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A novel hybrid methodology for loss of containment accident risk assessment of chemical storage tank based on RPN considering the expert epistemic uncertainty

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In the petrochemical industry, storage tank failures may lead to unfavorable consequences or even catastrophic events. The risk management of chemical tank farms must identify all possible failure modes and reduce the risk for critical failure modes. However, identifying and assessing failure modes often depends on experts' subjective judgment, and epistemic uncertainty will affect the validity of assessment results. This paper proposes a novel hybrid methodology for identifying and assessing failure modes of loss of containment (LOC) of storage tanks considering expert epistemic uncertainty. The improved FMECA method considering the expert epistemic uncertainty is used to compare and analyze the possible risk priority numbers (RPN) and RPN critical thresholds of the failure modes. In this process, the Dempster-Shafer theory is used to obtain all possible RPN intervals, and Data Mining is used to provide a reference for the occurrence of failure modes in the FMECA process, and the possible failure modes are expanded. This methodology is applied to a storage tank system, and the ranking of critical failure modes causing LOC of the storage tank is obtained, among which the most critical failure mode is Rupture disc failure. The assessment results will be more valid after considering the expert epistemic uncertainty. Risk management based on the current risk assessment results can effectively reduce the risk of LOC accidents, and then reduce the occurrence and severity of more serious accidents. The relevant results can provide a reference for subsequent related research and risk management in chemical industrial parks.

* 1. Introduction

Loss of Containment (LOC) events will occur in containers, pipelines, and other components of the storage tank system in the chemical industrial park, which will lead to severe consequences (Darbra et al., 2010). Currently, LOC events have received widespread attention and numerous researches on LOC events have been conducted and mainly focus on the quantitative risk assessment of LOC events (Dharmavaram and Klein, 2010). During the operation of chemical storage tank areas, the storage tank system will not only bear the damage caused by complex external environmental conditions and internal operational processes but also appear various potential component failures. Once these potential failure modes happen, the operation reliability of the storage tank system will decline to different degrees (Ding et al., 2023), which may result in LOC accidents and subsequently trigger more severe incidents. Therefore, conducting a failure mode analysis for LOC accidents in tank systems and implementing risk management for critical failure modes are of significant importance for reducing accident risks.

Failure mode, effects, and criticality analysis (FMECA) is an available system reliability analysis method, which can be used to identify potential failure modes and causes in a system or process (International Electrotechnical Commission, 1985). Renjith et al. (2018) applied the FMECA method and the fuzzy set theory to carry out risk assessment of LNG storage system and obtain the ranking of failure modes. Because the LOC accident in the chemical storage tank area belongs to the High-Impact Low-Probability (HILP) event, it is not feasible to obtain data through a large number of experiments or accident cases. Expert elicitation is a powerful support for obtaining information in the case of insufficient data, and it is also widely used in the risk assessment research of the current chemical industry (Jiang et al., 2024). However, the communication mode preference paradox often appears in the process of expert elicitation (Irwin and Mandel, 2023), that is, experts prefer to use intervals (such as 60% and 70% of the probability is between) or fuzzy values (such as “The probability is high”) rather than point values (such as 60%). In addition, due to the experience and cognitive level of the expert system, epistemic uncertainty will occur in the expert elicitation process. To solve this problem, Certa et al. (2017) proposed the FMECA method based on Dempster-Shafer theory (DST), which used intervals to obtain expert opinions to deal with expert epistemic uncertainty about FMECA parameters. Compared with the traditional probability theory, the most important feature of DST is that it allows to assign of probability mass to interval numbers, which is beneficial for dealing with the uncertain results of expert systems. In addition, the comprehensive acquisition of failure modes has a great influence on the validity of FMECA assessment results. However, in the aspect of accident assessment in chemical parks, there is little research has studied on the comprehensive acquisition of failure modes. Ding et al. (2023) applied the data mining technology to the chemical industry park to obtain the failure mode, and put forward the rules for searching and counting the device detection records. Data Mining (DM) is a method to extract useful information from a large database. DM has advantages in extracting and transforming hidden information from a large amount of data.

Therefore, this paper combines data mining methods with DST-FMECA methods to construct a hybrid risk assessment method for LOC accidents in storage tank systems in chemical parks. Based on data mining technology, this method obtains information from the accident database and obtains a complete failure mode of the LOC accident of the storage tank. On this basis, the FMECA method is used to analyze different failure modes and interval information is obtained in the process of expert elicitation. Based on the obtained interval information, the probability envelope of RPN of each failure mode is obtained by Dempster-Shafer theory, and finally the ranking of failure modes is obtained. Risk management and control for critical failure modes can reduce the risk of LOC accidents more effectively, which can provide a reference for related research.

