Dynamic risk assessment of oil and gas leakage in heating furnace: A DBT-DBN approach

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Abstract. The heating furnace has dynamic fluctuations of hazard factors in the actual circumstance and is the core equipment of hydrocracking unit, which is the main equipment of petrochemical enterprises. Owing to the limitation of conventional risk analysis approaches, a dynamic risk analysis approach based on dynamic Bow-tie model (short for DBT) and dynamic Bayesian network (short for DBN) was proposed. Taking the failure accident of oil and gas leakage of heating furnace as a case study, the timing sequence of equipment failure of heating furnace is analyzed first, the risk evolution process is obtained, and the dynamic tie model of accident is established. By mapping the dynamic tie model to the dynamic Bayesian network, the risk factors of oil and gas leakage in heating furnace are deduced in two-way reasoning. The dynamic risk trend of heating furnace was predicted eventually, the probability of oil and gas leakage caused by heating furnace is about 1.26E-07 after two year. Through diagnostic reasoning, 6 key factors and 3 accident paths were determined. The results are in accordance with the actual situation, proving that DBT-DBN model can effectively reflect the dynamic characteristics of accident scenarios and provide reference for the risk assessment of petrochemical enterprises.

1. Introduction
Hydrocracking unit contains a large amount of dangerous production materials and the equipment and catalysts are expensive, which will cause serious consequences once an accident occurs. Due to the seriousness of the accident consequences, the relevant personnel often only pay attention to how to prevent major accidents, but ignore the prevention and control of abnormal events. Heinrich Rule pointed out that a large number of abnormal events may have occurred before a major accident [1]. The occurrence of major accidents can be effectively avoided by identifying and correcting these unsafe factors in time due to the high frequency of abnormal events.

The current risk analysis research on hydrocracking unit mainly combines different traditional risk analysis methods to identify hazard factors based on their respective advantages, but these methods consider risk variables in a static way, which is insufficient to represent the dynamic evolution of actual risks in the chemical process. With the expansion of the production scale of petrochemical enterprises, such as equipment aging, human error, seasonal change and other important factors to be considered in risk assessment, bayesian network has been gradually used to carry out dynamic risk assessment.
research of process system at home and abroad. Maria, et al. found it very important to record and analyze the abnormal events [2-3], and to establish an appropriate accident model with the functions of hazard identification, accident analysis and prevention. Wang Yanping, et al. [4] analyzed the fire accident of hydrogen heating furnace in hydrocracking unit from the perspectives of chemical composition, metallographic structure and tensile test. Zarei, et al. [5] employed a Bow-tie diagram and Bayesian network to model the worst-case accident scenario and to assess the risks. Jin Zhe, et al. [6-7] analyzed the lock logic relationship in the production process of hydrocracking unit, providing a scientific basis for the implementation of the safety interlock protection of the unit and improving the safety protection measures of the unit. Bayesian network was widely used in probabilistic dynamic risk analysis and security assessment due to its strong probabilistic updating capability [8]. Bow-tie, as a combined model of fault tree and event tree, can conduct a comprehensive causal analysis of accident scenarios [9]. These works have made considerable efforts in qualitative and quantitative analysis, but few have depicted the dynamic change in risk. Dynamic risk assessment is a method to update and calculate the main risk value according to the system reliability, safety management, human factors, operating procedures, safety barriers and etc [10]. Chang et al. [11] used DBN to analyze the risk of hydrogen production unit leakage scenario. Bayesian network is an easy to update model, which is more and more used in industrial production risk analysis [12-13].

To sum up, most of the existing studies focus on the quantitative analysis of device risk, and generally do not consider the fuzziness of subjective evaluation. There are few studies that carry out quantitative analysis of the possibility and consequence of accidents. On this basis, taking the oil and gas leakage accident of heating furnace as a case study, the dynamic bow-tie model (DBT) of risk scene was first constructed. Then, DBT is mapped to DBN and bidirectional reasoning is carried out based on dynamic probability, so as to determine the key factors causing accidents and carry out dynamic safety risk assessment. Therefore, the combination of Bayesian network and real-time state parameters can solve the complex and uncertain situation in dynamic risk analysis, realize the transformation from static hierarchical analysis to dynamic network reasoning, accurately identify and manage risks, and promote the development and construction of petrochemical enterprises to solve the efficiency problem of resource investment through targeted solutions.

