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Risk assessment of hydrogen leakage in diesel hydrogenation process

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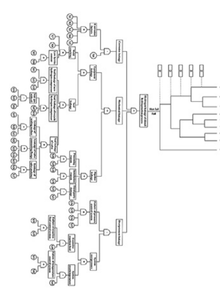
HIGHLIGHTS

- The DBN-based dynamic risk assessment system for hydrogen leakage in diesel hydrogenation process was developed.
- The dynamic variation of hydrogen leakage probability in diesel hydrogenation process was obtained.
- The most likely accident consequence scenarios were identified.
- The critical risk factors and safety barriers of hydrogen leakage in diesel hydrogenation process were obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrogen, the raw material of diesel hydrofining process, is flammable and explosive. Once the leaking hydrogen is exposed to ignition sources, it will cause huge losses to people's health and property safety. In this paper, a dynamic risk assessment method of hydrogen leakage based on Dynamic Bayesian Network is proposed to analyze the uncertainty and dynamics of hydrogen leakage risk in the diesel hydrogenation process and to make up for the shortage of dynamic risk assessment of diesel hydrogenation process nowadays. Through the case study of diesel hydrogenation process, the applicability and advantages of the proposed method are proved. The dynamic changes of hydrogen leakage probability, the critical risk factors and safety barriers of hydrogen leakage accident are obtained, and possible accident consequences in two years are identified. Meanwhile, the corresponding measures which provide theoretical guidance for the safety production of petrochemical enterprises are proposed to further reduce the risk of hydrogen leakage in the diesel hydrogenation process.

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Introduction

The demand and the quality requirements for diesel oil have been increasing due to the low energy consumption, high thermal efficiency and high cost performance. Sulfur, oxygen, nitrogen and other impurities in diesel oil may seriously affect the stability and combustion performance of oil products. As a result, it is necessary to hydrofining diesel oil.

Hydrogen, the raw material of diesel hydrofining, is flammable and explosive. Once it explodes, it may cause great damage to people's health and property safety. In March 1987, an explosion occurred in the hydrogenation unit of the Grangemouth Refinery in England, resulting in one death and economic losses of 78.5 million U.S. dollars. In February 2017, a major explosion occurred in the hydrogenation unit of Jiangnan project in Jilin Songyuan Petrochemical Co., Ltd., resulting in three deaths and economic losses of 9.2 hundred thousand U.S. dollars. In March 2018, an explosion accident occurred in the raw material buffer tank of the diesel hydrogenation unit of Jiangxi Jiujiang No.1 Petrochemical Enterprise, resulting in two deaths and economic losses of 9.1 hundred thousand U.S. dollars. Many recent studies have addressed hydrogen safety issues from various aspects. Jafari [1] et al. discussed the risk of hydrogen generator using natural gas reforming process to nearby residents through quantitative analysis. Al-shanini [2] et al. used the accident modeling method to evaluate the overall safety of hydrogen station from the aspects of human factors, management and organization factors. Michael [3] et al. simplified the hydrogen risk assessment method (HRAM) by appropriately reducing the computational fluid dynamics (CFD) modeling to determine the potential safety impact of hydrogen release. The above references only focused on the modeling of accident consequences or the hazard identification of hydrogen system, however, the leakage risk of hydrogen system was not involved.

There are some researches regarding the hydrogen system leakage. By establishing the hydrogen leakage model of high-pressure hydrogen storage vessel, Jin [4] et al. proposed a k-ε model which can be realized in CFD. Mao [5] et al. established the leakage model of hydrogen fuel cell ship, and obtained the hydrogen leakage amount and concentration distribution. Malakhov [6] et al. used CFD method to analyze the hydrogen leakage in semi-enclosed ventilation facilities. Although these researches focused on hydrogen system leakage, the risk assessment methods used in these researches were not dynamic.

Risk is the product of the accident probability and the accident consequences. In fact, the accident risk of chemical industrial systems is not constant over time, because the operating equipment of an industrial system may be affected by system environment and operating conditions, etc. Therefore, in modern industrial systems such as diesel hydrogenation system, the dimension of time should be integrated into the original meaning of risk, that is, the risk of accidents should be considered as dynamic risk changing accordingly over time [7]. For a more accurate estimation of the dynamic risk of equipment failure and accident occurrence, many scholars have done a lot of work on the dynamic risk assessment method. In particular, Bayesian Networks (BN) and Dynamic Bayesian Networks (DBN) have been widely used in probabilistic reasoning under uncertainty in risk analysis field. Xin and Khan [8] et al. developed a new method for mapping hazard scenarios into BN to enable real-time hazard source identification and determine the most likely accident scenarios. Mohammed and Khan [9] et al. combined DBN with Stochastic Petri Network and estimated accident probability by continuously updating prior probabilities and conditional probabilities. Ehsan [10] et al. used DBN to predict the corrosion fatigue life of subsea pipelines and simulate crack extensions that could lead to accidents. Zaman and Khan [11] et al. combined ecological risk assessment and DBN to assess the extent of damage to the Arctic from 42 risk factors due to oil spills. Bushra [12] et al. used a DBN model to identify 12 risk factors for ship travel in the Arctic and assessed the risk of ship-ice collision. A multi-hazard risk assessment model for agricultural water supply systems was developed by Atiyeh [13] et al. using BN to assess the risk hazard of factors such as river flow. Khakzad [14] proposed a DBN-based method to simulate the spatiotemporal evolution model of domino effect for chemical infrastructure. DBN can combine the advantages of Fault Tree and Event Tree to analyze the causal logic of accidents, so as to calculate the dynamic risk of accidents and point out the key inducements of accidents.