* 1. Materials and methods

In this paper, a hybrid risk assessment method based on data mining, DST and FMECA is proposed, aiming at obtaining the RPN and ranking of failure mode for LOC accidents of storage tanks in chemical parks. Figure 1 shows the procedure of this method. In the first step, it is necessary to determine the components of the storage tank system and the layout and function of each component, and use DM in the accident record database to obtain the frequency of each failure mode of components and provide a reference for the FMECA process. The second step is to obtain the parameter scores of FMECA by expert elicitation. In this process, considering the epistemic uncertainty of experts, experts are allowed to rank parameters in the form of intervals, and then all possible RPN intervals are obtained. Based on all RPN intervals, the ranking of all failure modes is obtained in the third step. These steps will be described in detail in the following Sections 2.1 to 2.3.



*Figure 1: The procedure of the proposed methodology*

* + 1. Step 1: Application of Data Mining for failure mode of storage tank system

It is necessary to determine the component type and layout of the storage tank system first. To provide a reference for the parameter Occurrence of the LOC accident FMECA process, the accident records will be searched in the chemical accident database to obtain the frequency of different failure modes. This work will refer to the search rules of Ding et al. (2023). Compared with the retrieval of inspection records, the retrieval of accident records can provide a reference for the Occurrence score in the expert elicitation process, to obtain more valid assessment results. In addition, the failure modes identified in the existing work can also be expanded.

* + 1. Step 2: Using DST-FMECA to obtain RPN intervals of failure modes

After determining the failure mode of the storage tank, it is necessary to obtain the RPN of each failure mode. Considering the epistemic uncertainty in the expert elicitation process, this paper refers to the DST-FMECA method proposed by Certa et al. (2017) to obtain all RPN intervals of each failure mode. In this step, firstly, the expert elicitation process is carried out to obtain the scores of parameters Severity (S), Occurrence (O), Detection (D) of different failure modes, and then the expert information is aggregated to obtain the RPN interval of each failure modes. RPN can be calculated using Equation (1),

|  |  |
| --- | --- |
|  | (1) |

In the expert elicitation stage, the validity of information depends on the knowledge level and experience of experts. Therefore, a team of *N* experts with many years of practical experience in research or engineering in related fields will be formed, and it is assumed that each expert has the same credibility and reliability in the process (Ayyub and Klir, 2006). The scoring rules of LOC accident parameters S, O, D can refer to the standard (International Electrotechnical Commission, 1985). Experts should score the parameters S, O, D according to the scoring rules, and points or intervals are allowed for the expert information. In addition, the score for O can also refer to the failure mode frequency of data mining in the second step. After this stage, there are *N* points or intervals can be obtained for each parameter of each failure mode. After obtaining the expert information, it is necessary to aggregate the expert information. The Basic probability assignment (BPA) of any score given by any expert is 1/*N*. In addition, because RPN is the product of S, O, D, there are *N*3 RPNs that can be obtained, and the BPA of each RPN is (1/*N*)3.

* + 1. Step 3: LOC accident assessment using Failure mode ranking

Because the interval evidences are used, the final RPN for comparing different failure modes will also be an interval, and it is not appropriate to compare only the upper or lower limit of the interval. Therefore, Certa et al. (2017) introduced a general threshold RPN\*. Assume that event *E*={RPN>RPN\*} and obtaining RPN\* with RPN greater than RPN\* needs to obtain the probability envelope of RPN based on Dempster-Shafer theory. The complementary event of *E*, ={RPN≤RPN\*}, will be completely contained in [0, RPN\*], and the probability envelope can be calculated using Equations (2) and (3),

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |

where, *i*=1, 2, …, *N*3. Then Equations (4) and (5) can be obtained,

|  |  |
| --- | --- |
|  | (4) |
|  | (5) |

Then set the credibility mass *m* for the event *E*. As shown in Figure 2, draw a straight-line *y*=*m* in the probability envelope formed by the Dempster-Shafer theory method. Then this straight-line will form an intersection (RPN\*, *m*) with the curve Pl(*E*) . However, different failure modes may produce the same RPN\*, which makes ranking difficult. Therefore, it is necessary to add an additional operation, that is, draw a straight-line *x*=RPN\*, which will form an intersection (RPN\*, *EBel*) with the curve Bel(*E*), where *EBel* is the minimum reliability of event *E* (Certa et al., 2017). For the failure modes which have the same RPN\*, the ranking can be obtained by comparing *EBel*.