2. Methodology
This section outlines the proposed method, as shown in Figure 1. First, based on the Bow-tie model, the dangerous source of oil and gas leakage in the heating furnace is identified. Then the Bayesian network structure is determined according to this, and the probability estimation model of the node prior probability and posterior probability table in the Bayesian network is established. Finally, based on the observed evidence, the real-time risk is analyzed based on the dynamic Bayesian network.

![Methodological framework](image)

**Figure 1. Methodological framework.**

2.1. Bow-tie approach
The Bow-tie can establish complete accident scenarios and conduct quantitative analysis [14]. The application of Bow-tie in the risk analysis of large systems, where common cause failures and dependent
failures are present, is limited. To consider new information in the context of dynamic risk analysis, the Bow-tie approach has been coupled with BN or mapped into BN. First of all, based on the top event as the core, the possible causes leading to its occurrence are analyzed forward, and the possible subsequent events after the occurrence of unsafe event are analyzed backward, and then barriers are set up for prevention and control [15-16].

Therefore, Bow-tie can be concluded that the preventive control barrier before the accident and the mitigation control barrier after the accident should be adopted at the appropriate location to formulate risk control measures and identify the relevant responsible persons to reduce the risk to an acceptable level. However, BT method is static and cannot be used in dynamic risk analysis, so it cannot be updated with probability. The application of Bayesian network can solve this problem[17].

2.2. Dynamic Bayesian network

DBN is a graphical technique that has started to be widely applied in the field of risk analysis. BN has been proved to be an effective risk assessment method for those data sources that are insufficient[18]. Known as an inference probabilistic method, DBN is composed of nodes, arcs and probability tables to represent a set of random variables and the conditional dependencies among them.

The conditional probabilistic tables (CPTs) show the conditional probabilities between the dependent variable and the parent nodes[19]. BN was composed of directed acyclic graph and network parameters, combing the structure property and data property organically. A directed acyclic graph contains nodes representing random variables and directed line segments. The logical relationship between nodes is connected by directed line segments. The network parameters include the prior probability attached to the root node and the conditional probability table attached to the child node, indicating the degree of dependence between variables.

The Bayes formula is:

$$p(B_i|A) = \frac{p(A|B_i)p(B_i)}{\sum_{i=1}^{n} p(A|B_i)p(B_i)}$$

(1)

The joint probability distribution of the simple Bayesian network is:

$$P(A, B, C) = P(C|A, B)P(A, B) = P(C|A, B)P(A)P(B)$$

(2)

Considering the conditional dependencies of variables, BN represents the joint probability distribution

$$P(\pi) = \prod_{i=1}^{n} P(X_i|\pi(X_i))$$

(3)

Under evidence K, the posterior probability of the node is:

$$P(\pi|K) = \frac{P(\pi|K)}{P(K)} = \frac{P(\pi|K)}{\sum_{\pi} P(\pi|K)}$$

(4)

The joint probability distribution of event x on t time slices in DBN network is:

$$P(X[1], X[2], ...X[T]) = P_AO(X[1]) \prod_{t=1}^{T} P_{A\rightarrow} (X[t+1]/X[t])$$

(5)

2.3. DBT conversion to DBN

Dynamic Bow-tie is transformed into dynamic Bayesian network, where the mapping relationship and logical relationship remain unchanged, used in the safety evaluation of the heating furnace, including graphic mapping and numerical mapping.

In Bow-tie, the interference factor, barrier and threat correspond to root nodes, intermediate nodes and leaf nodes respectively in BN, and the nodes are consistent with the bow-tie logical relationship. In the numerical mapping, the prior probability of the root node corresponds to the occurrence probability of the basic event in bow-tie, and the conditional probabilities of intermediate and leaf nodes are obtained through Boolean logic; In the graph mapping, the barrier, threat and top event of the Bow-tie model correspond to the root node, intermediate node and leaf node of BN respectively, and the unsafe events are gathered into a multi-consequence node.