The researches on leakage of diesel hydrogenation process from risk viewpoint could hardly be found in literatures. The purpose of this study is to propose a DBN-based method for dynamic risk analysis of hydrogen leakage in diesel hydrogenation process. In this method, the DBN model is used to evaluate the dynamic leakage risk of diesel hydrogenation process and the consequences of different leakage accidents caused by safety barriers failure, and identify the critical influencing factors of leakage faults through DBN diagnostic reasoning. In addition, some positive mitigation suggestions are put forward to reduce the risk of hydrogen leakage in diesel hydrogenation process, which can provide scientific guidance for the safety production of petrochemical enterprises.

Brief introduction of diesel hydrogenation process

Coker diesel oil and catalytic diesel oil are products obtained after secondary processing. They contain a lot of elements S, N, O and alkenes, which seriously affect the storage stability and combustion performance of oil products. As a result, it is necessary to remove S, N, O compounds and unstable substances (such as olefins and some aromatics) by hydrotreating the secondary processing oil to obtain high-quality products with good stability and quality.

The flow chart of diesel hydrogenation process studied in this paper is shown in Fig. 1. Under the conditions of appropriate temperature, pressure, ratio of hydrogen to oil, catalyst and space velocity, the feed oil reacts with hydrogen to make the impurities in the oil, i.e. sulfur, nitrogen and oxide be converted into H_2S, NH_3 and H_2O to be easily removed, and the metal impurities are trapped in the catalyst. In addition, some

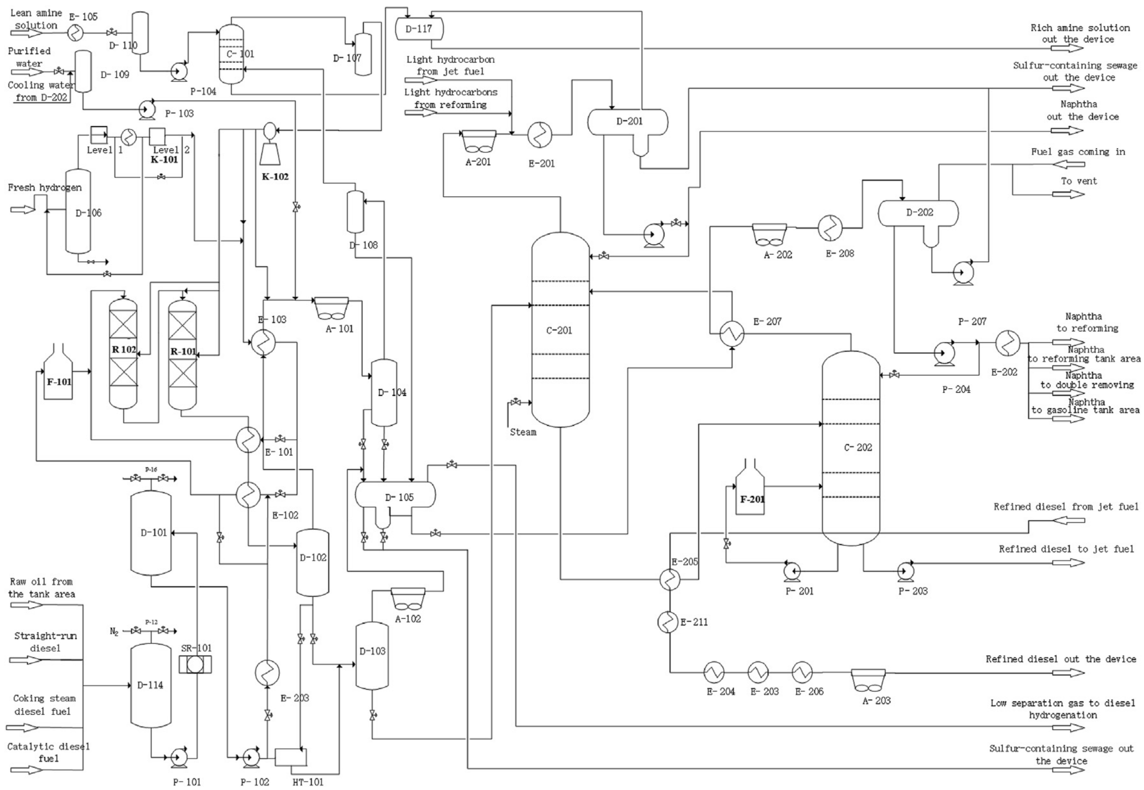

Fig. 1 – Flow-process diagram of diesel hydrogenation.

unsaturated hydrocarbon is hydrogenated and saturated, improving the stability and combustion performance of the oil [15].

In the diesel hydrogenation process, hydrogen and feed oil are mixed and reacted in hydrofining reactors R-101 and R-102. In addition to being used as reaction raw material, hydrogen also flows between heat exchangers as a heat exchange medium through pipes and valves. As a result, hydrogen leakage in the diesel hydrogenation process mainly occurs in reactors, heat exchangers, pipelines and valves, which may be caused by weld cracking, corrosion damage and aging failure of components.

Method and material

In this paper, the Dynamic Bayesian Networks (DBN) is used to finish hydrogen leakage risk assessment of diesel hydrorefining process. First, the topological structure of DBN is determined by hazard source identification and Bow-Tie modeling. Second, the prior probabilities are calculated by using Analytic Hierarchy Process (AHP) and fuzzy set theory, and the transition probabilities and conditional probabilities are determined according to equipment state degradation theory and logic gate theory to complete the parameter learning of DBN. Finally, the probability updating and diagnostic reasoning functions of DBN are used to evaluate the hydrogen leakage accident possibility and accident consequences of diesel hydrorefining process and to obtain critical risk factors.