*Figure 2: The schematic diagram of determining the* RPN\* *and* EBel

* 1. Case Study

To verify the effectiveness of the current method, this method is applied to the storage tank system. Figure 3 is a simple schematic diagram of a storage tank system, which includes some basic components, including tank shell, pipeline, check valve and so on, and some other components are not shown in the figure.



*Figure 3: The Simple schematic diagram of the storage tank system*

* + 1. Data mining in ZEMA chemical accident record database

In this paper, the German ZEMA database is used to carry out keyword retrieval. Based on the mining rules, 195 accident records from 1984 to 2024 were obtained. In these 195 accident records, there are accident reasons such as natural disasters, human error, and intentional attack. These reasons have nothing to do with the components of the storage tank system, so they are not included in the failure mode of the storage tank. The part of failure modes and corresponding occurrence times are shown in the Table 1. The current failure mode and the corresponding frequency can provide reliable historical data reference for experts to score. In addition, combined with previous research (Ding et al., 2023), we added the following failure modes: (24) Check valve scuff, (25) Check valve corrosion, (26) Agitator failure, (27) Breather valve scuff and (28) Breather valve corrosion.

Table 1: Failure modes and corresponding occurrence times in accident records obtained through data mining.

|  |  |  |  |
| --- | --- | --- | --- |
| Serial number | Component | Failure modes | Frequency of occurrence |
| 1 | Storage tank shell | Breakage | 5 |
| 2 | Crack | 5 |
| 3 | Welding defect | 3 |
| 4 | Corrosion | 3 |
| 5 | Stress deformation | 2 |
| 6 | Pipeline | Crack | 13 |
| 7 | Corrosion | 6 |
| 8 | Metal hose | Breakage | 8 |
| 9 | Joint breakage | 3 |
| 10 | Loose connection | 2 |
| 11 | Corrosion | 1 |
| 12 | Check valve | Breakage | 1 |
| 13 | Globe valve | Breakage | 8 |
| 14 | Scuff | 4 |
| 15 | Corrosion | 1 |
| 16 | Floating roof | Sink | 2 |
| 17 | Breather valve | Breakage | 2 |
| 18 | Manhole cover | Breakage | 1 |
| 19 | Flange | Breakage | 13 |
| 20 | Pump | Failure | 6 |
| 21 | Rupture disc | Breakage | 3 |
| 22 | Agitator | Breakage | 3 |
| 23 | Cooling system | Failure | 5 |

* + 1. Using the DST-FMECA method to obtain the probability envelope and ranking of RPN

It is necessary to obtain the scores of S, O, D for each failure mode. The specific process of expert elicitation in this paper is as follows: provide all the failure modes identified in the data mining process and their corresponding frequencies to experts. According to the information provided and their own knowledge level, the experts score the Severity, Occurrence, Detection of each failure mode with intervals or point values to get the evidence. The specific profiles of the three experts consulted in this paper are shown in Table 2.

Table 2: Basic information of three experts in this work

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Expert | Professional position | Service time (year) | Education level | Age |
| Expert 1 | Professor | 22 | PhD | 50 |
| Expert 2 | Professor | 10 | PhD | 36 |
| Expert 3 | Technician | 17 | Master | 42 |

The parameter scores of parts of the failure modes are shown in Table 3. For different failure modes, the respective RPN is obtained based on Equation (1). S, O, D of each failure mode have three focal elements, and the BPA of each focal element is evenly distributed as 1/3. Combining focal elements, 27 focal element combinations can be obtained for each failure mode.

Table 3: Expert scoring of parameters corresponding to each failure mode

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Serial number | S\* | | | O\*\* | | | D\*\*\* | | |
| E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 |
| 1 | [5,6] | [7,8] | [6,8] | [2,3] | [2,5] | [6,7] | [2,3] | [1,2] | [3,5] |
| 2 | [5,6] | [5,7] | [5,7] | [2,3] | [4,5] | [6,7] | [3,4] | [2,3] | [1,3] |
| 3 | [3,4] | [5,7] | [4,6] | [1,2] | [3,5] | [5,6] | [5,6] | [3,5] | [4,6] |

\*For S, 1~2: no or very minor effect on tank; 3~4: minor or low; 5~6: moderate or significant; 7~8: major or extreme; 9~10: very extreme or serious.

