A Simplified HAZOP Analysis based on Fuzzy Evaluation of Node Criticality for Chemical Plants

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Abstract — As a systematic safety evaluation method, traditional HAZOP (Hazard and Operability) analysis usually requires considerable manpower, materials, and financial resources, particularly for complex large-scale chemical plants. This research aims to propose a quantitative node criticality evaluation method to simplify HAZOP analysis. In consideration of the multiple uncertain factors that influence node criticality evaluation, a multi-factor fuzzy comprehensive evaluation model of node criticality was developed; AHP (analytic hierarchy process) method was introduced to determine the relative weights of evaluation factors. Based on node criticality grade, the simplification principle of HAZOP deviation analysis was established to optimize traditional analytical procedure. The proposed method was applied to perform a HAZOP analysis of a hydrocracking unit. The results show that the proposed method can provide effective and quantitative references to simplify HAZOP analysis.

Keywords - HAZOP analysis; fuzzy comprehensive evaluation; node criticality; chemical plant

I. INTRODUCTION

A process medium in chemical plants is usually flammable, explosive, and toxic. As such, an accident can lead to catastrophes. Therefore, systemic safety evaluation must be performed in chemical plants to ensure production safety. HAZOP analysis is widely used to identify process hazards in chemical plants [1,2,3].

Although HAZOP has been successfully conducted to analyze safety of chemical plants, HAZOP technique exhibits a repetitive and time-consuming nature. In traditional HAZOP analysis, a plant can be divided into a dozen or even dozens of small nodes, particularly for a large-scale chemical plant. Each node must also be analyzed in detail; for this reason, considerable manpower, materials, and financial resources are required. Thus, node criticality must be evaluated to simplify HAZOP analysis. An optimal HAZOP node order method has been proposed through graph theory and matrix calculus [4]. A model has been established to estimate HAZOP time and a standardized method has been applied to examine nodes [5]. Although HAZOP nodes, such as optimal node order and examining nodes, have been evaluated, node criticality evaluation of HAZOP has been rarely investigated. HAZOP node criticality evaluation involves multiple qualitative and quantitative factors because a chemical plant is normally a highly complex system. Therefore, the use of traditional single-factor evaluation method poses a great challenge in the comprehensive evaluation of an objective with multiple uncertain factors. With the development of fuzzy mathematical theory, fuzzy comprehensive evaluation method has been extensively used in many fields [6,7]. Compared with other single-factor evaluation methods, fuzzy comprehensive evaluation method through fuzzy transformation is considered as an optimum method to comprehensively evaluate an inherently ambiguous multi-factor objective [8]. The present study aims to establish a node criticality method based on fuzzy comprehensive evaluation to provide a simplified basis for a HAZOP team; thus, the efficiency of HAZOP analysis can be improved.

II. METHODOLOGY

Given the complexity of HAZOP node criticality evaluation, a two-layer fuzzy comprehensive model is established. The two-layer fuzzy comprehensive model is characterized by the following steps.

A. Establishing a Factor Set

Complex process conditions and various types of equipment are involved in chemical plants. Thus, representative factors affecting node criticality evaluation must be considered as evaluation indices. The evaluation factor set (U) of node criticality is established on the basis of physiochemical properties of process media, equipment list, operation manual, process flow diagram, maintenance record, and other data. A factor set is divided into two layers. The first layer consists of three sub-factor sets: U1 = (U11, U12, U13), where U11, U12, and U13 denote toxicity, fire and explosion hazard, and corrosion, respectively; U2 = (U21, U22, U23, U24), where U21, U22, U23, and U24 denote operation temperature, operation pressure, node capacity, and operation risk, respectively; and U3 = (U31, U32), where U31 and U32 denote equipment fault consequence and equipment fault probability, respectively. The second layer is denoted by U = (U1, U2, U3), where U1, U2, and U3 represent process medium properties, process conditions, and equipment risk, respectively.
B. Establishing an Evaluation Set

An evaluation set includes different evaluation grades and criteria. Four grades are established: $V = (V_1, V_2, V_3, V_4)$, where $V_1$, $V_2$, $V_3$, and $V_4$ denote unimportant, general, important, and very important. Evaluation criteria (Table I) are based on national and industrial standards and safety codes of China [9-11].