Dynamic Bayesian Network

Bayesian Network (BN) is an uncertain probabilistic reasoning model based on graph theory and probability theory [16]. BN is independent of time, as a result, it is difficult for BN to analyze dynamic characteristics of the system very well. It is necessary to introduce the Markov model to BN for the sake of making the model dynamic. Markov model is a theoretical model to describe the possible states of a system and their mutual transfer. By determining the initial state probability distribution and transition probability matrix of the system, a

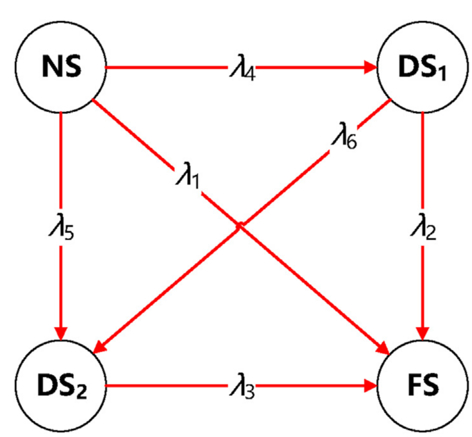

Fig. 2 – Multi-state degradation process of system components.

Table 1 – Transition probability of dynamic nodes between two continuous time slices [18].

$t+\tau$	t	NS	DS1	DS2	FS
NS		$e^{-(\lambda_1+\lambda_4+\lambda_5)\tau}$	0	0	0
DS1		$\frac{\lambda_4}{\lambda_1+\lambda_4+\lambda_5}\left(1-e^{-(\lambda_1+\lambda_4+\lambda_5)\tau}\right)$	$e^{-(\lambda_2+\lambda_6)\tau}$	0	0
DS2		$\frac{\lambda_5}{\lambda_1+\lambda_4+\lambda_5}\left(1-e^{-(\lambda_1+\lambda_4+\lambda_5)\tau}\right)$	$\frac{\lambda_6}{\lambda_2+\lambda_6}\left(1-e^{-(\lambda_2+\lambda_6)\tau}\right)$	$e^{-\lambda_3\tau}$	0
FS		$\frac{\lambda_1}{\lambda_1+\lambda_4+\lambda_5}\left(1-e^{-(\lambda_1+\lambda_4+\lambda_5)\tau}\right)$	$\frac{\lambda_2}{\lambda_2+\lambda_6}\left(1-e^{-(\lambda_2+\lambda_6)\tau}\right)$	$1-e^{-\lambda_3\tau}$	1

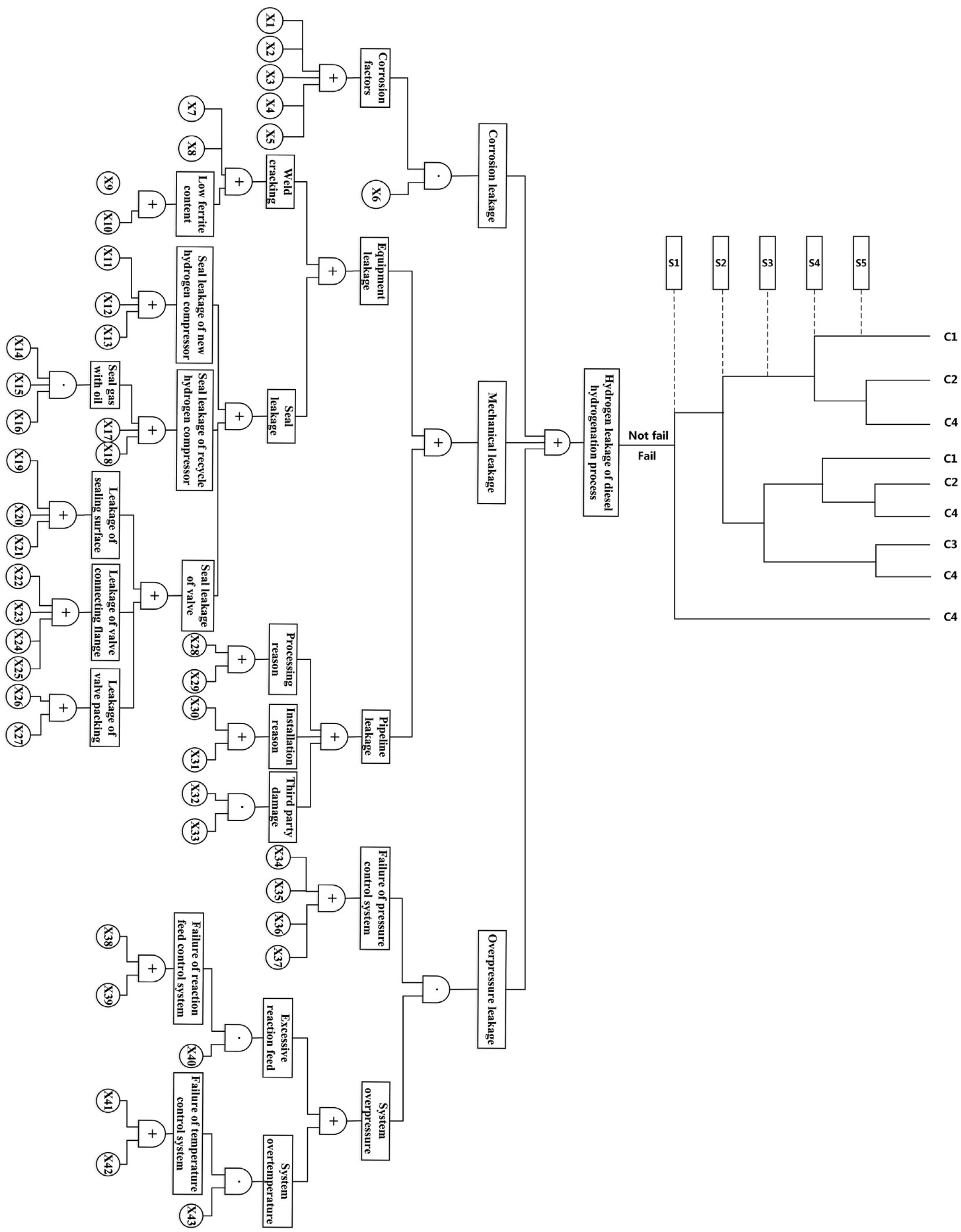

Fig. 3 – Bow-Tie model of hydrogen leakage in diesel hydrogenation process.