The basic event node is first created, based on the established bow-tie model of oil and gas leakage failure in heating furnace, and then the corresponding BN security evaluation model is generated in GeNie software according to the algorithm transform action relationship, as shown in Figure 2.
3. Dynamic risk analysis of oil and gas leakage failure in heating furnace

3.1. Hazard identification

Hazard identification is the preliminary work of risk assessment. It is necessary to identify possible accident types, influencing factors and risk evolution mechanism. Hydrocracking is carried out in two different types of reactions, one is hydrofining reaction, the other is hydrocracking reaction, which can produce clean, saturated, high-quality products. The hydrofining reaction is a pretreatment reaction to remove impurities in the raw materials, and the cracking reaction produces heavy products from heavy oil, which occur under a high temperature, high pressure and hydrogen condition. The chemical reaction process of raw oil on the surface of catalyst is generally divided into three steps: adsorption, reaction and desorption.

The main danger of heating furnace is that its medium and products are flammable and explosive. Once leakage occurs, it will not only cause huge economic losses, but also may cause serious consequences such as fire and explosion. The three inevitable factors leading to the occurrence of oil and gas leakage accidents in heating furnace, namely, combustible substances, fire sources, and explosion limits. In order to fully identify the causes of oil and gas leakage, Bow-tie was used to analyze all possible causes of oil and gas leakage in heating furnace from top to bottom and from left to right. A summary of 1 top event and 19 intermediate events are shown in Table 1.

| Symbol | Description                                      | Index | Description                               | Symbol | Description                        |
|---------|--------------------------------------------------|-------|-------------------------------------------|--------|-----------------------------------|
| T       | Oil and gas leakage failure                      | M7    | High temperature                          | M14    | Pipeline system failure            |
|         | Combustible material                             | M8    | Static electricity                         | M15    | Equipment problems                |
| M1      | Fire source                                      | M9    | External fire                              | M16    | Equipment electrostatic           |
| M2      | Failure to control the fire in time              | M10   | The firemen failed to control the fire in time | M17    | Human static electricity          |
| M3      | Process material outflow                         | M11   | Equipment failure                          | M18    | Electrical discharge              |
| M4      | Blocked diffusion                                | M12   | Electrostatic                              | M19    | Combustible substance             |
| M5      | Defective equipment                              | M13   | Construction defects                       |        |                                    |
| M6      |                                                  | -     |                                           |        |                                    |
Figure 3. Diagram of oil and gas leakage failure model based on Bow-tie.
Different accident consequences were caused by the role of different safety barriers, and finally formed the Bow-tie model of heating furnace leakage failure, as shown in Figure 3.

3.2. Failure model based on Bow-tie

A general BT model is established, as shown in Figure 4. BT describes the causes of oil and gas leakage fire in heating furnace and the potential consequences related to safety barrier performance. For clarity and simplicity, BT is presented in a simplified framework. On the left side of the BT model, there are three threats that cause the accident.

On the right side of BT, the diffusion of oil and gas will cause environmental pollution if there is no fire source. In case of fire, fire and explosion may occur after losing control. In narrow or congested areas, explosions are more powerful. When the evacuation passage is effective, the casualties can be reduced. All these consequences have resulted in casualties, economic losses and environmental damage.

![Figure 4. BT model for risk analysis of oil and gas leakage.](image)

3.3. Security evaluation model based on BN

The oil and gas leakage failure model of hydrogenation unit includes five safety barriers (spill, ignition, confined space, fire containment and evacuation). The failure of hydrogenation unit will lead to oil and gas leakage. In case of failure of safety barrier, accidents such as mishap, minor damage, catastrophic damage and significant damage cloud explosion will occur. The failure probability of each safety barrier and consequence is obtained by means of reference database and research literature. See Table 2 and Table 3.

