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Development of a risk assessment approach by combining SPA-fuzzy method with Petri-net

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ABSTRACT

Risk assessment can reveal the level of a safety situation which can be very important info for company safety management. Considering the multiple factors in risk assessment of a system and the vagueness nature of many factors, and using the benefits of the Petri-net in modeling and reasoning, a weighted fuzzy Petri-net (WFPN) based risk assessment approach which combines WFPN with the SPA-fuzzy method is proposed in this paper. The SPA-fuzzy method is utilized to establish the membership functions for fuzzy assessment, taking its advantage in comparing identity, contrary and discrepancy features of two different sets. In this study, the WFPN is redefined to model relationships between assessment factors, and the matrix-based fuzzy reasoning algorithm is provided to assess the factors in parallel. The application of the proposed risk assessment approach is illustrated by case studies: the risk assessment of a chemical storage tank area and the ignition accident assessment of hydrogen refueling stations.

1. Introduction

In the process industry, large quantities of raw materials or products are stored or handled, many of which are hazardous chemicals, such as flammable gases or liquids. If these substances catch fire or explosion, it may lead to unexpected consequences for the installation, the environment and the health of workers and neighbors. Indeed, significant accidents have happened in the process industry in recent decades, such as the December 11th, 2005 Buncefield Oil Storage Depots (B.O.S.D) fire which engulfed over 20 large fuel-storage tanks (Vautard R. et al., 2007), the massive tank fire of October 23rd, 2009 at the Caribbean Petroleum Refining (U.S. Chemical Safety Board, 2015), and the fire and explosion accident which occurred in the tank field of Lanzhou Petrochemical Corporation in Jan 7, 2010 (State Administration of Work Safety,2010). Safety issues are thus very important in these plants because inadequate safety control may lead to a catastrophic accident due to large quantities of hazardous materials involved. Plants involving hazardous chemicals are required to conduct risk assessments to determine risk levels and to take measures to reduce the risk to a safety level.

There are many methods available for risk assessment of chemical plants. The qualitative approach uses well known types of analysis, such as the Checklist (Argyropoulos et al., 2012; Zhang et al., 2017), Failure Mode and Effect Analysis (FMEA) (Nuclear Regulatory Commission, 1983; Chen et al., 2014) and Hazard and Operability analysis (HAZOP) (Fuentes-Bargues et al., 2016). Additionally, quantitative methods attempt to specify the safety level or the associated risk value of a system or an installation. A variety of these methods already exist, such as the approaches of Mond (Lewis, 1974) and Dow (Dow, 1994; Etowa et al., 2002) indices and the well-established methods of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) (Nuclear Regulatory Commission, 1983). Some researchers also proposed some risk assessment methods for risk assessment. For example, Luo et al. (2018) combined the fishbone diagram method and the risk matrix method to assess the safety of natural gas tanks. Ahmadi et al. (2020) integrated fuzzy DEMATEL and Bayesian networks to develop a dynamic risk assessment method and used it for the risk assessment of atmospheric storage tanks. Yin et al. (2020) used an approach integrating fuzzy fault tree analysis (FFTA) with similarity aggregation method (SAM) to assess the safety of natural gas storage tanks. Sarvestani et al. (2021) developed a dynamic risk assessment approach for propane storage tanks based on the bow-tie method.

With respect to the risk assessment in the process industry, there are

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many factors that may have impacts on the risk, and most of such factors have the characteristic of uncertainty or vagueness. Thus, fuzzy assessment methods are widely utilized for risk assessment purposes. For example, Miri et al. (2011) proposed a model using fuzzy risk assessment to determine the aggregative risk for an offshore well with possible data from various sources. Arunraj et al. (2013) proposed the cross-disciplinary approaches for industrial safety risk assessment using fuzzy set theory and Monte Carlo simulation. John et al. (2014) proposed a fuzzy risk assessment approach consisting of a fuzzy analytical hierarchy process, an evidential reasoning approach, fuzzy set theory and expected utility to facilitate the treatment of uncertainties in seaport operations and to optimize its performance effectiveness in a systematic manner.

Petri-net is a powerful tool to describe and model various relationships among parts of a system. Petri-net was proposed by Dr. Petri in 1962 when he developed the information flow model of the computer operating system (David and Alla, 1994). It is a graphical modeling and analysis tool, including elements like places, transitions, arcs and tokens. Petri-net has strict mathematical expression, intuitive graphical representation, and various technologies of system description and system behavior analysis. Petri-net can not only express knowledge, but also show the reasoning process, so it has been widely used in many fields. In the beginning, Petri nets are widely used in modeling and analysis of discrete event systems. In order to model and analyze more complex systems, a number of extensions are formed on the basis of ordinary Petri-net. To express and analyze uncertain knowledge, some researchers proposed fuzzy Petri-net (FPN) (Albert and Senen, 1994; Chen, 2002; Hu et al., 2011).

FPN is able to develop specific knowledge, and express structural characteristics among the rules of the knowledge base. The technique has got many applications in fields such as fault diagnosis and knowledge reasoning (Gao et al., 2003; Aziz et al., 2010; Liu et al., 2013). In the risk assessment of chemical plants, there are many uncertainties or vagueness, and the importance of each factor is different, hence, weighted fuzzy Petri-net (WFPN) is used to model the relationships between the factors and determine the final risk.

The fuzzy assessment method and its calculation are based on membership functions, so how to determine the reasonable membership functions is very important for fuzzy assessment. Set pair analysis (SPA) is also a kind of uncertainty theory. Its core idea is to consider both certainties and uncertainties as a certain-uncertain system. In this kind system, certainties and uncertainties influence each other and restrict each other. Two related sets in an uncertain system can form a set pair. SPA based research has been conducted in many fields (Jiang et al., 2004; Su and Mi, 2006; Xu and Zhang, 2009). In a previous study (Zhou, 2010), an SPA-fuzzy method which combines the set pair analysis method with fuzzy assessment was used to assess real-time risk. As fuzzy Petri-net has advantages in modeling and fuzzy reasoning, and the SPA-method can help to determine the membership functions for assessment, in this study, a comprehensive risk assessment approach which combines Petri-net with SPA-fuzzy method is presented. It can not only use Petri-net for reasoning like FPN, but also use SPA method to classify the characteristics between two sets into the identity, the contrary and the discrepancy, so it has unique advantages in dealing with uncertainty, especially for risk assessment according to certain standard. SPA can overcome the uncertainty of determining the model parameters in practical scenarios by establishing a set pair between actual factors and given standard, so as to the SPA is able to analyze risk factors objectively (Wang et al., 2022).

The remaining parts of this paper are organized as follows. In Section 2, a methodology of risk assessment is proposed. In Section 3, case studies of the application of this method are presented. The conclusions of this work are given in Section 4.

