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Original scientific paper

Refined Oil Loading and Unloading Process Risk Assessment using Stochastic Colored Petri Nets Integrated with Risk Factors

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Abstract: This paper presents a novel risk assessment method using Stochastic Colored Petri Nets (*SCPN*) specifically designed for the loading and unloading process of refined oil. The method incorporates a comprehensive analysis of risk factors by employing event trees and fault trees. Based on the real logistics operation process of an enterprise, four key risk factors and their corresponding evolution processes are identified, including equipment quality, improper operations, wrong instructions, and illegal operations. Subsequently, an *SCPN* model is constructed to integrate these risk factors and evaluate the system's performance using isomorphic Markov chain analysis. The overall risk assessment of the system is determined based on a risk function, which captures the system's risk level considering the influence of the identified risk factors. The results reveal that personnel engaging in illegal operation behaviors pose a high-risk factor, demanding preventive measures and increased attention. This research provides valuable insights for risk management in the refined oil loading and unloading process, emphasizing the significance of addressing risk factors and enhancing safety measures.

Keywords: hazardous chemicals; performance analysis; risk factor; risk assessment; stochastic colored petri nets

1 INTRODUCTION

Accidents in hazardous chemical logistics have been increasing in both frequency and severity in recent years, attracting the attention of governments to the safety management of hazardous chemicals. The logistics operation process management in hazardous chemical enterprises is complex, and the chemicals involved have characteristics such as flammability, explosiveness, and toxic corrosion. They are susceptible to various risk factors and are prone to accidents with significant consequences during logistics operations [1]. In order to reduce and prevent the occurrence of hazardous chemical accidents, relevant departments in China have implemented the "Regulations on the Safety Management of Hazardous Chemicals". However, serious accidents involving hazardous chemicals continue to occur repeatedly at the enterprise level.

Hazardous chemical accidents happen under the influence of many risk factors, and the existing accident cases play a certain role in reducing and preventing accidents. However, the level of accidents remains high in the chemical industry [2]. According to NCRR statistics in 2021, there were 122 chemical accidents and 150 deaths across the country. Prior to this, Wang et al. (2021) [3] statistically analyzed 280 major and above dangerous chemical accidents in China from 1981 to the first half of 2020. The accident types were roughly divided into fire, explosion, asphyxiation and poisoning. The causes of accidents included human factors, equipment factors and environmental factors. It has been confirmed that human factors are the primary cause of chemical accidents in China [4]. Zhou et al. (2022) [5] statistically analyzed the characteristics of dangerous accidents involving chemical products in China from 2015 to 2021 and found that operator errors, weak safety awareness, and poor crisis concept easily lead to casualties of hazardous chemical accidents. Wang et al. (2020) [6] statistically analyzed that the occurrence of chemical accidents was mainly caused by improper operations or equipment defects due to high temperature factors in the hot seasons from 1989 to 2019. Yang and Yao (2019) [7] based their study on 120 hazardous chemical accident cases. They extracted the elements of the disasters caused by these accidents and found that illegal operations were the main causes of such disasters.

The chemical carries the risk of serious accidents due to the special nature of its products [8]. For example, in 2019, the "3.21" chemical explosion accident occurred in Yancheng, Jiangsu Province, causing 78 deaths and 640 injuries. The accident occurred because the continuous heating of illegally stored nitrified waste lead to spontaneous combustion in the company's old solid waste warehouse. In 2020, the "12·19" chemical explosion accident occurred in Anda City, Heilongjiang Province, resulting in 3 deaths and 4 injuries. The accident occurred because the non-site operators violated operating procedures and made errors, resulting in the mixture of air, toluene, and metallic sodium, which caused an explosion. The occurrence of such major accidents highlights the importance of safety risk management as a crucial guarantee for the sustainable development of hazardous chemical enterprises. The loading and unloading operations play a crucial role in connecting the logistics system, but they are also exposed to various risk factors such as heavy weather conditions [9] and illegal operations, which often lead to hazardous accidents. Therefore, it is essential to control these risk factors. This paper introduces a new method for process modeling and risk assessment based on Stochastic Colored Petri Nets. Focusing on the refined oil loading and unloading activities, the study identifies risk factors through event tree and fault tree analysis, integrates these potential risk factors into the loading and unloading process, and utilizes Petri nets for modeling and performance analysis. This paper effectively identifies illegal operations as the most severe risk factor in the refined oil loading and unloading process and proposes corresponding risk management strategies.

2 LITERATURE REVIEW

The Petri nets were put forward by German scientist Carl Adam Petri in 1962; it is a mathematical model suitable for system description and analysis. It is used to explain the causal relationship between events and conditions, and widely used in system modeling, simulation and analysis.

