,1/VS	E,E,E,E,E			
P_{21}								E,E,E,E,E	1/SS,1/SS,E, 1/FS,1/FS	E,E,VS, E,VS
P_{22}								1/FS,1/SS,E, 1/VS,1/VS	E,E,E,E,E	SS,SS,1/FS, 1/FS,1/VS
P_{23}								E,VS,FS, E,VS	SS,1/SS,1/SS, 1/VS,1/VS	E,E,E,E,E

The consistency test was performed on the evaluation matrix C_{ij}, and the results demonstrated that the comparison matrix passed the consistency test: CR = 0.0944 < 0.1. Calculate the geometric average for each behavior unit using the first behavior example:

$$r_1 = [\ 0.54\ 0.63\ 0.85\ 1.05\ 0.56\ 0.63\ 0.80\ 0.98] \tag{16}$$

Finally, the propositional confidence level of the human factor risk database can be obtained by normalization processing, and the confidence levels for all input risk factors at the first level can be calculated, as listed in Table 4. The confidence levels for all transitions are presented in Table 5. Notably, the result was rounded to two decimal places.

Table 4. Propositional confidence.

Place	Confidence	Place	Confidence	Place	Confidence	Place	Confidence
P_{11}	0.11	P_{12}	0.13	P_{13}	0.05	P_{14}	0.16
P_{15}	0.26	P_{16}	0.11	P_{21}	0.23	P_{22}	0.16
P_{17}	0.18	P_{23}	0.20				

Table 5. Transition confidence.

Transition	Confidence	Transition	Confidence	Transition	Confidence
T_1	0.32	T_{10}	0.63	T_{19}	0.81
T_2	0.26	T_{11}	0.82	T_{20}	0.25
T_3	0.42	T_{12}	0.34	T_{21}	0.37
T_4	0.18	T_{13}	0.82	T_{22}	0.92
T_5	0.64	T_{14}	0.59	T_{23}	0.62
T_6	0.72	T_{15}	0.75	T_{24}	0.73
T_7	0.39	T_{16}	0.38	T_{25}	0.55
T_8	0.47	T_{17}	0.25		
T_9	0.27	T_{18}	0.87		

From the confidence data in Tables 4 and 5, a fuzzy Petri net model was constructed, and the risk factors in the risk database were roughly divided into four different types of risk databases: factor P_{1x}, system factor P_{2x}, state change P_{3x}, and accident cause P_{4x}. The following fuzzy rules could be established by combining the cyclohexane process, field investigation, and expert experience judgment. Notably, "→" denotes the resulting causal relationship.

(1) P_{11} The water in the jackets of two reactors is not drained → P_{31} Water is increased → P_{32} Catalyst is not activated → P_{41} The product is unqualified;

(2) P_{12} Do not close the exhaust valve after exhaust → P_{33} By-product accumulation → P_{34} Pressure increase → P_{42} Explosion;

(3) P_{21} Failure of front drum pressure display adjustment → P_{24} Failure of front drum pressure alarm → P_{34} Pressure increase → P_{42} Explosion;

(4) P_{13} Do not open the system pressure regulating valve before and after the globe valve → P_{34} Pressure increase → P_{42} Explosion;

(5) P_{22} Contact dispatching does not introduce tail hydrogen into the system → P_{35} Tail hydrogen flow is not up to standard → P_{36} Temperature surge → P_{43} Fire occurs;

(6) P_{14} Manual control pressure is not up to 0.6 MPa → P_{37} Activation conditions are not met → P_{38} Insufficient reaction → P_{41} The product is unqualified;

(7) P_{15} The steam valve of the reactor jacket is not opened → P_{37} Activation conditions are not met → P_{38} Insufficient reaction → P_{41} The product is unqualified;

(8) P_{16} The jacket steam valve is not closed → P_{36} Temperature surge → P_{25} The tail hydrogen is not cut off, the nitrogen is passed, and the heating steam is closed → P_{42} Fire occurs;

(9) P_{17} The jacket is not filled with soft water $\rightarrow P_{310}$ The temperature is too high $\rightarrow P_{41}$ The product is unqualified;

(10) P_{23} Front drum liquid level display adjustment is not controlled within 50~80% $\rightarrow$ P_{26} Front drum display alarm failure $\rightarrow P_{39}$ High liquid level $\rightarrow P_{44}$ Device damage;