2. Methodology

2.1. WFPN approach

2.1.1. Definition of WFPN

A Petri-net (PN) can be defined as a 5-tuple:

$$PN = (P, T, I, O, M) \tag{1}$$

where,

P is a set of places, which are usually represented as circles.

T is a set of transitions, which are usually represented as rectangles. $P \cup T \neq \varnothing$, and $P \cap T = \varnothing$.

I is an input function of transitions mapping from places to transitions. Directed arcs are used to connect places to transitions according to the input mapping.

O is an output function of transitions mapping from transitions to places. Directed arcs are used to connect transitions to places according to the output mapping.

M is a marking vector which associates tokens with places. Tokens are represented as dots in circles of places. The initial marking of a Petri-net is expressed as M_0.

Places are usually used to represent states of the parts of a system, and the marking M is therefore used to represent the state of the system. Transitions usually represent activities of the system. The execution of transitions changes the tokens in places and thus changes the system state.

The fuzzy Petri-net (FPN) is developed through integrating the fuzzy sets with the PN. FPN is defined as follows:

$$FPN = (P, T, I, O, M, F) \tag{2}$$

where, *(P, T, I, O, M)* determines a Petri-net. In a FPN, places are used to express the propositions in fuzzy rules, and transitions represent the fuzzy rules.

F is a function associating fuzzy sets to places.

The execution of transitions of a FPN corresponds to the fuzzy inference, and a place has at most one token indicating the place obtains a fuzzy value.

On the basis of FPN, a WFPN is defined as follows:

$$WFPN = (P, T, I, O, M, F, W, U) \tag{3}$$

where, *P, T, M,* and F are the same as the definition of a fuzzy Petri-net.

W is a function associating weights to input places of transitions.

U is a function associating certainty factors to output places of transitions.

Thus, I and O are redefined as follows:

I is a matrix of input places of transitions. The element $w_{ij} \in [0, 1]$ indicates the weight of place p_j on transition t_i.

O is a matrix of output places of transitions. Its element $u_{ij} \in [0, 1]$ indicates the certainty factor (CF) of transition t_i on place p_j.

2.1.2. Modeling with WFPN

In a fuzzy production rule, the antecedent propositions are represented by $a_1, a_2, \ldots, a_n$, and the conclusion is denoted as c_g. $f_1, f_2, \ldots, f_n$, and f_g are the fuzzy values of the propositions, $w_1, w_2, \ldots, w_n$ are weights of the propositions. The fuzzy production rules are given by:

"AND" rule: If a_1 (f_1, w_1) AND a_2 (f_2, w_2) AND … AND a_n (f_n, w_n), then c_g (f_g) (CF = u).

$$f_g = (f_1 \times w_1 + f_2 \times w_2 + \ldots + f_n \times w_n) \times u \tag{4}$$

"OR" rule: If a_1 (f_1) OR a_2 (f_2) OR … OR a_n (f_n), then c_g (f_g) (CF = $u_1, u_2, \ldots, u_n$).

$$f_g = \max(f_1 \times u_1, f_2 \times u_2, \ldots, f_n \times u_n) \tag{5}$$

where, CF means the certainty factor which reflects how certain a propositional statement is, and a certainty factor has a value of [0, 1]; u is the value of corresponding certainty factor.

Using WFPN model can not only represent fuzzy production rules with intuitive graphical model, but also establish structured fuzzy inference mechanism. Logical relationships can be represented by directed arcs between places and transition. The WFPN models of basic logical relationships "AND" and "OR" are illustrated in Fig. (1), where, the antecedent propositions and the conclusion are denoted by places, the rules are modeled by transitions, the fuzzy values of the propositions are expressed by values of tokens in places, and the weights of the propositions are expressed by the arc weights. The model of Fig. 1 (a) corresponds to the "AND" rule and can perform the fuzzy reasoning based on Eq. (4), and the model of Fig. 1 (b) corresponds to the "OR" rule and can perform the fuzzy reasoning based on Eq. (5).

In risk assessment, a risk factor is usually jointly influenced by multiple sub-factors, thus the WFPN model of the "AND" rule is commonly used in this circumstance.

2.1.3. Fuzzy reasoning

Using the WFPN model, we can reason about the fuzzy value of places in parallel through the matrix operation. To clearly express the matrix operation of the WFPN model, the following operator is defined:

$\oplus$: $A \oplus B = C$, where, A, B and C are matrices with elements a_{ij}, b_{ij}, and c_{ij} ($i = 1,2, \ldots, n; j = 1,2, \ldots, m$), respectively.

$$c_{ij} = \max\{a_{ij}, b_{ij}\} \tag{6}$$

Therefore, the fuzzy reasoning considering the fuzzy memberships can be implemented as follows.

Step 1 Initialize the matrices M_0, I, and O according to the established WFPN model.
Step 2 Set $k = 1$, where k is the iteration times of the fuzzy reasoning.
Step 3 Calculate the new marking M_k.

$$M_k = \left(O^T \times (I \times M_{k-1})\right) \oplus M_{k-}1 \tag{7}$$

If $M_k = M_{k-1}$ then go to Step 4; otherwise, let $k = k + 1$ and return to Step 3.

Step 4 End reasoning.

After the reasoning process completes, the fuzzy value of any place can be obtained from M_k.

2.2. SPA-fuzzy method

Set-pair analysis (SPA) is a mathematical theory addressing the interaction between certainty and uncertainty of systems. Set-pair is the basic unit which is composed of a couple of sets with certain connections. It is also the most basic concept in set-pair analysis and connection mathematics. The basic approach of set-pair analysis (SPA) is to compare the features between the set-pair. It is necessary to first abstract the features of the two sets, and then determine which features are identical, which are called the identity of the set-pair; and which features are contrary, which are called the contrary of the two sets; other features are neither identical nor contrary, and they are called the discrepancy of the set-pair. The identity and the contrary reflect certainties of a set-pair, and the discrepancy indicates uncertainty. Therefore, the connection degree is used to measure various certainties and uncertainties between a set-pair, and the analysis of uncertainties is represented by specific mathematical operations. In many cases, the risk assessment is to compare the actual value of each factor with certain assessment criteria, such that the set-pair analysis has certain advantages in these risk assessment situations.

Suppose in an uncertain system, two associated sets are X and Y, both have N features. They can be represented as:

$$X = \{x_1, x_2, \ldots, x_N\}, Y = \{y_1, y_2, \ldots, y_N\} \tag{8}$$

The sets X and Y form a set-pair. The connection degree (cd) of the set-pair includes identity degree, discrepancy degree and contrary degree. It is defined as follows (Zhao, 2000):

$$cd = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j \tag{9}$$

where, S is the number of features in the identical state in the two sets, and P is the number of features which are contrary between the two sets. F represents the number of features that are neither identity nor contrary of the two sets. S/N is called the identity degree, F/N is the discrepancy degree and P/N is the contrary degree of the two sets, respectively. The symbol 'j' means the contrary degree coefficient, and 'i' is the discrepancy degree coefficient.