\*\*For O, 1~2: unlikely or very remote probability; 3~4: remote or very low; 5~6: low or moderate; 7~8: moderately high or high; 9~10: very high or almost certain.

\*\*\*For D, 1~2: almost certainly or very high chance to detect the failure; 3~4: high or moderately high; 5~6: moderate or low; 7~8: very low or remote; 9~10: very remote or almost impossible.

The RPN is calculated for all failure modes, and the Belief and Plausibility curves of the probability envelope are obtained based on Equations (4) and (5). In addition, set the credibility mass *m*=0.9 (Certa et al., 2017) to obtain the RPN\* of each failure mode and the minimum belief *EBel* of RPN\*. The results of the most and least critical failure modes are shown in Figure 4, and all failure mode ranking results are shown in Table 4. The greater the RPN\*, the higher the risk of failure modes of the system, and the greater the minimum confidence value, the higher the risk confidence value of failure modes with the same RPN\* value. Figures 4(a) and 4(b) show that the most critical failure mode is Rupture disc failure with RPN\* value of 96, while the least critical failure mode is Check valve breakage and Metal hose corrosion with RPN\* value of 20. In addition, some failure modes have the same RPN\* value, so it is necessary to further compare the minimum belief for failure modes with the same RPN\* values. For example, the failure modes of Figure (c) and Figure (d) are Pipeline Corrosion and Breather Valve Breakage, respectively, and their RPN\* is 48, but *EBel* is 0.37 and 0.222, respectively, so the ranking of Pipeline Corrosion will be higher than that of Breather Valve Breakage. Giving priority to risk management and control of critical failure modes can reduce risks more effectively. When the cost is limited, the investment in managing and controlling low-critical failure modes can be reduced. Therefore, risk management and control can be carried out according to the ranking in Table 4.



Figure 4: The probability envelope of RPN of the (a) most critical, (b) least critical and (c, d) other failure modes.

* 1. Conclusion

To deal with the expert epistemic uncertainty in the FMECA process, and obtain the ranking of the complete failure modes of LOC accidents of the storage tank system, a hybrid risk assessment method based on the DM, DST and FMECA is proposed. The characteristic of current data mining is that it is based on accident records, and compared with previous methods, it can obtain the frequency of each failure mode. This can provide a reference for expert elicitation in the FMECA process, improve the expert’s cognitive level of related failure modes, and thus reduce the expert epistemic uncertainty. In addition, the FMECA process based on DST can effectively obtain RPN intervals and corresponding probability envelopes for each failure mode. The interval information is closer to the information that experts tend to give, and a more complete and valid risk assessment result can be obtained. A general threshold RPN\* is used to rank all the failure modes, and the ranking of all the failure modes impacts on the LOC accident is obtained. The case study shows that the Rupture disc failure is the most critical failure mode with RPN\* value of 96. Risk management for high-ranking failure modes can effectively reduce the LOC accident risk, and then reduce the occurrence and severity of more serious accidents. Meanwhile, the results can provide methods and reference information for subsequent risk management.

Table 4: The ranking result of all failure modes

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Ranking | Serial number | RPN\* | *EBel* | Ranking | Serial number | RPN\* | *EBel* | Ranking | Serial number | RPN\* | *EBel* |
| 1 | 25 | 96 | 0.148 | 11 | 7 | 48 | 0.37 | 21 | 5 | 30 | 0.444 |
| 2 | 6 | 80 | 0.111 | 12 | 1 | 48 | 0.222 | 22 | 21 | 27 | 0.111 |
| 3 | 28 | 80 | 0.111 | 13 | 17 | 48 | 0.222 | 23 | 13 | 27 | 0 |
| 4 | 8 | 64 | 0.259 | 14 | 14 | 48 | 0 | 24 | 10 | 24 | 0.407 |
| 5 | 15 | 64 | 0.185 | 15 | 20 | 48 | 0 | 25 | 18 | 24 | 0.222 |
| 6 | 2 | 63 | 0.111 | 16 | 9 | 45 | 0.185 | 26 | 22 | 24 | 0.074 |
| 7 | 16 | 54 | 0.333 | 17 | 27 | 45 | 0 | 27 | 11 | 20 | 0.407 |
| 8 | 23 | 54 | 0.333 | 18 | 26 | 40 | 0.148 | 28 | 12 | 20 | 0.407 |
| 9 | 24 | 54 | 0.296 | 19 | 4 | 36 | 0.37 |  |  |  |  |
| 10 | 3 | 48 | 0.407 | 20 | 19 | 36 | 0 |  |  |  |  |

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