The model was constructed by applying fuzzy rules, as shown in Figure 4. It is divided into four levels, and the final result of the accident risk database is calculated in turn. The first level, $k = 0$, is calculated from the system risk fuzzy reasoning algorithm [33]. The required inputs for Equation (11) are the input matrix *IN*, the output matrix *OUT*, the proposition confidence *R*, the transition confidence *F*, and the initial state matrix *M*(0). The output is *M*(1). The simulation model was built using the PN Toolbox, and the proposition confidence and transition confidence were manually entered, as listed in Tables 4 and 5. The simulation model performs the operation process of a Petri net and obtains the final accident probability.
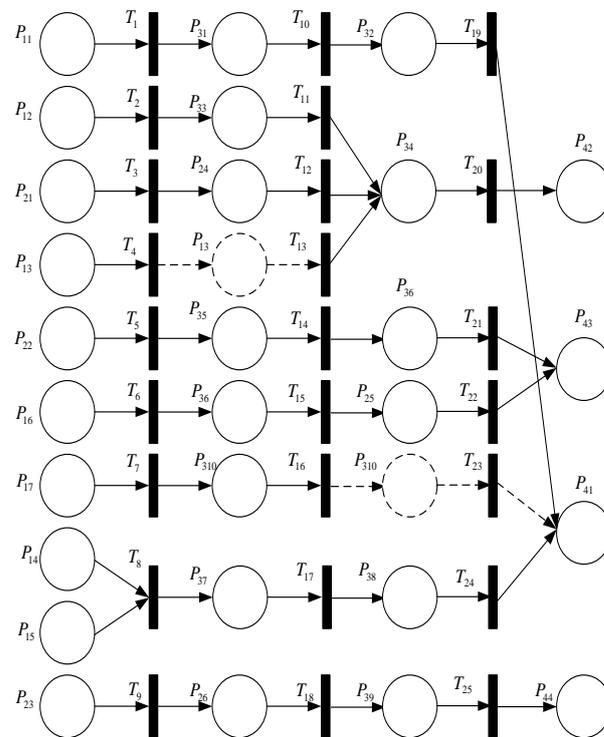

Figure 4. Multi-level fuzzy Petri net model for cyclohexane catalyst activation.

The model in Figure 4 shows that the input risk factors when calculating the first level are P_{11}, P_{12}, P_{21}, P_{13}, P_{22}, P_{16}, P_{17}, P_{14}, P_{15}, and P_{23}, whereas the output risk factors are P_{31}, P_{33}, P_{24}, P_{34}, P_{35}, P_{36}, P_{310}, P_{37}, and P_{26}. Nineteen risk factors in total were considered. The input_output risk pool was integrated into a 19×19 diagonal matrix, which is the propositional confidence *R*. When $k = 0$, the initial state matrix *M*(0) is consistent with the propositional confidence R. The figure shows that nine transitions are present in the first level, namely T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, and T_9, and presents the diagonal matrix with a transition confidence *F* of 9×9.

$$R = diag \begin{bmatrix} P_{11}, P_{12}, P_{21}, P_{13}, P_{22}, P_{16}, \\ P_{17}, P_{14}, P_{15}, P_{23}, P_{31}, P_{33}, \\ P_{24}, P_{34}, P_{35}, P_{36}, P_{310}, P_{37}, P_{26} \end{bmatrix}_{19 \times 19} \tag{17}$$

$$M(0) = diag \begin{bmatrix} P_{11}, P_{12}, P_{21}, P_{13}, P_{22}, P_{16}, \\ P_{17}, P_{14}, P_{15}, P_{23}, P_{31}, P_{33}, \\ P_{24}, P_{34}, P_{35}, P_{36}, P_{310}, P_{37}, P_{26} \end{bmatrix}_{19 \times 19} \tag{18}$$

$$F = \begin{bmatrix} T_1 & 0 & \cdots & 0 \\ 0 & T_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & T_9 \end{bmatrix}_{9 \times 9} \tag{19}$$

From Figure 4, the input matrix *IN* and output matrix *OUT* consider 19 risk factors as the horizontal coordinate and transition to the vertical coordinate to establish a 19×9 matrix. $M(1)$ is calculated according to Equation (11), which successively corresponds to the input and output risk factors of proposition confidence R. Nine input risk factors, $M(2)$, including the second-level input risk factors $P_{31}, P_{33}, P_{24}, P_{35}, P_{36}, P_{310}, P_{37}, P_{26}$, and the risk factor of transition $\_P_{13}$ were identified.

$$IN = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 & 0 \\ 0 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 1 \end{bmatrix}_{19 \times 9} \tag{20}$$

$$OUT = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{19 \times 9} \tag{21}$$

$$M(1) = diag \begin{bmatrix} P_{11}, P_{12}, P_{21}, P_{13}, P_{22}, P_{16}, \\ P_{17}, P_{14}, P_{15}, P_{23}, P_{31}, P_{33}, \\ P_{24}, P_{34}, P_{35}, P_{36}, P_{310}, P_{37}, P_{26} \end{bmatrix}_{19 \times 19} = diag \begin{bmatrix} 0.11, 0.13, 0.23, 0.05, 0.32, 0.11, \\ 0.18, 0.16, 0.26, 0.20, 0.31, 0.38, \\ 0.10, 0.00, 0.20, 0.27, 0.19, 0.35, 0.21 \end{bmatrix} \tag{22}$$

The final result was obtained by analogy, and the confidence level of the final risk database was $P_{41} = 0.173$, $P_{42} = 0.096$, $P_{43} = 0.266$, and $P_{44} = 0.130$.