Set $a = S/N$, $b = F/N$, $c = P/N$, Eq. (9) can be expressed as:

$$cd = a + bi + cj \tag{10}$$

In the field of multi-attribute and multi-grade risk assessment, the values of factors constitute a set, and the values of standards of assessment grades constitute another set. These two sets can be regarded as a set-pair. Thus, the risk grade determined by factor values can be evaluated by the connection degree of the set-pair. If the value of a factor is within the value range of a grade, it is looked as identical with the grade; for the immediately adjacent grades, the value is regarded as discrepant with it; and for all other grades, the value is looked as contrary to them.

Eqs. (9) and (10) are general defined connection degree of SPA. It has three element and can be called three-element connection degree. However, there may be multiple degrees of identity, discrepancy, or contrary between two sets in the actual assessment. In this case, Eq. (10) can be extended to determine the multi-element connection degree. Also

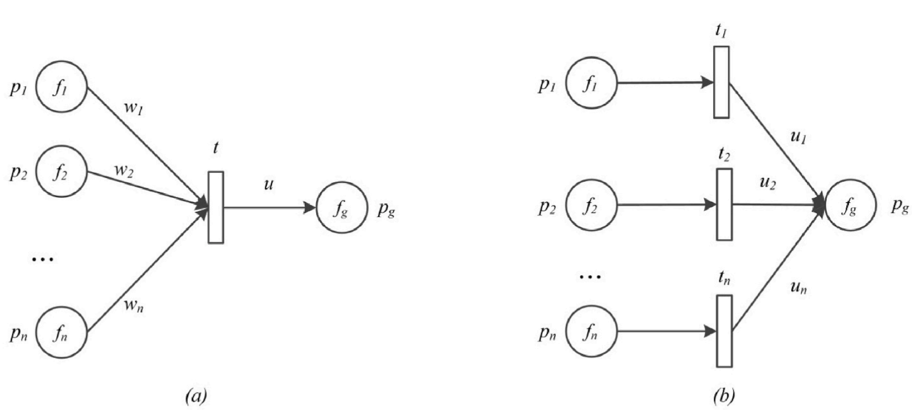

Fig. 1. WFPN models of fuzzy production rules: (a) WFPN model of "AND" rule; (b) WFPN model of "OR" rule.

assign a coefficient to the identity degree, thus the n-element connection degree can be expressed as follows:

$$cd = a_1 i_1 + a_2 i_2 + \ldots + a_n i_n \tag{11}$$

where, $a_k (k = 1, 2, \ldots, n)$ is the identity, discrepancy, or contrary degree, and $i_k (k = 1, 2, \ldots, n)$ is the corresponding coefficient.

The n-element connection degree of SPA can be used for multiple attributes assessment. For an assessment problem with n grades $G_1, G_2, \ldots, G_n$, and m assessment factors $f_1, f_2, \ldots, f_m$, if the assessment values of the factors are $v_1, v_2, \ldots, v_m$, the connection degree u_k can be expressed as follows:

$$u_k = a_{k1} i_1 + a_{k2} i_2 + \ldots + a_{kn} i_n \tag{12}$$

where, a_{kj} $(k = 1, \ldots, m, j = 1, \ldots, n)$ is the membership of v_k on grade G_j, and i_j is a symbol of grade G_j and has no practical meaning in an assessment.

In the set-pair analysis, the identical degree is considered to be 1, the contrary degree is -1, and the discrepancy degree is a value between 1 and -1. In the case of linear discrepancy relationship, if value v_k is in the grade G_i of index p_k, then

$$a_{kj} = \begin{cases} \dfrac{2v_k - X_{k(i-)U} - X_{k(i-2)U}}{X_{k(i-1)U} - X_{k(i-2)U}}, (j = i-1) \\ 1, (j = i) \\ \dfrac{2v_k - X_{k(i)U} - X_{k(i+1)U}}{X_{k(i)U} - X_{k(i+1)U}}, (j = i+1) \\ -1, (j \leq i-2 \; or \; j \geq i+2, 1 \leq i \leq n) \end{cases} \tag{13}$$

where, $X_{k(i)U}$ is the upper limit of the value range of grade G_i.

Fig. 2 shows the membership function for a_{kj}. X axis represents the values of factor p_k, and Y axis represents the membership. It can be seen that the membership function is a type of trapezoid membership function, but it has clear physical meaning, representing the discrepancy in set pairs.

In order to calculate the connection degree more intuitively and conveniently, the vector model is introduced as follows:

$$U = \begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \ldots & & & \\ a_{m1} & a_{m2} & \ldots & a_{mn} \end{pmatrix} \times \begin{pmatrix} i_1 \\ i_2 \\ \ldots \\ i_n \end{pmatrix} \tag{14}$$

Considering the weights $w_1, w_2, \ldots, w_m$ of the m factors, the connection degree can be obtained using the following equation:

$$R = W \times U = (w_1 \quad w_2 \quad \cdots \quad w_m) \times \begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \ldots & & & \\ a_{m1} & a_{m2} & \ldots & a_{mn} \end{pmatrix} \times \begin{pmatrix} i_1 \\ i_2 \\ \ldots \\ i_n \end{pmatrix} \tag{15}$$

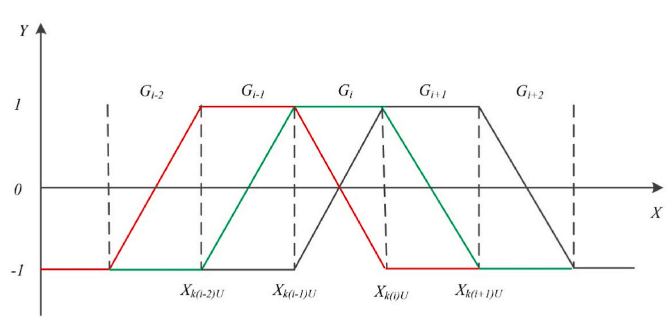

Fig. 2. SPA based membership function.

where, W is the weight vector.

2.3. Risk assessment process

Based on the definitions of WFPN, the risk assessment process is shown in Fig. 3.

Step 1 Determine risk factors.

The risk of a system in the process industry is usually influenced by many factors, such as equipment, human, management and environment. Determining these factors and the relationships between them is the basis of risk assessment.