| Symbol | Safety barrier     | Failure probability |
|--------|-------------------|---------------------|
| SB1    | Spill             | 4.25×10^{-4}        |
| SB2    | Ignition          | 3.74×10^{-3}        |
| SB3    | Confined space    | 3.96×10^{-3}        |
| SB4    | Fire containment  | 5.27×10^{-2}        |
| SB5    | Evacuation        | 6.78×10^{-2}        |

| Symbol | Event name                        | Probability  |
|--------|-----------------------------------|--------------|
| T      | Oil and gas leakage failure       | 1.26×10^{-7} |
| C1     | Mishap                            | 7.35×10^{-4} |
| C2     | Minor damage                      | 2.27×10^{-4} |
| C3     | Catastrophic damage               | 3.06×10^{-5} |
| C4     | Significant damage                | 1.07×10^{-5} |
It indicates that there is a certain leakage risk in the hydrogenation unit, and appropriate preventive and control measures should be taken. After the failure of hydrogenation unit, Mishap, Minor damage, Catastrophic damage and Significant damage cloud explosion will occur, and the probability order is Mishap > Minor damage > Catastrophic damage > Significant damage cloud explosion, which is consistent with API American petroleum Institute statistical results.

The oil and gas leakage DBN of heating furnace is shown in Figure 5. The establishment and calculation of the model are based on GeNiE software, and 24 time slices are set to simulate the operation time of two years.

3.4. Bayesian reverse reasoning
The prior probability value and conditional probability value are obtained from historical data and literature, and the posterior probability of each basic event is calculated, as shown in Table 4. It can be seen that X1、X9、X13、X14、X23 and X28 have the largest posterior probability. The probability of unit failure event (T) calculated by BN is 1.26E-07, as shown in Figure 6.

The posterior probability is used to predict and judge the accident occurrence process, which provides a reference for preventing accidents.

Table 4. Basic events and their probabilities.

| Index | Description | Prior probability | Posterior probability | Index | Description | Prior probability | Posterior probability |
|-------|-------------|-------------------|-----------------------|-------|-------------|-------------------|-----------------------|
| X1    | Failure of finding the fire in time | 7.45×10^-2 | 3.12×10^-1 | X20   | Welding defects | 1.13×10^-3 | 4.63×10^-2 |
| X2    | Failure of parking in time | 3.15×10^-2 | 2.68×10^-2 | X21   | Failure of engineering acceptance | 3.25×10^-3 | 2.73×10^-2 |
| X3    | Draining condensate | 3.60×10^-4 | 9.54×10^-2 | X22   | Failure of pipeline | 6.15×10^-3 | 5.74×10^-2 |
| X4    | Incomplete gas replacement | 6.51×10^-4 | 3.16×10^-2 | X23   | Failure of valve | 4.25×10^-3 | 9.13×10^-1 |
| X5    | Fuel gas flows out with liquid | 2.35×10^-4 | 7.43×10^-2 | X24   | Failure of alarm | 8.31×10^-3 | 3.58×10^-3 |
| X6    | No discharge facility | 2.20×10^-4 | 9.68×10^-3 | X25   | Failure of emergency stop | 4.22×10^-4 | 2.74×10^-3 |
| X7    | Discharge facility damaged | 3.08×10^-4 | 7.63×10^-3 | X26   | Improper selection | 7.56×10^-3 | 5.82×10^-2 |
| X8    | Not laid out as required | 1.82×10^-3 | 5.42×10^-2 | X27   | Corrosion damage | 9.15×10^-3 | 4.82×10^-2 |
| X9    | Personnel violations | 8.80×10^-3 | 8.75×10^-1 | X28   | Over temperature and pressure | 2.35×10^-2 | 7.54×10^-1 |
### 3.5. Forecast analysis

Based on DBN reasoning, figure 6 shows the probability of oil and gas leakage failure after 24 months (2 years) operation of the hydrogenation unit. The occurrence probability of oil and gas leakage increases with time, and the node probability is mostly below 1.26E-07, and its failure probability is small.