At present, many scholars model and analyze the risk of hazardous chemical management process with Petri nets. Srinivasan and Venkatasubramanian (1996) [10] first proposed a Time- Colored Petri nets integrating risk factor framework to model and analyze the production process of chemical plants. Balasubramanian et al. (2002) [11] constructed a general Petri nets model for analyzing the loading process of liquid ammonia, developed a fault mechanism to integrate into the sub-Petri component, and simulated to prove the feasibility of hazard identification. Nivolianitou et al. (2004) [12] taking the terminal loading and unloading activities of gaseous ammonia as examples, used Petri nets for business process modeling, and found that it can better perform the temporal characteristics of events. Zhou et al. (2017) [13] proposed a risk assessment method based on weighted fuzzy Petri nets, and used the Petri nets analysis method to conduct risk assessment, which improved the traditional security risk factor table analysis method. Kamil et al. (2019) [14] used Generalized Stochastic Petri nets to model the occurrence and propagation patterns of domino effect accidents in chemical plants, which helped to monitor process risks. Zhou and Reniers (2020) [15] used a weighted fuzzy Petri net considering veto factors to model, risk factors taken into account for simulation, and took the chemical production process as an example to verify its feasibility. Li Weijun et al. (2022) [16] aimed at the sewage system of natural gas transmission stations for the first time. On the basis of Fuzzy Hierarchical Coloring Petri nets through four process flows, they conducted risk identification from the perspective of process flow, and finally concluded that the risk impact of personnel behavior was the highest. In view of the risk factors of port loading and unloading of hazardous chemicals, Rao and Raghavan (1996) [17] were the first to identify the hazards of port loading and unloading operations based on the equivalent safety concept (ESC) and determined the dangerous events related to port facilities. Khan et al. (2021) [18, 19] combined past accidents and expert judgment to identify factors and established interdependencies, and built model of hazard accident factors based on Bayesian nets. Ay et al. (2022) [20] first applied the ARAMIS risk assessment method, in which fault tree was used to identify dangerous events and a case of loading and unloading operations of chemical tankers were used to verify its feasibility. Khan et al. (2022) [21] taking 352 dangerous goods accidents as samples, analyzed the human factors and the accident cause path of hazardous chemical accidents in the ports.

At present, scholars have used Petri nets to model the business operation process of hazardous chemicals and study risks. However, in the existing researches, the focus is mainly on the modeling and analysis of individual risk factors, as well as the classification and identification of risk factors. Therefore, this paper proposes a novel risk evaluation method based on Stochastic Coloring Petri nets. Firstly, a qualitative analysis of risk factors involved in the loading and unloading process of hazardous chemicals is conducted using fault trees and event trees. Subsequently, an *SCPN* model is established, incorporating the identified risk factors in the loading and unloading process of hazardous chemicals. The obtained *SCPN* model is isomorphic to a Markov chain for performance analysis, and the overall risk level of the system under the influence of different risk factors is studied.

3 RISK ASSESSMENT METHOD

In this paper, we propose a risk assessment method based on Stochastic Colored Petri nets, aiming to prevent further deterioration of risk factors and dangerous accidents. The technical route of the risk assessment method includes five steps, as shown in Fig. 1.

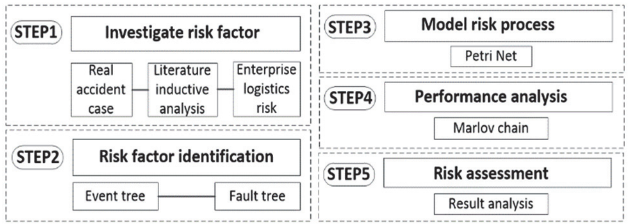


Figure 1 Technical roadmap of risk assessment method

Step 1: There are numerous risk factors that impact the safe operation of enterprises within actual logistics operation processes [22]. By investigating the actual processes of enterprises, this paper analyzes the risk factors present in the logistics links of these enterprises. It examines the risk factors based on previous real accident cases and research conducted by past scholars. The data for real accident cases are derived from sources such as the Ministry of Emergency Management, NRCC platform, National Bureau of Statistics, etc. Through inductive analysis of relevant literature, as well as other publications, patents, and literature, it is found that the causes of hazardous chemical accidents mainly consist of human, equipment, and environmental factors, with human factors being the primary contributors to disasters.

Step 2: Currently, many scholars have utilized the event tree [23] and fault tree [24] analysis methods for risk-based research. Event and fault trees offer a visual depiction of the formation of incidents, aiding in the analysis of intricate links and systems. We analyze and utilize the risk factors collected in step 1, expanding the logical relationship between the accidents that are prone to occur in the system links and their causes in the form of a tree diagram. This enables further identification of the evolutionary process of risk events caused by the risk factors.