TABLE I: GRADE CRITERIA OF EVALUATION FACTORS

<table>
<thead>
<tr>
<th>Evaluation factor</th>
<th>Grade criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxicty $U_{31}$</td>
<td></td>
</tr>
<tr>
<td>Suction LC50 (cm$^3$·m$^{-3}$)</td>
<td>$&gt;20000$</td>
</tr>
<tr>
<td>Skin LD50/ (mg·kg$^{-1}$)</td>
<td>$&gt;2000$</td>
</tr>
<tr>
<td>Mouth LD50/ (mg·kg$^{-1}$)</td>
<td>$&gt;2000$</td>
</tr>
<tr>
<td>Fire and explosion hazard $U_{32}$</td>
<td>Difficult-to-burn items or noncombustible substance</td>
</tr>
<tr>
<td>Corrosion $U_{33}$</td>
<td>Noncorrosive substance</td>
</tr>
<tr>
<td>Operation temperature $U_{34}$</td>
<td>$-20$ to $50$</td>
</tr>
<tr>
<td>Operation pressure $U_{35}$ (MPa)</td>
<td>$&lt;1.6$</td>
</tr>
<tr>
<td>Node capacity $U_{36}$ (m$^3$)</td>
<td>Gas</td>
</tr>
<tr>
<td>Operation risk $U_{37}$</td>
<td>Liquid</td>
</tr>
<tr>
<td>Equipment fault consequence $U_{38}$</td>
<td>Reactor contains above 70% water; no chemical reaction in the node; no direct-fired heater</td>
</tr>
<tr>
<td>Equipment fault probability $U_{39}$</td>
<td>In the node, all general grades of equipment exist with no serious consequences</td>
</tr>
</tbody>
</table>

C. Determining the Relative Importance of Evaluation Factors

Given that the importance of each evaluation factor on node criticality varies, the weight of each evaluation factor should be determined to reflect its importance. Weights are calculated via AHP, expert investigation method, and entropy weight method. Among these methods, AHP is commonly applied to rank relative importance. The weight of the factors in the same layer can be determined by comparing alternatives with one another through AHP. In the current study, AHP is selected to obtain the weight of the evaluation factor. Pair-wise comparison matrix ($A$), which is established by experts, can be expressed as follows:
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where \( u_{k} \) represents the importance of the \( k \)th evaluation factor corresponding to the \( m \)th evaluation factor. Consistency test is conducted after maximum eigenvalue and the corresponding eigenvector of the pair-wise comparison matrix are solved. Weight vector can be obtained.

D. Calculating a Fuzzy Evaluation Matrix

A fuzzy evaluation matrix represents fuzzy mapping from factor set to evaluation set. This matrix is constructed via single-factor evaluation:

\[
A = \begin{bmatrix}
  u_1 & \cdots & u_k & \cdots & u_m \\
  a_{11} & \cdots & a_{1k} & \cdots & a_{1m} \\
  \vdots & \cdots & \vdots & \cdots & \vdots \\
  a_{n1} & \cdots & a_{nk} & \cdots & a_{nm} \\
\end{bmatrix}
\]

where \( a_{km} \) represents the importance of the \( k \)th evaluation factor corresponding to the \( m \)th evaluation factor.

Consistency test is conducted after maximum eigenvalue and the corresponding eigenvector of the pair-wise comparison matrix are solved. Weight vector can be obtained.

\[
R = \begin{bmatrix}
  R_1 \\
  R_2 \\
  \vdots \\
  R_m \\
\end{bmatrix}
= \begin{bmatrix}
  r_{11} & \cdots & r_{1j} & \cdots & r_{1m} \\
  \vdots & \cdots & \vdots & \cdots & \vdots \\
  r_{nj} & \cdots & r_{pj} & \cdots & r_{pm} \\
  \vdots & \cdots & \vdots & \cdots & \vdots \\
  r_{nm} & \cdots & r_{nm} & \cdots & r_{nm} \\
\end{bmatrix}
\]

(1)

where \( R_j \) represents the fuzzy evaluation matrix corresponding to the \( j \)th evaluation factor, \( r_{jl} \) denotes the membership of the \( j \)th evaluation factor corresponding to the \( l \)th evaluation grade, \( m \) is the number of evaluation factors, and \( n \) is the number of evaluation grades.

In this study, trapezoidal function is used to determine the membership between factor and evaluation grade (Figure 1).

E. Fuzzy Comprehensive Evaluation

Fuzzy evaluation index system consists of a two-layer factor set. Thus, comprehensive evaluation results are calculated from the bottom. The first step involves single-factor fuzzy comprehensive evaluation; the second step involves second-grade fuzzy comprehensive evaluation; the third step involves total fuzzy comprehensive evaluation.

1) Single-factor fuzzy comprehensive evaluation

Based on fuzzy evaluation matrix and its weight vector, the fuzzy comprehensive evaluation result \( A_i \) of the first-layer evaluation factor corresponding to the \( i \)th factor in the second-layer factor set is calculated as follows:

\[
A_i = W^T \cdot R = \left( w_{i1}, w_{i2}, \ldots, w_{ip} \right) \cdot \begin{bmatrix}
  r_{11} & \cdots & r_{1j} & \cdots & r_{1m} \\
  \vdots & \cdots & \vdots & \cdots & \vdots \\
  r_{nj} & \cdots & r_{pj} & \cdots & r_{pm} \\
  \vdots & \cdots & \vdots & \cdots & \vdots \\
  r_{nm} & \cdots & r_{nm} & \cdots & r_{nm} \\
\end{bmatrix}
\]

(2)

where \( W_j \) denotes the \( j \)th factor weight in the first-layer factor set corresponding to the \( i \)th factor in the second-layer factor set, \( p \) is the number of factors in the second-layer factor set.
factor set, and “O” represents fuzzy operator, which uses $M(\land, \lor)$ model in this study.