Figure 7 shows the dynamic probability of different consequences caused by oil and gas leakage. The occurrence probability of C1, C2, C3 and C4 in the 24th month is 7.16E-03, 1.82E-03, 3.06E-04 and 8.97E-05, respectively. It shows that it is very likely to succeed to take measures such as drainage in time after oil and gas leakage. If not, the probability of C4 is far less than that of C2 and C3. Although the current safety barrier has slowed down the development of the accident, the severity of the accident depends on the stability of the emergency system.

| Index | Description                        | Prior probability | Posterior probability |
|-------|------------------------------------|-------------------|-----------------------|
| X10   | Reached spontaneous ignition point | 3.61×10⁻²         | 1.79×10⁻²             |
| X11   | High equipment temperature         | 2.50×10⁻³         | 5.47×10⁻²             |
| X12   | Poor grounding                     | 5.12×10⁻⁴         | 2.29×10⁻³             |
| X13   | Man-made fire source               | 1.8×10⁻²          | 7.82×10⁻¹             |
| X14   | Improper hot work                 | 8.82×10⁻³         | 6.57×10⁻¹             |
| X15   | Car without flame arrester         | 2.12×10⁻³         | 1.48×10⁻³             |
| X16   | No effective fire protection plan  | 2.28×10⁻³         | 2.12×10⁻³             |
| X17   | Harsh environment                  | 5.69×10⁻⁴         | 8.65×10⁻³             |
| X18   | Firefighting facility problem      | 3.68×10⁻⁴         | 4.52×10⁻³             |
| X19   | Installation failed                | 6.40×10⁻²         | 5.88×10⁻²             |
| X20   | Fatigue crack                      | 3.60×10⁻⁴         | 8.54×10⁻²             |
| X21   | Separation of materials and equipment | 4.15×10⁻³     | 3.74×10⁻³             |
| X22   | Material spray filtration          | 8.20×10⁻⁴         | 8.25×10⁻³             |
| X23   | Personnel walking                  | 3.38×10⁻²         | 1.79×10⁻²             |
| X24   | Clothes friction                   | 4.26×10⁻⁴         | 3.35×10⁻³             |
| X25   | Short circuit                      | 1.02×10⁻⁴         | 8.24×10⁻³             |
| X26   | Lamp arc                           | 3.12×10⁻⁴         | 4.62×10⁻³             |
| X27   | Damaged insulation                 | 3.25×10⁻³         | 2.58×10⁻³             |
| X28   | Failure of lightning rod           | 2.17×10⁻³         | 7.53×10⁻²             |
| X29   | Failure of installing lightning protection | 6.89×10⁻⁴ | 5.87×10⁻⁴             |

**Figure 6.** Dynamic probability prediction of oil and gas leakage in the heating furnace.

**Figure 7.** Dynamic probability prediction of oil and gas leakage consequences.
3.6. Sensitivity analysis

The sensitivity reflects the sensitivity of the blade node to the failure state of the root node. Therefore, sensitivity analysis is widely used in system characteristic analysis and abnormal feature discovery. High risk events affecting system failure can be found through sensitivity evaluation, which provides basis for improving system reliability.

Figure 8. Oil and gas leakage failure sensitivity analysis.

As shown in Figure 8, the sensitivity analysis of oil and gas leakage out of control is based on the Oil and gas leakage failure accident (T=1 or T=0) to determine the sensitivity change of each node event X9, X14, X20, X23, X24, X28 are high-sensitivity events (darkest colour). Sensitivity changes can be used to classify and distinguish node event sensitivities and provide a reference basis for individual event key control. Through the analysis of the influence intensity of the parent node on the child node, it can be seen that the most possible way to produce the oil-gas mixture is:X23(X24)→M14→M11→M6→M1. The most possible way to generate static fire source is:X14→M9→M2. The most likely way to not control the fire in time is:X16→M10→M3.

4. Conclusion

(1) Combining Bow-tie and BN methods can effectively perform qualitative and quantitative risk assessment of heating furnace failure.

(2) The risk scenario is transformed into BN to optimize the calculation process and improve the calculation efficiency, which provides a new idea for dynamic integrity safety assessment.

(3) The key causal factors are to design equipment, personnel, engineering technology, and management aspects respectively, and reflect that the fire accident is the result of the multi-factor comprehensive effect. Among them, there are many causes of equipment failures. It is necessary to prevent and control the four factors of equipment pressure, welding, safety valve failure, and alarm failure. From the sensitivity analysis, human factors have a significant impact on oil and gas failure accidents.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (71971110) and 2017 Six talent peaks project in Jiangsu Province and the Key R&D plan of Jiangsu Province in 2020 (BE2020729). The authors gratefully appreciate these supports.
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