Based on the logic gate conditions provided by the fault tree, the transformation of the relationship from the fault tree to the Petri nets is conducted, as depicted in Fig. 2 and Fig. 3. In Fig. 2, the input place of the transition contains tokens. When the transition takes place, the tokens from the input place are consumed, and new tokens are generated at the output place. In Fig. 3, each input place must contain at least one token before the transition can occur. Once the transition is executed, the tokens from the input place are consumed, and new tokens are generated at the output place.

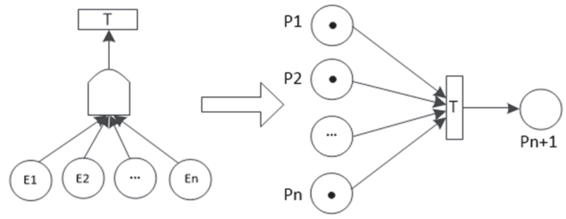


Figure 2 Fault tree "AND gate" relationship transformation to Petri nets

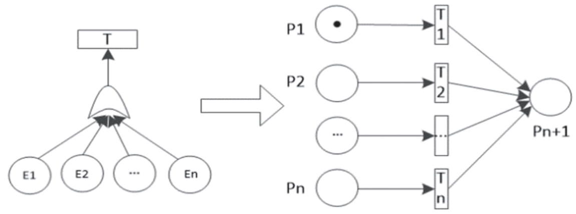


Figure 3 Fault tree "OR gate" relationship transformation to Petri nets

Step 3: This paper is based on the actual logistics operations of enterprises and uses *SCPN* (Stochastic Colored Petri Net) as the main tool for integrating risk factors in the process modeling. In *SCPN*, "stochastic" represents the assignment of an execution rate to each transition, enabling effective simulation of system processes under continuous time. "Colored" represents the binding of color sets to each place, where different color sets represent different system resources. By defining color sets, the integration of risk factors is achieved, and the evolution process of risk factors is reflected through state transitions. Futhermore, the relationship transformation between fault trees and Petri nets in Step 2 provides a theoretical foundation. The definition of a Stochastic Colored Petri nets is as follows:

Definition 1: The Stochastic Colored Petri nets [28, 29] is an octet: $SCPN = (P, T, Arc, \Sigma, C, E, M_0, \lambda)$.

(1) P and T represent respectively the collection of place and transition; Arc represents a collection of directed arcs, and $P \cap T = P \cap Arc = Arc \cap T = \Phi$; $Arc \in P \times T \cup T \times P$, dom($Arc$) ∪ cod($Arc$) = $S \cup T$, where dom and cod represent the definition domain and the value domain respectively.

(2) Σ represents a set of colors that describe the type of data of the token.

(3) C represents the color collection including the place color collection $C(p)$ and the transition color collection $C(t)$.

(4) E represents the arc expression function satisfying $\forall a \in Arc$: [Type($E(a)$) = $C(p)$ MS ∩ Type (Var($E(a)$) ⊆ Σ]; The arc expression function maps each arc into an expression of type $C(p)$ MS.

(5) M_0 represents the initial marking of the *SCPN*.

(6) $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_n\}$ is the set of the average implementation rate of transition, representing the average number of implementations per unit time when implementable.

Definition 2: Assume $SCPN = (P, T, Arc, \Sigma, C, E, M_0, \lambda)$, if present $t \in T$, make $M_0[t > M'$, M' is said to be directly accessible from M_0. If there is a transition sequence $t_1, t_2, \ldots, t_k$ and identification sequence $M_1, M_2, \ldots, M_k$ that satisfies $M_0[t_1 > M_1[t_2 > M_2 \ldots M_{k-1}[t_k > M_k$, M_k is said to be reachable from M_0.

Step 4: From the definition of Petri nets, it is evident that in the *SCPN* model, a transition necessitates a delay between its ability to be implemented and its actual implementation. Here, we assume that the random delay between the implementation and implementation of a transition (T) is treated as a continuous random variable X_i, which follows an exponential distribution. Its distribution function is: $\forall_t \in T$, $F^t = 1 - e^{-\pi t x}$, where $\lambda_t > 0$ is the average implementation rate of the transition (T_i), and the variable $X_i \geq 0$. It can be seen from the definition that Petri nets have reachability. We first construct the reachable marking graph of the *SCPN* model, and convert the implementation transition (T_i) annotated on each arc of the *SCPN* model into the corresponding average implementation rate λ_t, meaning that the *SCPN* model can be isomorphized to a one-dimensional Markov chain. If the steady state probability of n states in a Markov chain is a row vector $X = (X_1, X_2, \ldots, X_n)$, the stability probability is calculated by Eq. (1) according to the nature of the Markov chain.

$$\begin{cases} XQ = 0 \\ \sum_i x_i = i(1 \leq i \leq n) \end{cases} \tag{1}$$

Solving the system of linear equations yields the stable probability $P[M_i] = X_i$ $(1 \leq i \leq n)$ for each reachable marking with Q being the state transition matrix.