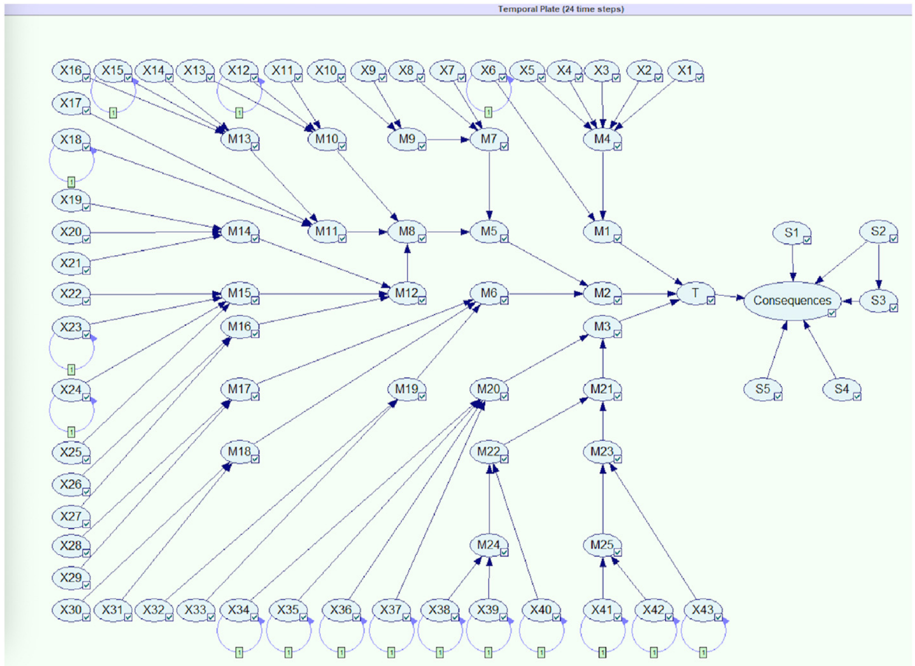

Fig. 4 — Dynamic Bayesian Network model of hydrogen leakage in diesel hydrogenation process.

Table 2 — Prior probability table for basic events of static nodes.

Basic events	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Prior probability
X1 Hydrogen corrosion	L	L	L	L	L	4.80×10^{-4}
X2 Hydrogen embrittlement	L	L	L	M	M	1.80×10^{-3}
X3 Sulfide corrosion	H	M	H	H	VH	2.56×10^{-2}
X4 Sludge corrosion	L	M	L	M	L	1.50×10^{-3}
X5 Ammonium salt corrosion	M	L	M	H	VH	1.12×10^{-2}
X7 Damage of surfacing layer by spatter of welding slag	L	L	VL	L	L	3.39×10^{-4}
X8 Hydrogen induced cracks appeared in surfacing layer	L	L	VL	L	VL	1.38×10^{-4}
X9 Slow cooling rate of welding	L	L	VL	L	L	3.39×10^{-4}
X10 Excessive welding line energy	L	L	VL	L	L	3.39×10^{-4}
X11 Insufficient finish of cylinder sealing surface	L	L	L	L	VL	2.32×10^{-4}
X13 Unreasonable packing box structure	VL	L	L	L	VL	1.44×10^{-4}
X14 Excessive heavy components in seal gas	M	M	M	M	M	5.00×10^{-3}
X16 Oil not discharged in time after condensation	M	M	M	M	H	8.00×10^{-3}
X17 Air leakage at impeller side	L	L	L	L	L	4.80×10^{-4}
X19 Improper transportation and storage of valves	M	M	M	M	VL	2.10×10^{-3}
X20 Valve's uneven wear during use	M	M	M	M	H	8.00×10^{-3}
X21 Impurities cause scratches on the sealing surface	M	M	M	M	VL	2.10×10^{-3}
X22 The symmetry of flange is poor in installation	L	M	M	L	M	2.60×10^{-3}
X25 Uneven bolt pretightening force	M	M	M	L	M	3.60×10^{-3}
X26 Aging of valves filler	M	M	M	M	VH	1.04×10^{-2}
X27 The pretightening force of bolt is too small	M	L	L	L	L	7.22×10^{-4}
X28 The machining accuracy of pipe joint is too low	L	L	L	L	L	4.80×10^{-4}
X29 The surface finish of pipe joint does not meet the requirements	L	L	L	L	L	4.80×10^{-4}
X30 Poor expansion welding technology	L	L	VL	L	L	3.39×10^{-4}
X31 Workers did not follow the installation process	M	L	M	L	M	2.30×10^{-3}
X32 Accidental collision of pipeline	L	L	L	L	VL	2.32×10^{-4}
X33 Pipeline safety protection measures are not in place	L	L	L	L	VL	2.32×10^{-4}

Markov Chain model is constructed to predict the state probability of the system at a certain time in the future.

DBN model can be obtained by introducing a Markov model to BN. DBN model contains a series of time points, namely a series of time slices, and each time slice contains a BN of initial time. A typical DBN model with two time slices is composed of the time slice *t* which represents the current moment and time slice *t*+1 which represents the next moment [17]. In the same time slice, the dependence between variables is called conditional probability. In different time

Table 3 – The modified conditional probability table of AND logic gate node.

Node A		Yes		No	
Node B		Yes	No	Yes	No
Node C	Yes	0.96	0.02	0.02	0
	No	0.04	0.98	0.98	1

Table 4 – The conditional probability table of noisy OR logic gate node.