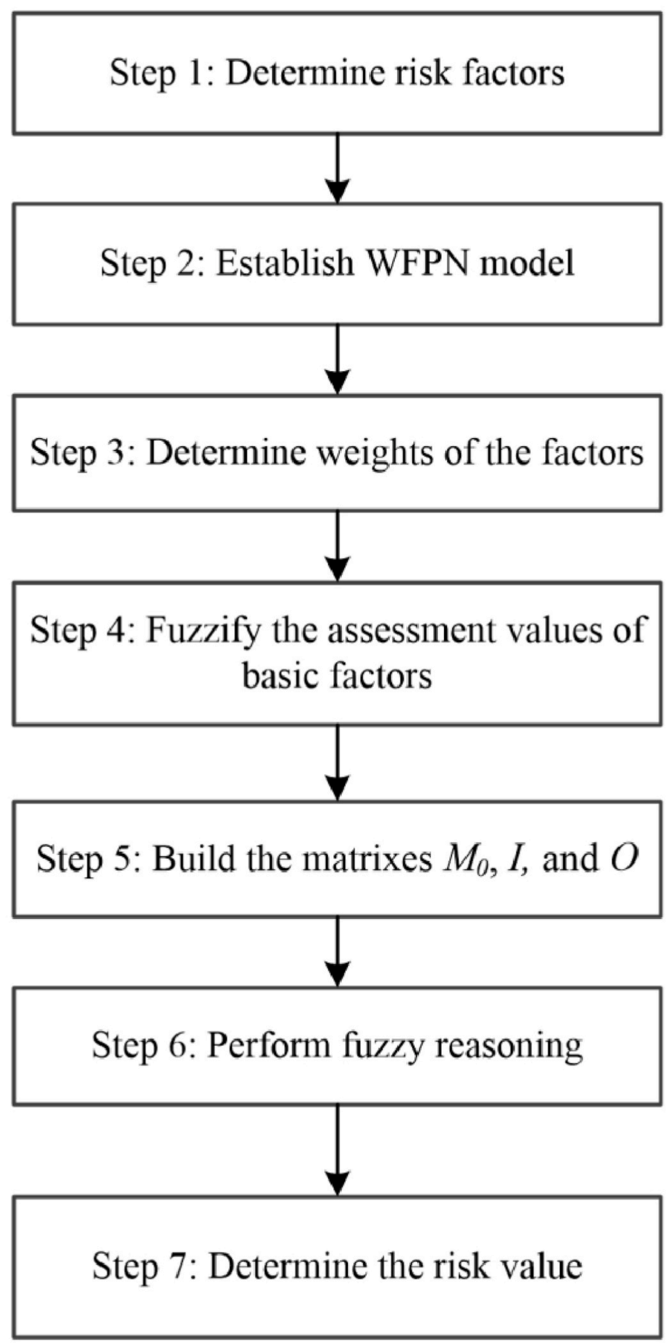

Fig. 3. Flowchart of risk assessment.

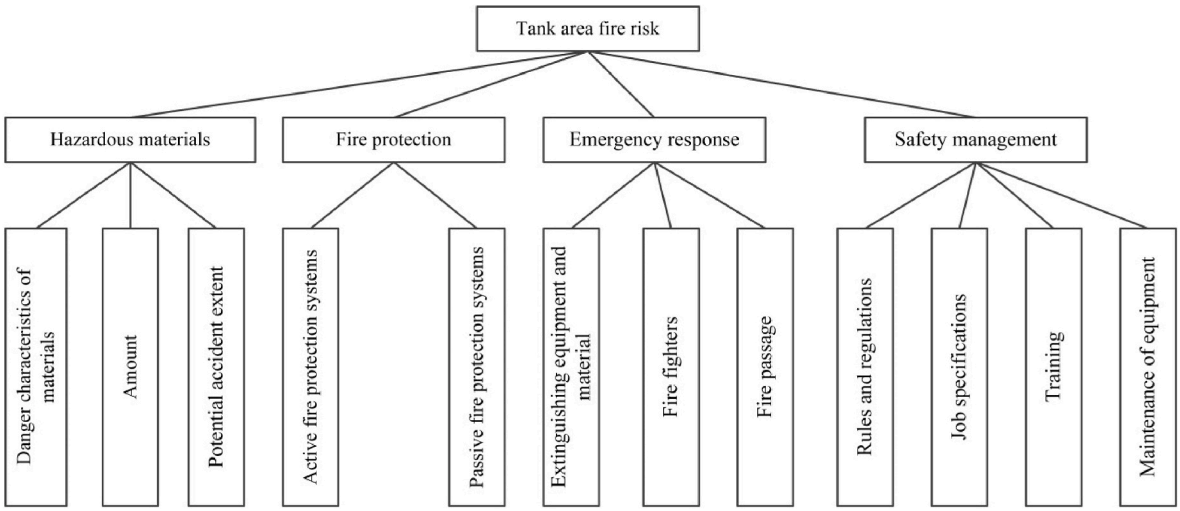

Fig. 4. Risk indices of chemical storage tank area.

Step 2 Establish WFPN model.

Based on the risk assessment factors and their relationships, the WFPN model can be established.

Step 3 Determine weights of the factors

In the WFPN models, the "AND" relationship of evaluation factors determined by formula (1) needs the weights of the factors to clarify their importance. While the "OR" relationship determined by formula (2) does not need the weights of the factors (In fact, all these weights are 1).

If the importance of the risk factors is different, their weights have impacts on the result of risk. There are many methods that can be used to determine the weights, such as the Delphi method which concentrates the knowledge and experience of experts to determine the weight of each factor (Zhou et al., 2020), the entropy weight method which determines weights based on the principle of information entropy (Zhao et al., 2022), and the Analytic Hierarchy Process (AHP) method which determines the importance of factors by making pairwise comparisons (Satty, 1980; Zhao et al., 2023). AHP is a structured technique for organizing and analyzing complex decisions, and is used to determine weights in this study.

Step 4 Fuzzify the assessment values of basic indices.

To assess the risk of a system, the judgment set which is the set of the assessment grades should be determined, and the basic risk factors (corresponding to the place which is not an output place of any transition) should be assessed.

The assessed values of the basic factors are fuzzified based on certain membership function. In this work, the SPA-fuzzy method is used to determine the membership functions.

Step 5 Build the matrixes M_0, I, and O.

Based on the structure of the established WFPN model and the weights of the factors, the matrixes *I* and *O* can be obtained. The matrix M_0 can be determined according to the assessment values of the basic factors and their fuzzification results.

Step 6 Perform fuzzy reasoning

Carry out the fuzzy reasoning using the aforementioned fuzzy reasoning algorithm (perform Eq. (7) until M_k equals M_{k-1}), and obtain the reasoning results.

Step 7 Defuzzify the results and determine the risk value

According to the result of the fuzzy reasoning, the value in the place representing the system risk contains the memberships on all assessment grades. Based on this value, the risk level can be determined according to certain criterion. In this work, the center of gravity method is used to defuzzify the fuzzy result.

The center of gravity method is expressed as follows (Akkurt et al., 2004):

$$G = \frac{\sum_{i=1}^{n} f_S(x) \bullet x}{\sum_{i=1}^{n} f_S(x)} \tag{16}$$

where, S is a fuzzy subset in the domain of real number R; $f_S(x)$ is the membership function; and G is the gravity value.