Step 5: Risks are inevitable in system. The occurrence of risk accidents is the result of the co-evolution of risk factors within a specific time and occasion. Risks also possess the characteristics of uncertainty, damage and measurability [30, 31]. The probability and consequences of an event are often typically used to describe risk. For the overall system risk, the occurrence of consecutive events leads to dangerous accidents [32]. The calculation of the system risk value is presented in Eq. (2), where R_i represents the system risk value, P_{event} represents the probability of an accident, and I_{event} represents the potential consequences of an accident. The assessment of accident consequences is provided in Tab. 1.

$$R_i = \sum_{i=1}^{n} P_{\text{event}(i)} \times I_{\text{event}(i)} \tag{2}$$

Table 1 Consequence of accidents

Score	Casualties	Environment implication	Property damage
1	Slight injury to one person	No impact	≤ ten thousand
3	Serious injury to one person	Locally controllable	ten thousand - one hundred thousand
5	Permanently disabled to one person	Locally uncontrollable	one hundred thousand - million
7	One death or permanent disability	Severe Locally uncontrollable	million - five millions
10	Multiple deaths	Major uncontrollable	≥ five millions

4 CASE ANALYSIS

4.1 Risk Events Identification

According to field research, A petrochemical enterprise has not experienced any major hazardous chemical accidents in logistics safety, but general logistics safety accidents occur from time to time. Based on accident statistics, 70% of accidents are caused by employees' illegal operations. Because most employees lack the understanding of the nature of oil products, their illegal operations occasionally lead to risk events. Through the investigation of the safety management status of loading and unloading operations at Company A and analysis of accident information, the risk events associated with refined oil loading and unloading operations are identified, as shown in Tab. 2.

Table 2 Loading and unloading operations risk events identification table

Number	Risk events
①	Unlocking and unloading oil without permission
②	Leave work without permission
③	Oil discharge was not closely observed
④	The valve is not closed after the oil is loaded
⑤	Use an iron rod tube to measure the oil level
⑥	Incorrect use of interface devices
⑦	The tool is not regularly serviced
⑧	Opening the wrong valve causes oil string

4.2 Risk Factors Identification

Based on the previous information, we can infer that human unsafe behavior is the main factor leading to the occurrence of hazardous accidents. Taking employees' illegal operations as examples. By analyzing and summarizing relevant literature on the consequences of illegal operations by loading and unloading personnel [18-21, 25-27], a generic event tree for illegal operations in finished oil loading and unloading operations is provided, as shown in Fig. 4. After the occurrence of illegal operation events, possible subsequent events may include equipment failure, oil leakage, ignition of ignition sources, and spread of fire. The consequential events that can result from these include leaks, fires, explosion accidents, equipment maintenance, and safety status.

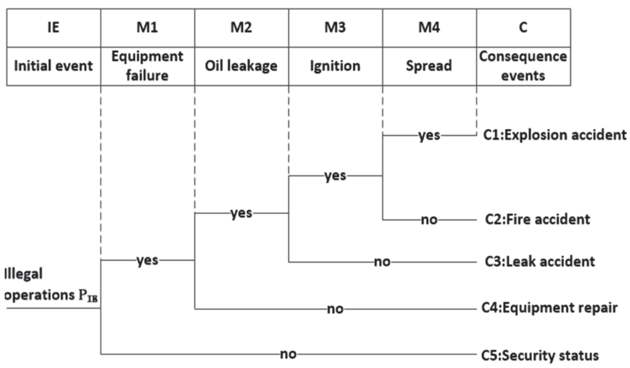


Figure 4 Common event tree for illegal operation

Through the analysis of the event tree, it is evident that the most serious accident during loading and unloading operations is an explosion accident. Therefore, we consider the occurrence of an explosion accident as the top event for top-to-bottom event decomposition. The occurrence of the top event "explosion accident" can be attributed to two main causes: excessive pressure or the exacerbation of a fire accident. Excessive pressure primarily occurs due to equipment failure caused by aging and poor equipment quality, among other factors. On the other hand, the occurrence of a fire is typically caused by the leakage of refined oil and the presence of ignition sources. As shown in Fig. 5, the bottom events of accidents consist of illegal operations, improper operation, incorrect instruction, equipment quality issues, ignition sources, and other environmental factors.