A				B				C	
NS	DS_1	DS_2	FS	NS	DS_1	DS_2	FS	No	Yes
Yes	No	No	No	Yes	No	No	No	1.00	0.00
Yes	No	No	No	No	Yes	No	No	0.64	0.36
Yes	No	No	No	No	No	Yes	No	0.34	0.66
Yes	No	No	No	No	No	No	Yes	0.26	0.74
No	Yes	No	No	Yes	No	No	No	0.64	0.36
No	Yes	No	No	No	Yes	No	No	0.44	0.56
No	Yes	No	No	No	No	Yes	No	0.30	0.70
No	Yes	No	No	No	No	No	Yes	0.16	0.84
No	No	Yes	No	Yes	No	No	No	0.34	0.66
No	No	Yes	No	No	Yes	No	No	0.30	0.70
No	No	Yes	No	No	No	Yes	No	0.20	0.80
No	No	Yes	No	No	No	No	Yes	0.10	0.90
No	No	No	Yes	Yes	No	No	No	0.26	0.74
No	No	No	Yes	No	Yes	No	No	0.16	0.84
No	No	No	Yes	No	No	Yes	No	0.10	0.90
No	No	No	Yes	No	No	No	Yes	0.00	1.00

slices, the time probability dependence of the same variable at different times is called the transition probability, which can be obtained by Markov model.

In this paper, the following two assumptions are adopted to simplify the modeling of DBN:

(1) Stationary assumption: the topology of DBN always remains constant, and the conditional probabilities between parent and child nodes also remain constant.
(2) Markov assumption: the system variable state at the next moment $t+1$ is only affected by the state at moment t, and is independent of that at the previous moments t-1, t-2, …, 1. That is, the variable state of DBN has memorylessness and relative independence.

Determination of transition probability table

The multi-state degradation process of system components is shown in Fig. 2. Each dynamic node contains four states, namely normal state (NS), first degradation state (DS1), second degradation state (DS2) and failure state (FS). NS indicates that the structure and function of the system components are complete and can work normally. DS1 and DS2 indicate that the system components are damaged to different degrees (the damage degree of DS2 is higher than that of DS1), but they can still work. FS indicates that the system components have been completely damaged and cannot continue to work. At the

Table 5 – Transition probability between two continuous time slices of dynamic nodes X6.

$t+\tau$ / t	NS	DS1	DS2	FS
NS	0.9918	0	0	0
DS1	0.0025	0.9926	0	0
DS2	0.0049	0.0025	0.9975	0
FS	8.1744×10^{-4}	0.0049	0.0025	1

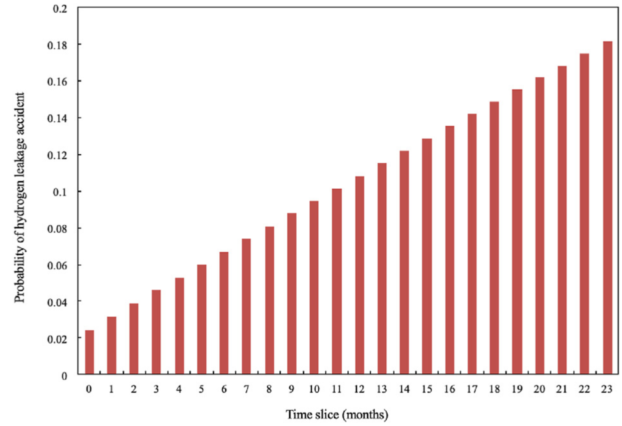

Fig. 5 – Occurrence probability of hydrogen leakage accident in diesel hydrogenation process.

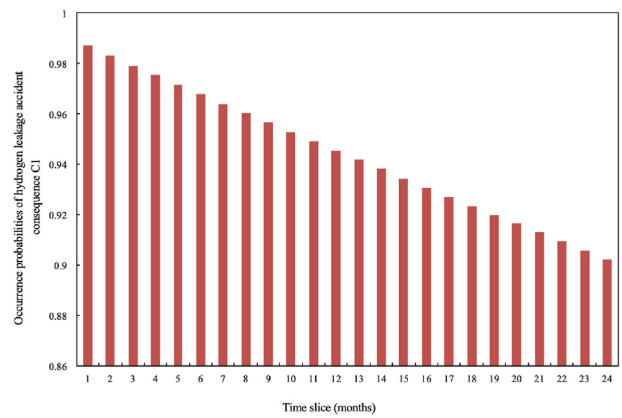

Fig. 6 – Occurrence probability of accident consequence C1.

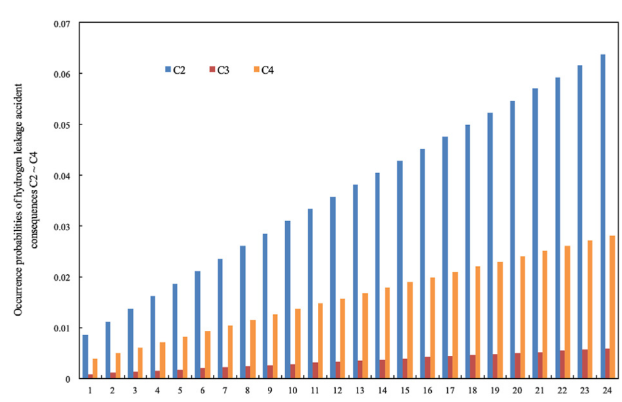

Fig. 7 – Occurrence probabilities of accident consequences C2 ~ C4.

initial time, the system components are in NS state. As time goes on, the system components gradually degenerate to DS1 and DS2 states, according to the Markov model, and finally completely fail.

In the multi-state degradation process of system components, the failure rate (λ) is assumed to be a fixed constant [18], and the failure rates (λ_1~λ_6) between two states are shown in Fig. 2 and satisfy the following equations:

$$\begin{aligned} &\lambda_2 = \lambda_5 \\ &\lambda_3 = \lambda_4 = \lambda_6 \\ &\lambda_1 + \lambda_4 + \lambda_5 = \lambda \\ &\lambda_1 : \lambda_4 : \lambda_5 = 1:3:6 \end{aligned} \tag{1}$$

The transition probabilities of system components between two continuous time slices (t and $t+\tau$) are shown in Table 1, where τ is the time interval between two continuous time slices.