3. Case studies

3.1. Case 1

Risk assessment of a tank area can reveal its safety situation, and be helpful for accident prevention. In this work, the risk assessment of a storage tank area is taken as an example to illustrate the proposed risk assessment approach.

There are three parts of a dangerous chemical storage tank area in a chemical plant. The storage of dangerous substances includes 80 tons of ethyl acetate, 60 tons of methanol, and 40 tons of liquid ammonia. The tank area is divided into three fire zones with 45m and 50m safety distances between them, and the zones are separated by solid firewalls. The tank area is equipped with automatic monitoring alarm system, automatic sprinkler system, and electrical fire protection equipment.

The fire-fighting and accident rescue rely on the fire brigade of the plant and the fire brigade nearby. The fire brigade of the plant has 15 firemen, and is equipped with 105 fire extinguishers of 65 kg/35 kg/8 kg and 1 ton of foam concentrate in the tank area. The fire brigade nearby has 42 firemen, and is equipped with 200 fire extinguishers of 65 kg/35 kg/8 kg and 5 tons of foam concentrate. There is a 4m width fire passage in the tank area.

The safety management of the plant is relatively adequate, job specifications are complete, and the implementation is in good

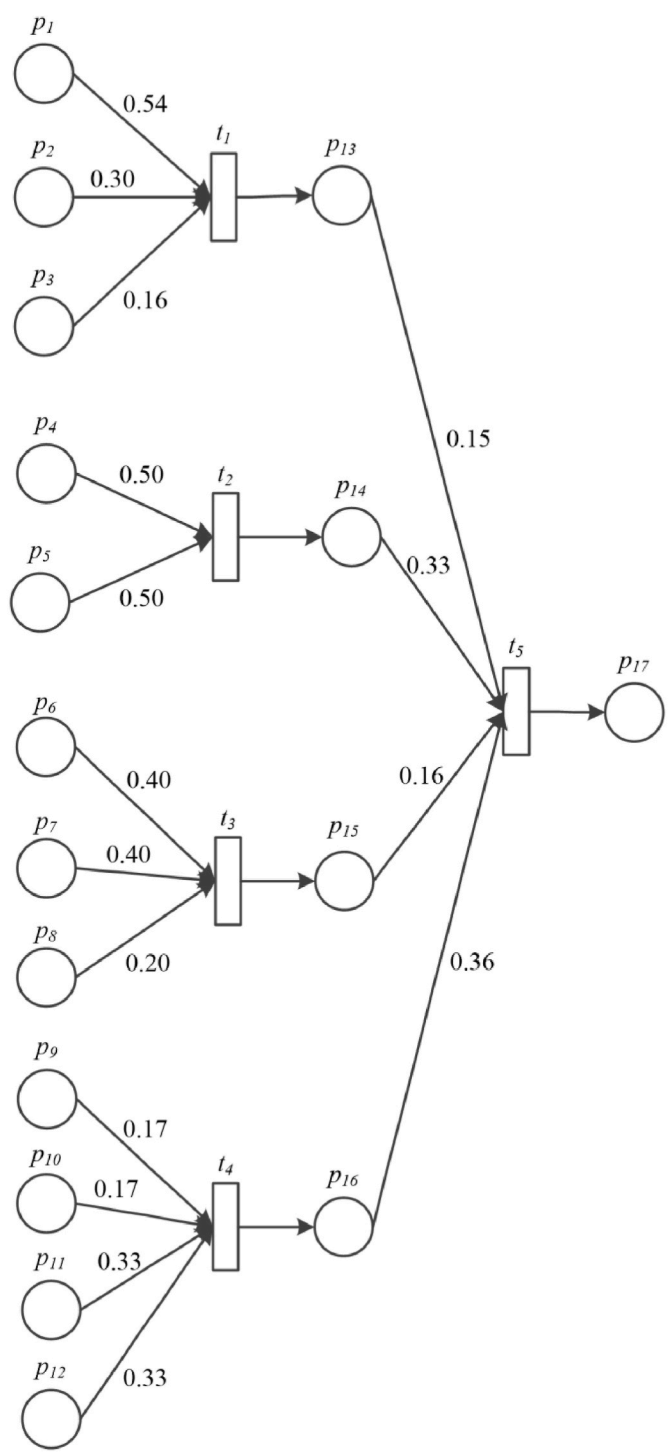

Fig. 5. WFPN model for storage tank area risk assessment.

condition; the leaders of the plant and the safety management personnel and other employees have participated in corresponding safety training, and hold certificates of qualification.

The tank area locates in a rather out-of-the-way place, the population density is small, and there is no settlement within the 500m area from the chemical storage tank area.

3.1.1. *Risk secassessment indices*

Determining the risk indices is important for the risk assessment of a chemical storage tank area. The main factors that influence the fire risk need to be summarized into a series of indices with clear concepts and clear boundaries, and the indices should be organized according to their internal connections and relationships.

For a chemical storage tank area which contains major hazards, the fire is the result of the dangerous materials and the failure of safety measures. According to the characteristics of fire in a chemical storage area, the risk indices are determined from the aspects including characteristics of hazardous materials, fire protection ability, emergency response, and safety management. The risk factors of each aspect are refined and determined, which are shown in Fig. 4.

The factors can be further detailed. In a tank area storing flammable materials, eliminating ignition sources is important for the fire prevention, and this mainly depends on safety management. The factor "rules and regulations" reflects the management and prevention of ignition sources. In this work, only two layers of factors are considered in the risk assessment, which is taken as an example to illustrate the proposed risk assessment method.

3.1.2. *WFPN model*

Fig. 5 shows the WFPN model according to the indices and their relationships. The meanings of the transitions and the places are listed in Table 1. The determined weights of the indices are marked on the input arcs the transitions in Fig. 5.

3.1.3. *Judgment set and membership functions*

In this study, the assessment results are divided into 5 grades: very high, high, medium, low and very low.

For the convenience of fuzzification, the qualitative evaluation levels are represented as 1–5 points: a point of 5 is very high, a point of 4 corresponds to high, the point of 3 stands for medium, the point of 2 is low, and a point of 1 is very low. Hence, SPA-fuzzy method based membership functions are used to determine the membership degrees of the assessment result of each basic factor on the assessment grades. As each grade does not have a value interval, the trapezoid membership functions shown in Fig. 2 are simplified into triangular functions, which are used to fuzzify the assessment values of the basic factors.

Triangular membership functions are shown in Fig. 6.

3.1.4. *Risk assessment*

According to the current situation of the tank area, the assessment of the basic indices is shown in Table 2.