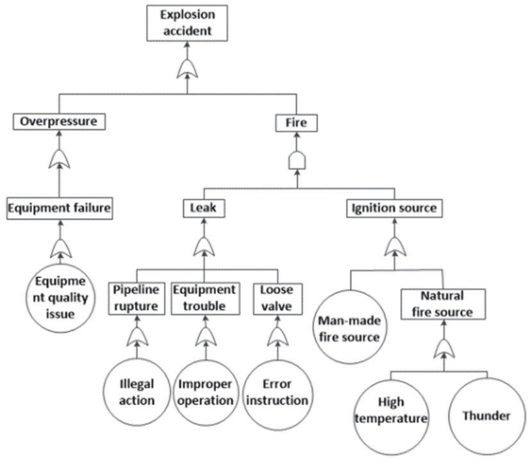


Figure 5 Fault tree for refined oil loading and unloading operations

4.3 Petri Nets Model Integration Risk Factors

This paper serves as a reference for the port loading and unloading operations process of a specific petrochemical enterprise, with a focus on the unloading operation of refined oil. An example is provided to illustrate the process. Upon the arrival of an oil tanker at the port, the refined oil is pumped into the oil conveying arm and subsequently transported to the terminal valve area. When the valve opens, the oil flows through the conveying pipeline and into the storage tank. The unloading process is depicted in Fig. 6.

Figure 6 Port loading and unloading process of refined oil

The fault tree decomposes the bottom event of the accident from top to bottom, reflecting the evolution process of the accident, and models the refined oil loading and unloading process by integrating the bottom event as a risk factor. After the loading and unloading of refined oil begins, the oil pump starts considering the equipment failure due to equipment quality problems, resulting in the rising pressure and temperature of the refined oil, and then stops the oil pump action. If the refined oil is stably transported to the oil transfer arm, consider the equipment damage caused by improper operation of the operator, resulting in the leakage of the refined oil, and implement the action of stopping the oil pump. If the refined oil is stably transported to the valve area, consider the danger of the unclosed valve due to the operator accepting the wrong instruction, causing the refined oil to leak from the valve, and implement the action of closing the valve. If the oil is stably transported to the conveying pipeline, consider the rupture of the pipeline caused by the illegal operation of the operator, resulting in the leakage of refined oil, and implement the action of closing the valve. In the event of oil leakage, consider that contact ignition sources will cause fire and explosion accidents. The *SCPN* model of refined oil loading and unloading operations incorporating risk factors is shown in Fig. 7.

The meaning of place and transition in the model is shown in Tab. 3, and the meaning of color sets and variables is shown in Tab. 4.

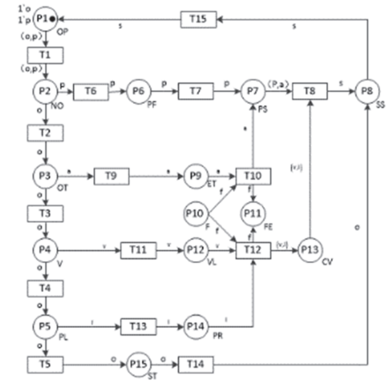


Figure 7 *SCPN* model of refined oil unloading operation based on risk factors

Table 3 Place and transition meaning table

Place	Meaning	Transition	Meaning
P_1	Start of uninstallation	T_1	Prepare the oil pump to the start-up state
P_2	Start of oil pump	T_2	Stable delivery to the oil transfer arm
P_3	Arrival of oil transfer arm	T_3	Stable delivery to the valve area
P_4	Arrival of valve area	T_4	Stable delivery to the pipeline
P_5	Arrival of conveyor line	T_5	Stable delivery to storage tanks
P_6	Oil pump failure	T_6	Oil pump aging failure
P_7	Stop of oil pump	T_7	Reach a dangerous state of stress
P_8	Steady state	T_8	Traffic is reduced to none
P_9	Equipment device	T_9	Improper operation by personnel
P_{10}	Ignition source	T_{10}	Oil leakage
P_{11}	Fire, explosion	T_{11}	Personnel accept the wrong instruction
P_{12}	Unclosed valve	T_{12}	Oil leakage
P_{13}	Closed valve	T_{13}	Personnel generate illegal actions
P_{14}	Ruptured pipeline	T_{14}	End of unloading oil
P_{15}	Oil tank	T_{15}	Restore the normal state of the device

Table 4 Color set and variable declaration

Color set declaration	Meaning	Variable	Meaning
Colset OP = product oil × pump	Refined oil and oil pump	Var *o* oil	Refined oil resources
Colset NO = unit with no	Oil pump start state	Var p pump	Oil pump status
Colset OT = unit with ot	Oil transfer arm	Var *a* ot	The status of the oil transfer arm
Colset V = unit with vo	Valve area	Var *v* vo	The valve status
Colset PL = unit with pl	Pipeline	Var l pl	The status of the delivery pipeline
Colset PF = unit with pf	Oil pump failure	Var *f* fe	The type of ignition source
Colset PS = unit with ps	Oil pump stop command	Var *s v*, *l*, *p*, *a*	A combination type
Colset SS = unit with ss	Steady state of the system		
Colset ET = unit with et	Equipment damage		
Colset F = unit with f	Ignition source		
Colset FE = unit with fe	Fire and explosion accident		
Colset VL = unit with vl	Unclosed valve		
Colset CV = unit with cv	Closed valve		
Colset PR = unit with pr	Ruptured pipeline		
Colset ST = unit with st	Storage tank		

4.4 Model Performance Analysis

As shown in Fig. 7, the initial set of marking for the system model is M_0 = (1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0).