Dynamic risk assessment of hydrogen leakage in diesel hydrogenation process

Risk identification and Bow-Tie modeling

In the diesel hydrogenation process, due to the operation condition of high temperature and pressure and the presence of elements H, O, S and N, hydrogen corrosion, hydrogen embrittlement, sulfide corrosion, sludge scale corrosion and ammonium salt corrosion may cause damage to the reactors, heat exchanger tube bundles, pipelines and other equipment

Table 6 – Prior probabilities, posterior probabilities of basic events and their absolute differences and relative differences.

Basic events	Prior probability	Posterior probability	Absolute difference	Relative difference
X1 Hydrogen corrosion	4.80×10^{-4}	7.08×10^{-4}	2.28×10^{-4}	0.47
X2 Hydrogen embrittlement	1.80×10^{-3}	2.65×10^{-3}	8.54×10^{-4}	0.47
X3 Sulfide corrosion	2.56×10^{-2}	3.77×10^{-2}	1.21×10^{-2}	0.47
X4 Sludge corrosion	1.50×10^{-3}	2.21×10^{-3}	7.12×10^{-4}	0.47
X5 Ammonium salt corrosion	1.12×10^{-2}	1.65×10^{-2}	5.31×10^{-3}	0.47
X6 Failure of corrosion protection layer	2.25×10^{-2}	2.92×10^{-2}	6.68×10^{-3}	0.30
X7 Damage of surfacing layer by spatter of welding slag	3.39×10^{-4}	1.44×10^{-3}	1.10×10^{-3}	3.24
X8 Hydrogen induced disbonding cracks appeared in surfacing layer	1.38×10^{-4}	5.87×10^{-4}	4.49×10^{-4}	3.24
X9 Slow cooling rate of welding	3.39×10^{-4}	1.37×10^{-3}	1.03×10^{-3}	3.04
X10 Excessive welding line energy	3.39×10^{-4}	1.37×10^{-3}	1.03×10^{-3}	3.04
X11 Insufficient finish of cylinder sealing surface	2.32×10^{-4}	9.06×10^{-4}	6.74×10^{-4}	2.90
X12 Collapse failure of O-ring	1.00×10^{-2}	3.91×10^{-2}	2.91×10^{-2}	2.90
X13 Unreasonable packing box structure	1.44×10^{-4}	5.60×10^{-4}	4.17×10^{-4}	2.90
X14 Excessive heavy components in seal gas	5.00×10^{-3}	8.06×10^{-3}	3.06×10^{-3}	0.61
X15 Failure of liquid separation system	5.91×10^{-2}	6.16×10^{-2}	2.50×10^{-3}	0.04
X16 Oil not discharged in time after condensation	8.00×10^{-3}	8.47×10^{-3}	4.70×10^{-4}	0.06
X17 Air leakage at impeller side	4.80×10^{-4}	1.87×10^{-3}	1.39×10^{-3}	2.90
X18 Failure of auxiliary sealing ring of stationary ring	6.45×10^{-3}	2.52×10^{-2}	1.87×10^{-2}	2.90
X19 Improper transportation and storage of valves	2.10×10^{-3}	7.69×10^{-3}	5.59×10^{-3}	2.66
X20 Valve's uneven wear during use	8.00×10^{-3}	2.93×10^{-2}	2.13×10^{-2}	2.66
X21 Impurities cause scratches on the sealing surface	2.10×10^{-3}	7.69×10^{-3}	5.59×10^{-3}	2.66
X22 The symmetry of flange is poor in installation	2.60×10^{-3}	9.20×10^{-3}	6.60×10^{-3}	2.54
X23 Loose fastening bolts	3.65×10^{-3}	1.29×10^{-2}	9.26×10^{-3}	2.54
X24 Failure of flange gasket	3.65×10^{-3}	1.29×10^{-2}	9.26×10^{-3}	2.54
X25 Uneven bolt pretightening force	3.60×10^{-3}	1.27×10^{-2}	9.14×10^{-3}	2.54
X26 Aging of filler	1.04×10^{-2}	3.87×10^{-2}	2.83×10^{-2}	2.72
X27 The pretightening force of bolt is too small	7.22×10^{-4}	2.69×10^{-3}	1.96×10^{-3}	2.72
X28 The machining accuracy of pipe joint is too low	4.80×10^{-4}	2.06×10^{-3}	1.58×10^{-3}	3.28
X29 The surface finish of pipe joint does not meet the requirements	4.80×10^{-4}	2.06×10^{-3}	1.58×10^{-3}	3.28
X30 Poor expansion welding technology	3.39×10^{-4}	1.45×10^{-3}	1.11×10^{-3}	3.28
X31 Workers did not follow the installation process	2.30×10^{-3}	9.85×10^{-3}	7.55×10^{-3}	3.28
X32 Accidental collision of pipeline	2.32×10^{-4}	2.49×10^{-4}	1.64×10^{-5}	0.07
X33 Pipeline safety protection measures not in place	2.32×10^{-4}	2.49×10^{-4}	1.64×10^{-5}	0.07
X34 Failure of emergency relief interlock switch	7.78×10^{-3}	9.25×10^{-3}	1.46×10^{-3}	0.19
X35 Failure of emergency relief valve	2.25×10^{-2}	2.67×10^{-2}	4.22×10^{-3}	0.19
X36 Failure of pressure sensor	6.68×10^{-3}	7.94×10^{-3}	1.26×10^{-3}	0.19
X37 Failure of overpressure alarm	1.00×10^{-2}	1.19×10^{-2}	1.89×10^{-3}	0.19
X38 Failure of feed flow control valve	6.05×10^{-2}	6.28×10^{-2}	2.32×10^{-3}	0.04
X39 Failure of reaction feed pump	1.97×10^{-2}	2.05×10^{-2}	7.99×10^{-4}	0.04
X40 Failure of flow indicator	1.02×10^{-2}	1.28×10^{-2}	2.50×10^{-3}	0.24
X41 Failure of cold hydrogen temperature control valve	6.05×10^{-2}	6.26×10^{-2}	2.06×10^{-3}	0.03
X42 Failure of fuel flow control valve	6.05×10^{-2}	6.26×10^{-2}	2.06×10^{-3}	0.03
X43 Failure of temperature indicator	1.02×10^{-2}	1.35×10^{-2}	3.25×10^{-3}	0.32