2) Second-grade fuzzy comprehensive evaluation

According to $A_i$ and the corresponding weight vector, the fuzzy comprehensive evaluation result ($S$) of the second-layer factor set can be obtained using the following equation:

$$S = W^2 \cdot A = (w_1, w_2, \ldots, w_p) \cdot \begin{bmatrix} a_{i1} & a_{i2} & \cdots & a_{is} \\ a_{i1} & a_{i2} & \cdots & a_{is} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{is} \end{bmatrix}$$

\[ (3) \]

3) Total fuzzy comprehensive evaluation

The total fuzzy comprehensive evaluation result ($T$) is obtained using the weighted mean method as follows:

$$T = \frac{\sum_{i=1}^{n} s_i \cdot V_i}{\sum_{i=1}^{n} s_i}$$

\[ (4) \]

where the corresponding scores of $V_1, V_2, V_3,$ and $V_4$ are 1, 2, 3, and 4.

In this study, the three criticality grades are presented. Node criticality is regarded as general (I) when $0 < T < 2$; node criticality is considered important (II) when $2 \leq T < 3$; node criticality is regarded as very important (III) when $T \geq 3$.

F. HAZOP Analysis Based on Node Criticality

According to the evaluation grade of HAZOP node criticality, the corresponding simplified analysis principle of node is proposed; in the simplified approach, the equipment in the highest-grade node is highlighted to allow reasonable allocation of limited resources.

In addition to common deviations of the combined guide words and frequently used process parameters (flow, temperature, pressure, and liquid level), specific deviations, such as operability, leakage, corrosion, impurity, maintenance, and pH, of all equipment in the very important node should be analyzed in detail.

The analysis contents of equipment in the important node are simplified slightly compared with those in the very important node. In addition to common deviations, specific deviations should be considered in the analysis of equipment, including key equipment, equipment operating under extreme conditions, important instruments, and pipelines. For other equipment, common deviations are involved.

In the general node, common deviation analysis of damageable equipment is performed. However, deviations of other equipment, whose fault consequence effect can be ignored, are not analyzed.

III. CASE STUDY

A hydrocracking unit in the petrochemical plant of China enters a hydrocracking reactor. Cracked gaseous and oil products are separated by high and low separators. Further separation occurs in a stabilizer and a fractionator. Final products include light hydrocarbon, naphtha, aviation kerosene, diesel, and hydrogenation tail oil.

A hydrocracking unit is divided into 28 nodes according to the node division principle implemented by the HAZOP analysis team.

The detailed analysis process of each node criticality evaluation is omitted in this paper. Nevertheless, pair-wise comparison matrices of the first-layer factor set and the second-layer factor set via AHP are shown as follows.

$$A_i = \begin{bmatrix} 1 & 1 & 2 \\ 2 & 1 & 3 \\ 1 & 1 & 3 \end{bmatrix}$$

$$A_i = \begin{bmatrix} 1 & 1 & 3 & 4 \\ 1 & 1 & 3 & 4 \\ \frac{1}{3} & \frac{1}{3} & 1 & 2 \\ \frac{1}{4} & \frac{1}{4} & 1 & 1 \end{bmatrix}$$

The weight vectors of the first-layer factor set and the second-layer factor set are derived and presented as follows:

$$W_i = (0.31, 0.53, 0.16) \quad W_i = (0.38, 0.38, 0.15, 0.19)$$

$$W_i = (0.67, 0.33) \quad W_i = (0.34, 0.53, 0.12)$$

The node evaluation results and the corresponding grade of each node based on fuzzy comprehensive evaluation are shown in Table II. In Table 2, 6 nodes of very important grade account for 21.4% of the total nodes; furthermore, 13 nodes of important grade and 9 nodes of general grade account for 78.6% of the total nodes. This result is in accordance with safety management principle (20/80 rule).