Table 5 Reachable marking the contained place

Reachable marking	Place	Reachable marking	Place
M_0	P_1	M_7	P_5
M_1	P_2	M_8	P_{12}
M_2	P_3	M_9	P_7, P_{11}
M_3	P_6	M_{10}	P_8
M_4	P_4	M_{11}	P_{14}
M_5	P_9	M_{12}	P_{15}
M_6	P_7	M_{13}	P_{11}, P_{13}

Following the transfer of tokens, the marking of the system changes. Upon the execution of transition T_1, the reachable marking set transforms into M_1 = (0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0). Tab. 5 displays the places included in each reachable marking.

From this, we can observe that upon completion of all the transitions, the system reaches a reachable marking, as depicted in Fig. 8.

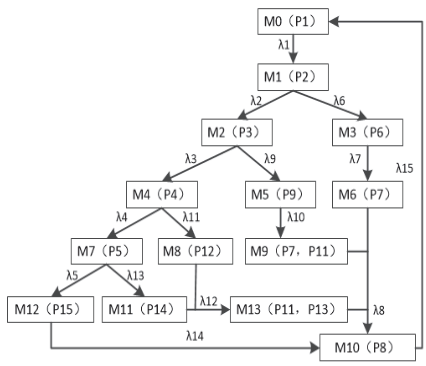


Figure 8 Reachable marking diagram

According to the reachable marking graph, an isomorphic one-dimensional Markov chain is acquired, as shown in Fig. 9.

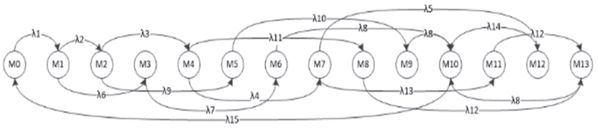


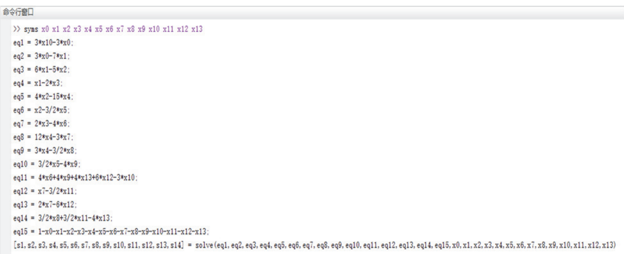
Figure 9 Isomorphic Markov chain

If the steady-state probability of 14 states in the system is a row vector $P = (P(M_0), P(M_2), ..., P(M_{13}))$, the following system of equations can be listed according to Eq. (1).

$$\begin{cases} \lambda_{15}P(M_{10})-\lambda_1 P(M_0)=0 \\ \lambda_1 P(M_0)-(\lambda_1+\lambda_6)P(M_1)=0 \\ \lambda_2 P(M_1)-(\lambda_3+\lambda_9)P(M_2)=0 \\ \lambda_6 P(M_1)-\lambda_7 P(M_3)=0 \\ \lambda_3 P(M_2)-(\lambda_4+\lambda_{11})P(M_3)=0 \\ \lambda_9 P(M_2)-\lambda_{10}P(M_5)=0 \\ \lambda_7 P(M_3)-\lambda_8 P(M_6)=0 \\ \lambda_4 P(M_4)-(\lambda_5+\lambda_{13})P(M_7)=0 \\ \lambda_{11}P(M_4)-\lambda_{12}P(M_8)=0 \\ \lambda_{10}P(M_5)-\lambda_8 P(M_9)=0 \\ \lambda_8 P(M_6+M_9+M_{13})+\lambda_4 P(M_{12})-\lambda_{15}P(M_{10})=0 \\ \lambda_{13}P(M_7)-\lambda_{12}P(M_{11})=0 \\ \lambda_5 P(M_7)-\lambda_{14}P(M_{12})=0 \\ \lambda_{12}P(M_8+M_{11})-\lambda_8 P(M_{13})=0 \\ \sum_{i=0}^{14} P(M_i)=0 \end{cases} \tag{1}$$

Assuming that the occurrence times of transitions in the loading and unloading operation process model are random variables following an exponential distribution, represented by a constant parameter λ_i, which denotes the average number of occurrences per unit time when feasible. Based on field research, by timing the transition delays of the process steps, the average delay of each transition represented by each process step is obtained as t (min) = (t_1, t_2, …, t_{15}) = (20, 10, 15, 5, 30, 60, 30, 15, 60, 40, 20, 40, 60, 10, 20). The average implementation rate of each transition is given as λ(times/h) = (λ_1, λ_2, …, λ_{15}) = (3, 6, 4, 12, 2, 1, 2, 4, 1, 3/2, 3, 3/2, 1, 6, 3).