The above calculation results demonstrate that:

(1) After establishing the risk places for human factors, system factors, state changes, and accidents, of all the 23 risk factors that lead to accidents, six (approximately 26%) were human factors, seven (approximately 30%) belonged to system factors, and the risk factors that belonged to state changes accounted for approximately 43%. Notably, system factors had the greatest impact on accident occurrence. The second was the change in state, whereas human factors had the smallest probability of influencing accident occurrence;

(2) When initially calculating the risk factors, for a single risk factor, the risk confidence of the tailing hydrogen flow not meeting standards, the front drum pressure alarm failure, by-product accumulation, and temperature inflation were the highest, indicating that these four risk factors are the most critical to the accident;

(3)   The confidence level for the four final accident risk factors was between 0.1 and 0.3, indicating that the accident likelihood is not high. The confidence level of the explosion risk was 0.096, indicating the smallest likelihood of accident occurrence. Second, the risk confidence level of unqualified products was 0.173, whereas that of device damage was 0.13. The probability of a fire occurring was the highest, and the risk confidence level was 0.266. Notably, accident occurrence is the result of a shift from a quantitative to a qualitative change under the combined action of various factors. Despite the low likelihood of accident occurrence, no risk factor should be ignored.

To verify the superiority and effectiveness of the proposed theories and methods as well as the risk indicators of the proposed model, the interval type-2 fuzzy VIKOR [34] method was applied to the cyclohexane process flow and evaluated. The method involves first applying the interval type-2 fuzzy improved weight calculation method to consider the internal relationship between the influencing factors. Subjective and objective weights were combined to determine the comprehensive weight of each factor. There after, a risk evaluation model based on the interval type-2 fuzzy improvement VIKOR method was established to analyze the maximum benefit value and maximum regret degree of each scheme and calculate the compromise risk value of the scheme. Finally, a risk assessment was conducted based on the cyclohexane production data to analyze the system pressure, reaction temperature, and other influencing factors, as well as calculate the risk value of each scheme. To draw a clear comparison between the two methods, the Spearman coefficient equation is introduced as follows:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)} \tag{23}$$

The results of two schemes are listed in Table 6. Notably, the Spearman correlation coefficient of this scheme was 0.947, which clearly highlights the similarity between the scheme results and actual data. The Spearman correlation coefficient is used for studying the correlation between two variables based on data. If it is greater than 0.9, the two sorting sets are highly consistent. The closer the value is to 1, the higher the accuracy. The Spearman correlation coefficient of the interval type-2 fuzzy VIKOR method was 0.914. Wu [35] mentioned that the Spearman correlation coefficient of the interval type-2 fuzzy TOPSIS method was 0.858 and the Spearman correlation coefficient of the interval type-2 fuzzy COPRAS method was 0.829. Therefore, compared with traditional methods, the model proposed in this paper yields realistic results.

Table 6. Scheme comparison.

Method	P_{41}	P_{42}	P_{43}	P_{44}
Interval type-2 fuzzy Petri net	0.173	0.096	0.266	0.130
Interval type-2 fuzzy VIKOR	0.462	0.403	0.505	0.416

Therefore, the following problems should be considered during cyclohexane production: the tail hydrogen flow failing to meet standards, the front steam drum pressure alarm failing, and by-product accumulation and temperature inflation occurring. Therefore, protection measures should be improved through the real-time monitoring of relevant process parameter data. Therefore, the investigation of hidden fire dangers should be emphasized, and hidden dangers should be quickly identified. Moreover, daily inspection and maintenance of production equipment should be conducted to avoid accidents.

5. Conclusions

In this paper, interval type-2 fuzzy sets are introduced into the fuzzy Petri net model, and expert language variables are transformed into interval type-2 fuzzy sets through the

evaluation process. The confidence degree is obtained by synthesizing the fuzzy AHP, and the interval type-2 fuzzy Petri net risk evaluation model is constructed by combining the FPN mathematical model. The model is used to evaluate the influence relationship between factors based on type-1 fuzzy sets and combines the evaluations of multiple experts to effectively reduce information loss and improve evaluation accuracy. In terms of the selection of risk points, four risk databases are distinguished according to different expert evaluation criteria, and the model is built by combining the graphics and mathematics of FPN. Finally, the proposed model is applied to the cyclohexane production process. Compared with the actual results, the model has strong operability and feasibility and is effective for identifying and preventing risks. In future research, the model can also be extended to other evaluation research fields. This study is limited in that although the consistency test is applied and multiple averages are used in the calculation to minimize the error of human subjective factors, subjective factors cannot be completely avoided. However, the model is universal and can be used to adjust the corresponding indicators according to the needs of different enterprises.

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