<table>
<thead>
<tr>
<th>Node No.</th>
<th>Node criticality value</th>
<th>Grade</th>
<th>Node No.</th>
<th>Node criticality value</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1</td>
<td>II</td>
<td>15</td>
<td>2.379</td>
<td>II</td>
</tr>
<tr>
<td>2</td>
<td>1.97</td>
<td>I</td>
<td>16</td>
<td>2.371</td>
<td>II</td>
</tr>
<tr>
<td>3</td>
<td>3.163</td>
<td>III</td>
<td>17</td>
<td>2.341</td>
<td>II</td>
</tr>
<tr>
<td>4</td>
<td>3.472</td>
<td>III</td>
<td>18</td>
<td>1.94</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>3.295</td>
<td>III</td>
<td>19</td>
<td>1.921</td>
<td>I</td>
</tr>
<tr>
<td>6</td>
<td>3.262</td>
<td>III</td>
<td>20</td>
<td>2.519</td>
<td>II</td>
</tr>
<tr>
<td>7</td>
<td>2.567</td>
<td>II</td>
<td>21</td>
<td>3</td>
<td>III</td>
</tr>
<tr>
<td>8</td>
<td>2.525</td>
<td>II</td>
<td>22</td>
<td>2.93</td>
<td>II</td>
</tr>
<tr>
<td>9</td>
<td>2.234</td>
<td>II</td>
<td>23</td>
<td>3.093</td>
<td>III</td>
</tr>
<tr>
<td>10</td>
<td>2.208</td>
<td>II</td>
<td>24</td>
<td>1.912</td>
<td>I</td>
</tr>
<tr>
<td>11</td>
<td>2.164</td>
<td>II</td>
<td>25</td>
<td>1.969</td>
<td>I</td>
</tr>
<tr>
<td>12</td>
<td>1.935</td>
<td>I</td>
<td>26</td>
<td>1.93</td>
<td>I</td>
</tr>
<tr>
<td>13</td>
<td>2.437</td>
<td>II</td>
<td>27</td>
<td>1.925</td>
<td>I</td>
</tr>
<tr>
<td>14</td>
<td>2.44</td>
<td>II</td>
<td>28</td>
<td>1.7</td>
<td>I</td>
</tr>
</tbody>
</table>
Further HAZOP analysis is performed on the basis of the preceding result. The grade of Node 5 is very important, and the hydrocracking reactor is the key equipment in Node 5, even in the whole unit. Thus, only the HAZOP analysis results of the hydrocracking reactor with specific deviations are illustrated in this study because of space constraints (Table III).

### TABLE III HAZOP ANALYSIS RESULTS OF THE HYDROCRACKING REACTOR FOR SPECIAL DEVIATIONS

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Possible cause</th>
<th>Consequence</th>
<th>Existing protection measure</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channeling of catalyst bed</td>
<td>1. Catalyst loading defects  2. Catalyst damages</td>
<td>1. Local excessive reaction, uneven temperature distribution of catalyst bed  2. Catalyst activity is not adequately used  3. Deactivation of partial catalyst aggravates  4. Serious catalyst coking</td>
<td>1. Temperature detection of catalyst bed  2. Standardization of catalyst loading operation procedure  3. Pressure detection of catalyst bed</td>
<td>1. Intrinsic safety type of line analyzer should be installed for recycle hydrogen  2. High-high pressure differential warning system of catalyst bed and warning screen should be installed</td>
</tr>
<tr>
<td>Abnormal start-up operation</td>
<td>1. Leakage  2. Air in the system is not completely removed  3. Water in the system is not completely removed</td>
<td>1. Fire accident  2. Explosive mixtures may be produced  3. When hot oil enters reactor, overpressure may occur because of vaporization of water</td>
<td>1. Operating procedure of gas replacement  2. Sample analysis prior to hydrocarbon feedstock introduction  3. Recirculation of dry, hot gas</td>
<td></td>
</tr>
<tr>
<td>Leakage</td>
<td>1. Sharp fluctuation in temperature and reactor pressure  2. Damage of sealing components and flange sealing surface</td>
<td>1. Leakage of reactor inlet flange may cause fire and explosion accidents</td>
<td>1. Firefighting steam  2. Flammable gas alarm</td>
<td>1. Seam protection ring should be installed in high-temperature or high-pressure flange</td>
</tr>
</tbody>
</table>

The deviation numbers obtained via traditional HAZOP analysis and HAZOP analysis based on node criticality are shown in Figure 2. In the very important grade node, the deviation numbers of these two methods are the same. In important and general grade nodes, the deviation numbers of the former are higher than those of the latter. Thus, the total deviation numbers of the hydrocracking unit are reduced from 547 to 370, and analysis efficiency is improved by 32.36%.

IV. CONCLUSION

In this study, a HAZOP analysis method based on the fuzzy comprehensive evaluation of node criticality was proposed. The method has been applied to evaluate representative plants. The total deviation numbers of the analyzed hydrocracking unit are reduced by 32.36% compared with those of traditional HAZOP analysis. This finding suggests that the proposed method can provide effective and quantitative references for HAZOP analysis.

Further research should be conducted to adjust evaluation factors, evaluation grade criteria, and weight vectors to apply the proposed method in the HAZOP analysis of other chemical plants.

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REFERENCES