By using Matlab to solve the equation system depicted in Fig. 10, the steady-state probabilities of each reachable marking are obtained, as shown in Tab. 6.



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命令行窗口
>> syms x0 x1 x2 x3 x4 x5 x6 x7 x8 x9 x10 x11 x12 x13
eq1 = 3*x10-3*x0;
eq2 = 3*x0-7*x1;
eq3 = 6*x1-5*x2;
eq4 = x1-2*x3;
eq5 = 4*x2-15*x4;
eq6 = x2-3/2*x5;
eq7 = 2*x3-4*x6;
eq8 = 12*x4-3*x7;
eq9 = 3*x4-3/2*x8;
eq10 = 3/2*x5-4*x9;
eq11 = 4*x6+4*x9+4*x13+6*x12-3*x10;
eq12 = x7-3/2*x11;
eq13 = 2*x7-6*x12;
eq14 = 3/2*x8+3/2*x11-4*x13;
eq15 = 1-x0-x1-x2-x3-x4-x5-x6-x7-x8-x9-x10-x11-x12-x13;
[s1,s2,s3,s4,s5,s6,s7,s8,s9,s10,s11,s12,s13,s14] = solve(eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8,eq9,eq10,eq11,eq12,eq13,eq14,eq15,x0,x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13)
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Figure 10 Matlab numerical operations

Table 6 Reachable marking stability probability

Reachable marking	Stability probability	Reachable marking	Stability probability
M_0	0.182339	M_7	0.100026
M_1	0.078145	M_8	0.050013
M_2	0.093774	M_9	0.023444
M_3	0.039073	M_{10}	0.182339
M_4	0.025007	M_{11}	0.066684
M_5	0.062516	M_{12}	0.033342
M_6	0.019536	M_{13}	0.043761

4.5 Risk Assessment

As shown in Fig. 11 and Fig. 12, when the change rates λ_6 and λ_9 gradually increase from 1 to 10, assuming that the number of dangerous events per unit time increases, it can be observed that the probabilities of their common influence $P(M_0)$, $P(M_3)$, $P(M_6)$, $P(M_{10})$ gradually increase. This indicates that an increased fault rate of the oil pump, resulting from aging or equipment quality issues, as well as damage to the oil transfer arm caused by improper operation of personnel can lead to the oil pump's fault and subsequent shutdown. Additionally, improper operation by personnel can also increase the probabilities of $P(M_1)$, $P(M_5)$, $P(M_9)$, implying a higher likelihood of equipment damage leading to oil leakage accidents.

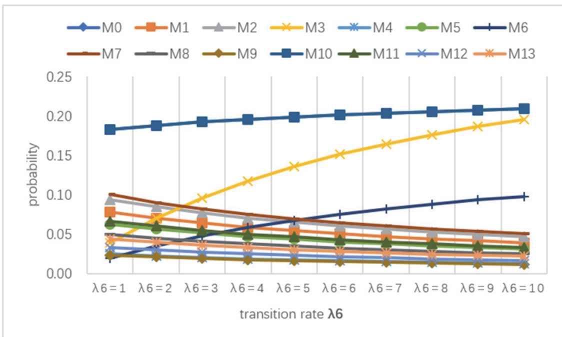

Figure 11 The probability of state stability with the change of λ_6

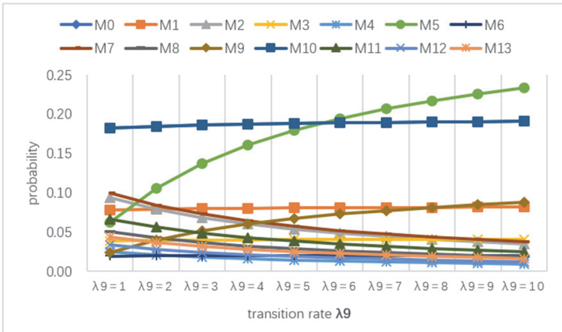

Figure 12 The probability of state stability with the change of λ_9

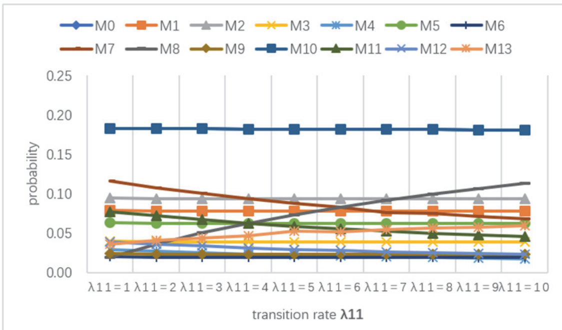

Figure 13 The probability of state stability with the change of λ_{11}

As shown in Fig. 13 and Fig. 14, as the transition rates λ_{11} and λ_{13} gradually increase from 1 to 10, it can be observed that their common influence $P(M_{13})$ gradually increases. When personnel improperly follow incorrect instructions leading to the valve not being closed and further engage in illegal operations, the probability of oil leakage accidents will be elevated.