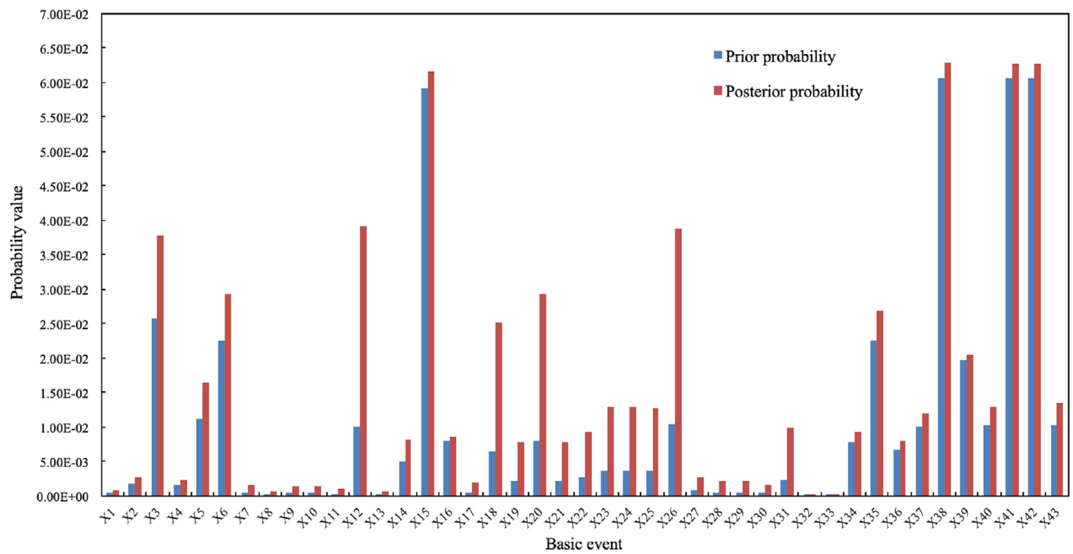

Fig. 8 – Prior probability and posterior probability of each basic event.

materials, which makes the equipment easy to crack and leads to hydrogen leakage accidents. As time goes by, many components such as screws, sealing rings and sealing fillers may gradually age, and the sealing surfaces of valves and equipment will gradually be worn, resulting in the leakage of hydrogen medium [19–21].

Excessive reaction feed and system overtemperature may lead to system pressure rising, if the pressure control system also fails at the same time, it may cause the system overpressure leakage. The pressure control system mainly includes pressure sensors, overpressure alarm, emergency relief interlock switch and emergency relief valve.

Through the work of hazard identification, a total of 43 basic events are identified. In addition, 5 safety barriers are identified to prevent hydrogen leakage of diesel hydrogenation process from further evolving into serious consequences, including leakage detection alarm (S1), emergency shutdown (S2), manual shutdown (S3), repair and plugging (S4) and ignition prevention (S5). Possible consequences of safety barriers failure include near miss (C1), small-scale vapor cloud and oil spill (C2), large-scale vapor cloud and oil spill (C3) and fire and explosion (C4).

The Bow-Tie (BT) model of hydrogen leakage in the diesel hydrogenation process is established as shown in Fig. 3.

Dynamic Bayesian Network modeling

Based on the BT model of hydrogen leakage accident in the diesel hydrogenation process, the DBN model is mapped as shown in Fig. 4 by using GeNIe software. In the mapping process, the parent, intermediate and child nodes in the DBN model are mapped by the basic, intermediate and top events in the BT model, and the safety and consequence nodes are mapped by the safety barriers and consequences in the BT model. Moreover, the prior probabilities of the parent nodes in the DBN model are the same as the occurrence probabilities of the basic events in the BT model, and the failure probability setting mode of the safety barrier nodes is the same. In addition, the correlation between nodes can be demonstrated by assigning conditional probability tables to intermediate, child, safety barrier and consequence nodes.

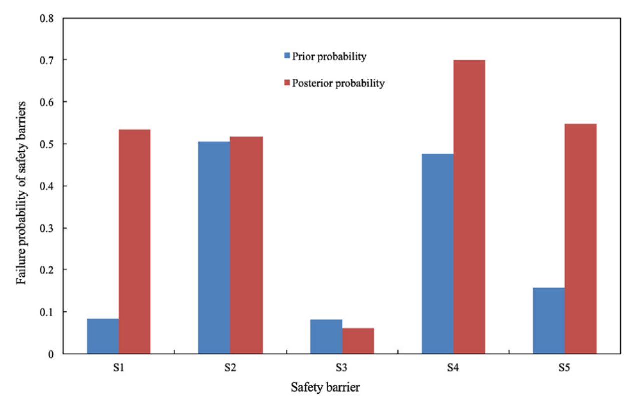

Fig. 9 – Prior probabilities and posterior probabilities of safety barriers failure.

Table 7 – Prior probabilities and posterior probabilities of safety barriers.