The initial matrixes are determined:

$$M_0 = \begin{pmatrix} -1 & -1 & -1 & 0 & 1 \\ -1 & -1 & 0 & 1 & 0 \\ -1 & -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & -1 \\ 0 & 1 & 0 & -1 & -1 \\ -1 & 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 & -1 \\ 0 & 1 & 0 & -1 & -1 \\ -1 & 0 & 1 & 0 & -1 \\ 0 & 1 & 0 & -1 & -1 \\ 0 & 1 & 0 & -1 & -1 \\ 0 & 1 & 0 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 \end{pmatrix}$$

$$I = \begin{pmatrix} 0.54 & 0.30 & 0.16 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.50 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.40 & 0.40 & 0.20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.35 & 0.19 & 0.35 & 0.11 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.15 & 0.33 & 0.16 & 0.36 & 0 \end{pmatrix}$$

Table 1
Meanings of the transitions and the places in the WFPN model shown in Fig. 5.

Transition/ Place	Meaning	Transition/ Place	Meaning
p_1	Danger characteristics of materials	p_{12}	Maintenance of equipment
p_2	Amount of materials	p_{13}	Hazardous materials
p_3	Potential accident extent	p_{14}	Fire protection
p_4	Active fire protection system	p_{15}	Emergency response
p_5	Passive fire protection system	p_{16}	Safety management
p_6	Extinguishing equipment and material	p_{17}	Tank area risk
p_7	Fire fighters	t_1	Assessing hazardous materials
p_8	Fire passage	t_2	Assessing fire protection
p_9	Rules and regulations	t_3	Assessing emergency response
p_{10}	Job specifications	t_4	Assessing safety management
p_{11}	Training	t_5	Assessing tank area fire risk

$$O=\begin{pmatrix} 0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{pmatrix}$$

Using the fuzzy reasoning algorithm, we can obtain:

$$M_3=M_2=\begin{pmatrix} -1.000 & -1.000 & -1.000 & 0.0 & 1.000\\ -1.000 & -1.000 & 0.0 & 1.000 & 0.0\\ -1.000 & -1.000 & 0.0 & 1.000 & 0.0\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ -1.000 & 0.0 & 1.000 & 0.0 & -1.000\\ -1.000 & 0.0 & 1.000 & 0.0 & -1.000\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ -1.000 & 0.0 & 1.000 & 0.0 & -1.000\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ -1.000 & -1.000 & -0.540 & 0.460 & 0.540\\ 0.0 & 1.000 & 0.0 & -1.000 & -1.000\\ -0.800 & 0.200 & 0.800 & -0.200 & -1.000\\ -0.350 & 0.650 & 0.350 & -0.650 & -1.000\\ -0.404 & 0.446 & 0.173 & -0.527 & -0.769 \end{pmatrix}$$

From M_3, we can obtain the memberships on all evaluation levels of the evaluated risk, which is the marking in place p_{17}.

Defuzzifying the result, we obtain the crisp value 2.57. This value is between grade low and grade medium and closer to the medium grade. Thus, the risk of this tank area can be considered medium. Using the traditional fuzzy assessment approach, we can obtain the same result.

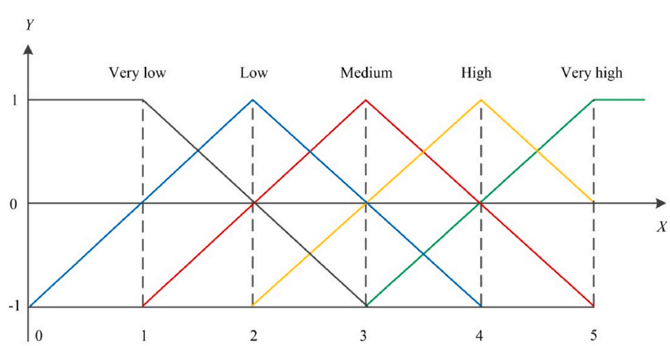

Fig. 6. Membership functions of the risk assessment of Case 1.

Table 2
Assessment of the basic indices.

Index	Value	Index	Value
Danger characteristics of materials	Very high	Fire fighters	Medium
Amount of materials	High	Fire passage	Low
Potential accident extent	High	Rules and regulations	Medium
Active fire protection system	Low	Job specifications	Low
Passive fire protection system	Low	Training	Low
Fire-fighting equipment	Medium	Maintenance of safety equipment	Low

3.2. Case 2

In the study of Kang et al. (2022), the leakage and explosion risk of hydrogen refueling stations were evaluated using an approach of multi-level variable weight fuzzy Petri-net (MVWFPN). In their work, the fuzziness of factors was expressed by the confidence value, which is a number between 0 and 1. In this work, the case is adapted to illustrate the proposed approach, and SPA based memberships are used to fuzzify the values.

Considering the occurrence of ignition accident in hydrogen refueling stations, the established Petri-net model according to the influencing factors is shown as Fig. 7and Table 3.

In the work of Kang et al. (2022), risk levels were determined according to the confidence value. The risk levels are listed in Table 4.

Therefore, the membership functions are determined as shown in Fig. 8.

Confidence values of initial places are listed in Table 5.

Through the Petri-net model, initial matrices can be obtained as follows,

$$M_0=\begin{pmatrix} 1 & 0.5 & -1 & -1\\ 1 & 1 & -1 & -1\\ -1 & 1 & 1 & -1\\ 0 & 1 & -1 & -1\\ -1 & -1 & -1 & -1\\ 0 & 1 & -1 & -1\\ -1 & -1 & -1 & -1\\ 0 & 1 & -1 & -1\\ -1 & -1 & -1 & -1\\ -1 & -1 & -1 & -1\\ -1 & -1 & -1 & -1 \end{pmatrix} I=\begin{pmatrix} 1&0&0&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0&0&0\\ 0&0&1&0&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&0&0.5&0.5&0&0&0&0&0\\ 0&0&0&0&0&0&0.5&0.5&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&1&0 \end{pmatrix}$$

Table 3
Meanings of places in the WFPN model shown in Fig. 7.

Transition/ Place	Meaning	Transition/ Place	Meaning
p_1	Too large flow of hydrogen in the pipeline	p_7	Spark
p_2	Failure of temperature control device	p_8	Failure of ignition protection device
p_3	Collision of tool or equipment	p_9	Failure of internal ignition protection layer
p_4	Existence of ignition source in the external environment	p_{10}	Failure of external ignition protection layer
p_5	Overheating of hydrogen	p_{11}	Accident of ignition
p_6	Failure of electrostatic protection device		