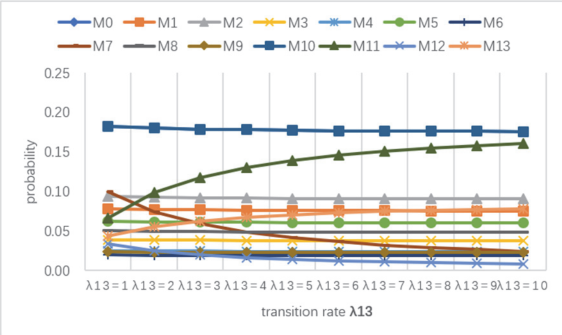

Figure 14 The probability of state stability with the change of λ_{13}

From Tab. 5, we can know that the reachable marking of the system in different states the place it contains. Based on Tab. 1, we can determine the consequences of the events contained in each place in the model, as shown in Tab. 7.

Table 7 Consequences of the place

Place	Score	Place	Score
P_1	1	P_9	5
P_2	1	P_{10}	3
P_3	1	P_{11}	10
P_4	1	P_{12}	7
P_5	1	P_{13}	1
P_6	3	P_{14}	7
P_7	1	P_{15}	1
P_8	1		

According to the calculation of Eq. (2), it can be concluded that the overall risk value of the system changes in response to different transitions and the rates at which these transitions are implemented, as shown in Fig. 15. The figure indicates that the overall risk of the system gradually increases under the influence of different transition rates of λ_{13} and λ_9. Specifically, as the transition rate of λ_{13} increases, the system risk value continues to rise significantly, surpassing the impact of other transitions on the system's risk, indicating that the transition T_{13} has the greatest impact on the system, followed by λ_9. As for the influence of λ_6 and λ_{11} at different transition rates, the overall risk of the system fluctuates. When the implementation rate of a transition increases, fluctuations occur due to the higher probability of low-risk events compared to high-risk events.

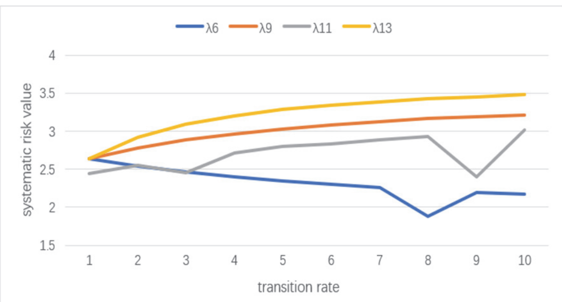

Figure 15 System risk values at different rates of change

Through case analysis, we have found that in the refined oil loading and unloading process of Company A, the descending order of the system risk peaks is λ_{13}(3.478), λ_9(3.213), λ_{11}(3.015), and λ_6(2.170), corresponding to personnel illegal operations, improper personnel operation, personnel receiving incorrect instructions, and equipment quality issues, respectively. From this, it can be inferred that the most serious risk event in the system process is the pipeline rupture caused by personnel illegal operations in the oil pipeline section, and personnel illegal operations is the risk factor that has the greatest impact on the system risk. Compared with traditional expert subjective judgments, this paper systematically identifies the risk factors existing in the loading and unloading operations and conducts risk assessment of the overall process, which indirectly confirms that human factors are the main causes of hazardous chemical accidents. However, this study still has certain limitations. Loading and unloading is only a part of the business process. In future research, it is necessary to conduct a more comprehensive risk identification and assessment of the overall business process of a company.

5 CONCLUSION

This study highlights the importance of addressing human illegal operations as a significant cause of high-risk accidents in the refined oil loading and unloading process. We propose a novel risk evaluation method utilizing Stochastic Colored Petri nets (*SCPN*) to assess the impact of risk factors on system security. By integrating event tree and fault tree analysis, we qualitatively analyze the evolution of risk factors in the process and model them within the traditional loading and unloading process. The Markov analysis method is employed for performance analysis, effectively demonstrating the influence of the identified risk factors on the overall system risk. Through a case analysis, we successfully evaluate the safety risk of the system and provide a valuable reference for similar risk studies. The findings from the enterprise case study suggest that the company should focus on strengthening training programs, enhancing safety awareness among employees, and improving the training of professional talents. Additionally, incorporating measures to address employees' illegal operations within the assessment system can help clarify responsibilities and obligations for all parties involved. Overall, this research contributes to the field of risk assessment by providing a practical and effective approach for evaluating system safety in the refined oil industry.

In the future, we will focus on conducting comprehensive identification, quantification, and evaluation of risk factors in system processes. This will include studying various aspects such as ethical risk factors, psychological risk factors, and business risk factors.

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