Safety barrier	Prior probability	Posterior probability	Absolute difference	Relative difference
S1 Leak detection alarm	0.083	0.535	0.452	5.446
S2 Emergency shutdown	0.506	0.516	0.01	0.020
S3 Manual shutdown	0.082	0.061	−0.021	−0.256
S4 Repair and plug	0.476	0.699	0.223	0.468
S5 Ignition prevention	0.158	0.549	0.391	2.475

In order to complete the DBN modeling, the following parameters are calculated: prior probability, conditional probability and transition probability. The prior probability and transition probability are parameters for static nodes and dynamic nodes respectively.

The prior probability is calculated by combining expert scoring with fuzzy set theory. The weight of expert opinions is calculated first by AHP method [22], and the expert scoring shown in Table 2 is used to calculate the prior probability by fuzzy set method [23]. In order to improve the accuracy of the evaluation results as much as possible, the opinions of 5 senior experts who have worked in diesel hydrogenation enterprises for about 10 years are adopted in this paper. The prior probabilities of all static nodes are listed in Table 2.

The modified "AND" gate, "OR" gate [24], noisy "AND" gate model and noisy "OR" gate model [18] are used to specify the conditional probability relationship of static and dynamic nodes. To save unnecessary repetition, this paper only lists the probability relationships of modified "AND" gate and noisy "OR" gate in Table 3 and Table 4, respectively.

According to the transition probability formula in Table 1, the transition probability table of dynamic nodes are calculated, and the event X6 is listed as an example in Table 5.

Case study

Risk predictive analysis

Based on the probability update function of DBN, the probability diagram of hydrogen leakage accident and accident consequences in two years are shown in Figs. 5–7.

The probability of hydrogen leakage accident in diesel hydrogenation process at the initial time is estimated to be 2.43×10^{-2}, and the probabilities of accident consequences are: $C1 = 9.87 \times 10^{-1}$, $C2 = 8.55 \times 10^{-3}$, $C3 = 7.78 \times 10^{-4}$, and $C4 = 3.76 \times 10^{-3}$. In the 24th month, the probability of hydrogen leakage in diesel hydrogenation process is estimated to be 1.81×10^{-1}, and the probabilities of accident consequences are calculated to be $C1 = 9.02 \times 10^{-1}$, $C2 = 6.39 \times 10^{-2}$, $C3 = 5.81 \times 10^{-3}$, $C4 = 2.81 \times 10^{-2}$.

As shown in Figs. 5–7, the occurrence probability of hydrogen leakage accident and that of accident consequences C2 ~ C4 increase linearly with time, and the occurrence probability of accident consequence C1 (i.e. no serious consequence) decreases linearly with time.

Diagnostic reasoning

By introducing the evidence, the top event is set to occur in the 24th month to calculate the posterior probabilities of basic events. After the posterior probability obtained, it is compared with the prior probability to determine the critical inducement events that may cause the largest contribution to hydrogen leakage in diesel hydrogenation process. The prior probability and posterior probability of each basic event are shown in Table 6 and Fig. 8.

The relative difference (ROV) is used as the basis for judging critical basic events [25], and its calculation formula is shown in equation (2). The relative differences of basic events are shown in Table 6.

$$\mathrm{RoV}(Xi) = \frac{\pi(Xi) - \theta(Xi)}{\theta(Xi)} \tag{2}$$

where, $\pi(Xi)$ and $\theta(Xi)$ are the posterior probability and the prior probability of the basic event Xi respectively.

X12, X18, X20 and X26 are selected as the critical basic events which may contribute the most to the hydrogen leakage accident in diesel hydrogenation process. The four critical events identified are all the causes of seal leakage. Enterprises should focus on protecting the O-ring between the cup grooves of the new hydrogen compressor and the auxiliary static seal ring of the circulating hydrogen compressor from failure, preventing the uneven wear and aging of the valve packing when the valve is in use, and regularly maintaining the hydrogen compressors and the valves to timely find out the failure of the parts and repair them to reduce the probability of seal leakage.

The identification process of critical safety barriers is the same as that of critical basic events. The prior probabilities, posteriori probabilities and relative differences between them of five safety barriers failure are shown in Table 7 and Fig. 9.

The safety barriers with large posteriori probability and relative difference of failure, i.e. S1 and S5, are selected as the critical safety barriers which may contribute the most to fire and explosion (C4). Enterprises should pay attention to the safety barriers of leakage detection alarm and ignition prevention, and regularly maintain and monitor them, so as to ensure that the staff can find out the hydrogen leakage accident in time and prevent the occurrence of ignition source, then reduce the severity of the consequences of hydrogen leakage accident in diesel hydrogenation process as far as possible.

Conclusions

DBN is a tool that can effectively reflect the causality and the dynamics of hazard factors over time, and is thereby widely used in risk assessment work. Many fundamental works on dynamic risk assessment methods have been carried out by groups such as Center for Risk, Integrity and Safety Engineering (C-RISE). In the works of these groups, DBN has been applied to various aspects such as agriculture, chemical industry and ships. The groups also aim to combine DBN with other assessment methods such as ecological hazard assessment methods to explore the potential of DBN for risk assessment. In this paper, based on the previous works, the application of DBN to the diesel hydrorefining process is developed to assess the potential and dynamic risks.

In this paper, a DBN model for dynamic leakage risk assessment of diesel hydrogenation process is established through the mapping of BT model. The DBN model is established by identifying risk factors and analyzing relevant safety standards. Based on the developed DBN model, a new risk analysis method is proposed to predict the dynamic risk of hydrogen leakage in diesel hydrofining process.

Based on the diagnostic inference of DBN, the basic events X12, X18, X20 and X26 are determined to be the main influencing factors for possible leakage accidents in diesel hydrogenation process, and S1 and S5 are determined to be the critical safety barriers to prevent accidents from further evolving into more serious consequences. In addition, the reliability parameters of critical events such as failure rate and repair rate should be paid more attention, and corresponding safety control measures should also be put forward to further reduce the leakage risk in the process of diesel hydrofining.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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