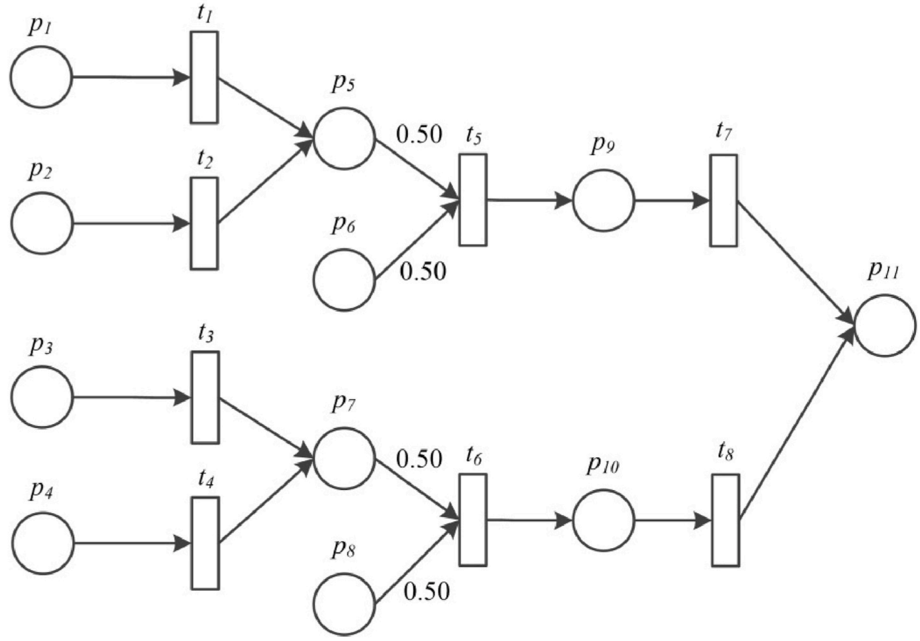

Fig. 7. WFPN model of ignition accident in hydrogen refueling stations.

Table 4
Risk levels of Case 2.

Risk level	Low	Medium	High	Very high
Range of confidence value	(0, 0.6]	(0.6, 0.7]	(0.7, 0.9]	(0.9, 1.0]

$$O=\begin{pmatrix}0&0&0&0&1&0&0&0&0&0&0\\0&0&0&0&1&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0&0&0\\0&0&0&1&0&0&1&0&0&0&0\\0&0&0&0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&0&0&1&0\\0&0&0&0&0&0&0&0&0&0&1\\0&0&0&0&0&0&0&0&0&0&1\end{pmatrix}$$

$$M_4=M_3=\begin{pmatrix}1&0.5&-1&-1\\1&1&-1&-1\\-1&1&1&-1\\0&1&-1&-1\\1&1&-1&-1\\0&1&-1&-1\\0&1&1&-1\\0&1&-1&-1\\0.5&1&-1&-1\\0&1&0&-1\\0.5&1&0&-1\end{pmatrix}$$

Thus, the memberships of the ignition accident is (0.5 1 0–1), and the defuzzified value is 0.58, which indicates the risk of the ignition accident is at the low risk level and near to the medium level. The result is somewhat different from that of the work of Kang et al. (2022) because the place weights are considered differently and the transition probabilities are not considered in this study. The same result can also be obtained by manual calculation transition by transition according to the approach presented in Section 2 (Eq. (4) and Eq. (5)).

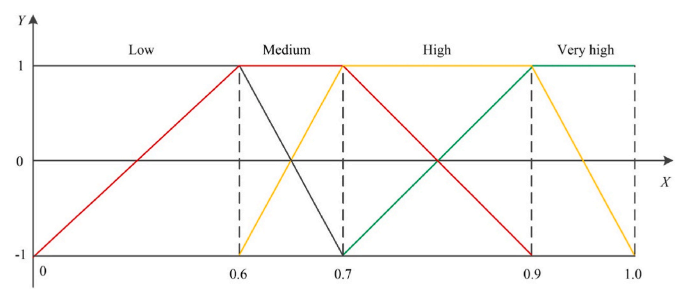

Fig. 8. Membership functions of the risk assessment of Case 2.

Table 5
Confidence values of initial places in Case 2.

Place	Confidence value	Place	Confidence value
p_1	0.45	p_4	0.65
p_2	0.60	p_6	0.65
p_3	0.75	p_8	0.65

4. Conclusions

In the process industries, large quantities of hazardous materials may be stored or handled. An accident such as fire and explosion is destructive and may cause great losses. Risk assessment of is important to reveal the safety level situation and improve safety management.

In the risk assessment, there are many factors having impacts on the risk. Most of these factors have the characteristic of uncertainty or vagueness. Taking advantage of weighted fuzzy Petri-nets in modeling and analysis, a novel approach for the risk assessment is proposed.

The risk assessment structure which reflects the relationships between the factors can be easily modeled by WFPN, and the fuzzy reasoning of WFPN can implement the risk assessment. The WFPN is redefined according to the risk assessment, and the fuzzy reasoning algorithm is improved. The SPA-Fuzzy method is used to establish the membership functions for fuzzy assessment. Since risk assessment, in many cases, is to compare parameter values with certain criteria, it is advantageous by measuring identity, contrary and discrepancy using the set-pair analysis method. The proposed method is illustrated by cases of the fire risk assessment of a tank farm and the ignition accident risk of hydrogen refueling stations.

After the assessment structure (assessment factors, assessment level, the relationships between observed value and standard value or membership functions, etc.) is determined, the assessor enters the observation value of each risk factor, and the assessment result or the corresponding risk grade can be obtained by using this approach. Determining the observation values of the risk factors may involve some subjectivity, such as determining the factor “training of employees”, which often requires the assessor to make subjective judgment. In this case, the subjective arbitrariness can be reduced by predetermining some criteria, such as the assessment value of the "training of employees" factor can be expressed as the proportion of employees participating in the designated professional training. There are many risk factors that can be compared with safety standards or norms to determine their assessment values, e.g., for the factor "number of fire extinguishers", general safety specifications stipulate that a certain type of plant should be equipped with a certain number of fire extinguishers according to the area. Thus, the risk factor value can be determined by comparing the actual quantity of extinguishers with the required quantity, so that the determined assessment value is relatively objective.

For the output of the risk assessment using the proposed approach, because of the defuzzification (the center of gravity adopted in this paper), a precise value will be obtained. This value can be used as the risk value, and the risk level can be determined according to the grade range in which it is located.

CRediT authorship contribution statement

Jianfeng Zhou: Writing – original draft, Methodology. **Genserik Reniers:** Writing – review & editing.

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

Data will be made available on request.

References

Ahmadi, O., Mortazavi, S.B., Mahabadi, H.A., Hosseinpouri, M., 2020. Development of a dynamic quantitative risk assessment methodology using fuzzy DEMATEL-BN and leading indicators. Process Saf. Environ. Protect. 142, 15–44.

Akkurt, S., Tayfur, G., Can, S., 2004. Fuzzy logic model for the prediction of cement compressive strength. Cement Concr. Res. 34, 1429–1433.

Albert, J.B., Senen, B., 1994. Fuzzy reasoning supported by Petri nets. IEEE Trans. Fuzzy Syst. 2 (2), 135–150.

Argyropoulos, C.D., Christolis, M.N., Nivolianitou, Z., Markatos, N.C., 2012. A hazards assessment methodology for large liquid hydrocarbon fuel tanks. J. Loss Prev. Process. Ind. 25, 329–335.

Arunraj, N.S., Mandal, S., Maiti, J., 2013. Modeling uncertainty in risk assessment: an integrated approach with fuzzy set theory and Monte Carlo simulation. Accid. Anal. Prev. 55, 242–255.

Aziz, M.H., Bohez, E.L.J., Parnichkun, M., Saha, C., 2010. Classification of fuzzy Petri nets, and their applications. World Academy of Science, Engineering and Technology 72, 394–401.

Chen, S.-M., 2002. Weighted fuzzy reasoning using weighted fuzzy Petri nets. IEEE Trans. Knowl. Data Eng. 14 (2), 386–397.

Chen, X., Wu, X., Qin, J., 2014. Risk assessment of an oxygen-enhanced combustor using a structural model based on the FMEA and fuzzy fault tree. J. Loss Prev. Process. Ind. 32, 349–357.

David, R., Alla, H., 1994. Petri nets for modeling of dynamic systems - a survey. Automatica 30 (2), 175–202.

Dow, 1994. DOW's Fire & Explosion Index Hazard Classification Guide, seventh ed. American Institute of Chemical Engineers, New York.

Etowa, C.B., Amyotte, P.R., Pegg, M.J., Khan, F.I., 2002. Quantification of inherent safety aspects of the Dow indices. J. Loss Prev. Process. Ind. 15, 477–487.

Fuentes-Bargues, J.L., Gonzalez-Gaya, C., Gonzalez-Cruz, M.C., Cabrelles-Ramírez, V., 2016. Risk assessment of a compound feed process based on HAZOP analysis and linguistic terms. J. Loss Prev. Process. Ind. 44, 44–52.

Gao, M.M., Zhou, M.C., Huang, X.G., Wu, Z.M., 2003. Fuzzy reasoning Petri nets. IEEE Trans. Syst. Man Cybern. Syst. Hum. 33 (3), 314–324.

Hu, H.S., Li, Z.W., Al-Ahmar, A., 2011. Reversed fuzzy Petri nets and their application for fault diagnosis. Comput. Ind. Eng. 60 (4), 505–510.

Jiang, Y.L., Xu, C.F., Yao, Y., Zhao, K.Q., 2004. Systems information of set pair analysis and its applications. In: Proceedings of the Third International Conference on Machine Learning and Cybernetics. Shanghai, China.

John, A., Paraskevadakis, D., Bury, A., Yang, Z., Riahi, R., Wang, J., 2014. An integrated fuzzy risk assessment for seaport operations. Saf. Sci. 68, 180–194.

Kang, J., Wang, L., Jin, H., Zhang, J., 2022. Proposed model of potential accident process at hydrogen refueling stations based on multi-level variable weight fuzzy Petri net. Int. J. Hydrogen Energy 47 (67), 29162–29171.

Lewis, D.J., 1974. The Mond Fire, Explosions and Toxicity Index, Applied Plant Lay-Out and Spacing, Loss Prevention Symposium. CEP.

Liu, H.-C., Liu, L., Lin, Q.-L., Liu, N., 2013. Knowledge acquisition and representation using fuzzy evidential reasoning and dynamic adaptive fuzzy Petri nets. IEEE Trans. Cybern. 43 (3), 1059–1072.

Luo, T., Wu, C., Duan, L., 2018. Fishbone diagram and risk matrix analysis method and its application in safety assessment of natural gas spherical tank. J. Clean. Prod. 174, 296–304.

Miri, Lavasani S.M., Yang, Z., Finlay, J., Wang, J., 2011. Fuzzy risk assessment of oil and gas offshore wells. Process Saf. Environ. Protect. 89, 277–294.

Nuclear Regulatory Commission, 1983. PRA Procedure Guide. NUREG/CR-2815, USA.

Sarvestani, K., Ahmadi, O., Mortazavi, S.B., Mahabadi, H.A., 2021. Development of a predictive accident model for dynamic risk assessment of propane storage tanks. Process Saf. Environ. Protect. 148, 1217–1232.

Satty, T.L., 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York.

State Administration of Work Safety, 2010. Reporting of Lanzhou petrochemical corporation accident. Available at: http://www.chinasafety.gov.cn/newpage/Contents/Channel_5330/2010/0118/83133/content_8313.htm (in Chinese).

Su, H.-S., Mi, G.-S., 2006. Set pair analysis applied for identifying power transformer faults. In: Proceedings of the Fifth International Conference on Machine Learning and Cybernetics. Dalian, China.

U.S. Chemical Safety Board, 2015. Final investigation report caribbean Petroleum tank terminal explosion and multiple tank fires. available at: http://www.csb.gov/caribbean-petroleum-refining-tank-explosion-and-fire/.

Vautard, R., Ciais, P., Fisher, R., Lowry, D., Bréon, F.M., Voge, F., et al., 2007. The dispersion of the Buncefield oil fire plume: an extreme accident without air quality consequences. Atmos. Environ. 41, 9506–9517.

Wang, X., Liu, X., Wang, L., Yang, J., Wan, X., Liang, T., 2022. A holistic assessment of spatiotemporal variation, driving factors, and risks influencing river water quality in the northeastern Qinghai-Tibet Plateau. Sci. Total Environ. 851, 157942.

Xu, Y., Zhang, Y., 2009. A online credit evaluation method based on AHP and SPA. Communications in Nonlinear Science and Numerical Simulation 14, 3031–3036.

Yin, H., Liu, C., Wu, W., Song, K., Liu, D., Dan, Y., 2020. Safety assessment of natural gas storage tank using similarity aggregation method based fuzzy fault tree analysis (SAM-FFTA) approach. J. Loss Prev. Process. Ind. 66, 104159.

Zhang, X., Shen, Q., Zhao, D., 2017. Risk assessment on chemical plants by the method of safety checklist analysis. Process Saf. Prog. 36 (1), 95–101.

Zhao, J., Tian, J., Meng, F., Zhang, M., Wu, Q., 2022. Safety assessment method for storage tank farm based on the combination of structure entropy weight method and cloud model. J. Loss Prev. Process. Ind. 75, 104709.

Zhao, K.Q., 2000. Set Pair Analysis and its Preliminary Application. Zhejiang Science Press, Hangzhou, China (in Chinese).

Zhao, P., Ali, Z.M., Ahmad, Y., 2023. Developing indicators for sustainable urban regeneration in historic urbanareas: Delphi method and Analytic Hierarchy Process (AHP). Sustain. Cities Soc. 99, 104990.

Zhou, G., Zhu, J., Luo, S., Wu, Z., Jiang, Y., 2020. An evaluation method of fragile states index based on climate shock: a case of Bangladesh. J. Environ. Manag. 275, 111142.

Zhou, J., 2010. SPA–fuzzy method based real-time risk assessment for major hazard installations storing flammable gas. Saf. Sci. 48, 819–822.