Hazard Analysis and Quantitative Risk Assessment of Port Operation for Dangerous Goods Container

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Abstract. The occurrence of the Tianjin 8.12 accident indicates that it may lead to extremely serious production safety accidents once the risk of port operations for dangerous goods container is out of control. It could cause huge loss to personnel, property and social security, and difficulty in emergency handling of accidents. For the hazard analysis and quantitative risk assessment of port operation for dangerous goods container, this study proposes a risk assessment method that combines analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE). Firstly, statistically analyze relevant accident cases in China in recent years, and use the fishbone diagram method to establish a system of multi-level and multi-dimensional risk assessment. Secondly, the AHP is used to assign the weight of the evaluation indicator system. Finally, the FCE method is raised to establish the fuzzy mapping relationship. The evaluation vector calculated by the fuzzy matrix and the weight vector is used to achieve the quantitative assessment conclusion. The method is validated by an instance application of dangerous goods containers port operation of a company.

1. Introduction

Dangerous goods are substances and articles that have dangerous properties, e.g., explosion, flammability, poison, infection, corrosion, and radioactivity. In the process of transportation, storage, production, operation, use and disposal, it is easy to cause personal injury, property damage or environmental pollution and requires special protection[1]. As a large-scale loading vessel with certain strength, rigidity and specifications for turnover, the container can be used to transfer goods directly from the consignor to the consignee without removing goods from boxes[2]. As a basic carrier of logistics systems with standardized production and operation, it has been widely used in highway and waterway transportation of dangerous goods[3].

In the current study, the safety risk analysis and assessment for road transportation and railway transportation of dangerous goods are relatively centralized and mature. The main research methods[4-11]are rough set, BP neural network, index model, Monte Carlo method, Bayesian network, etc. The establishment of a comprehensive indicator system[12-14] for safety risk assessment focuses on the dangerous goods characteristics, transportation routes, infrastructure, and the safety status of transportation enterprises.

This study will propose a comprehensive evaluation model based on the risk influencing factors likelihood and consequence severity. The model quantifies the risk using specific elements present during the operation to determine the safety risk of dangerous goods container operations. Section 2 of the paper introduces the technical route and methods in this study, including four important steps: establishing an indicator system, assigning indicator weights, determining fuzzy evaluation rules, and...
risk assessment analysis.

2. Technical method
The technical route to be used in this study is shown in Figure 1. Based on existing risk control theories, this paper proposes a comprehensive evaluation method of safety risk for dangerous goods container port operation that combines analytic hierarchy process and fuzzy evaluation method. The method constructs an evaluation model indicator set based on the statistical analysis of accident cases, characteristics and key influencing factors of the dangerous goods container port operation. The analytic hierarchy process is used to solve the hierarchical structure and weight distribution of evaluation indicators to achieve quantitative assessment according to previous studies\(^{[15-17]}\). Finally, the fuzzy comprehensive evaluation rules are used to conduct case application and evaluation result analysis.

Figure 1. Roadmap for risk assessment using AHP and FCE.

3. Safety risk assessment of dangerous goods container port operations

3.1. Indicator system

3.1.1. Accidents causes analysis of dangerous goods container port operation. Statistical analysis of 116 dangerous goods container port operations accidents occurred in port areas of major port cities of China such as Dalian, Tianjin, Qingdao, Nanjing, Zhourshan, Ningbo, Guangzhou, and Shanghai from 2005 to 2018. The statistics and analysis of the factors leading to the accident are shown in Table 1.
Table 1. The factors causing the accidents of dangerous goods container port operations.

| Cause                        | Number (Percentage) | Cause                        | Number (Percentage) |
|------------------------------|---------------------|------------------------------|---------------------|
| **Man**                      | 60 (51.7%)          | **Management**               | 8 (6.9%)           |
| Not paying attention to the surrounding | 15                  | Not clean and isolate inflammable and explosive materials | 3                   |
| Violation operation          | 13                  | processing against rules    | 2                   |
| Not paying attention to self-safety | 13                  | Environmental chaos, no protection, no supervision | 1                   |
| Violation crossing and walking | 8                   | Illegal subcontracting      | 1                   |
| Blind rescue                 | 4                   | No fire permit               | 1                   |
| Concealing dangerous goods   | 2                   | **Machine**                 | 23 (19.8%)         |
| Falling down                 | 2                   |                             |                     |
| Improper operation leads to collision | 1               | Equipment failure            | 3                   |
| Not wearing personal protective equipment | 1                | Corrosion and rupture of pipeline | 3                   |
| Testing operation environment | 1                   | Equipment parts drop        | 2                   |
| **Environment**              | 2 (1.7%)            | Equipment overturning       | 1                   |
| The gust of wind slammed the tarpaulin | 1              | Equipment welding off       | 1                   |
| Lightning strike             | 1                   | Partial load fracture collapse | 1             |
| **Goods**                    | 23 (19.9%)          | Leak electricity             | 1                   |
| Unstable goods causes falling and collapsing | 13               | Elbow split                 | 3                   |
| Remnant goods falling        | 2                   | Others                       | 4                   |
| Auto ignition                | 5                   |                              |                     |
| Goods reaction               | 3                   |                              |                     |

It can be seen from the statistics that, first, among the 116 accidents, the proportion of accidents caused by “man” factors is the highest, at 51.7%, most of which are due to subjective factors caused by the ability and quality of the workers themselves, such as “not paying attention to the surrounding”, “violation operation”, “not paying attention to self-safety”. Then, the proportion of accidents caused by “equipment” and caused by “goods” are also as high as 19.8%.

3.1.2. Risk identification based on fishbone diagram. The fishbone diagram was proposed by Japanese researchers in the 1960s. It was originally used in the shipyard's process quality management. It is named for its graphic shape and is widely used in process safety analysis because of its features of intuitive and easy to use. Using this method combined with the statistical analysis results of port operations accidents of dangerous goods containers, considering the six aspects of working scale, risk, site, system and management, emergency response capability and accident statistics, the results of identifying the operations safety risks are shown in Figure 2.
In summary, this paper constructs a universally applicable risk assessment indicator set for port operations of dangerous goods containers, as shown in Table 4. The indicator system consists of six 1st-level indicators and 19 2nd-level indicators.

Table 2. Safety risk assessment indicator set for dangerous goods container port operations.

| Object layer | 1st-level indicator | 2nd-level indicator | Content of indicator evaluation |
|--------------|---------------------|---------------------|---------------------------------|
| Working scale A1 | Number of workers B1 | Number of personnel per shift in dangerous goods container operations |
| | Annual throughput B2 | Annual throughput of dangerous goods containers |
| | Funding guarantee B3 | The proportion of annual expenditure on enterprises production safety |
| | Number of facilities B4 | Number of operations-related equipment and automation levels |
| Goods risk A2 | Oxidation, corrosion and other goods B5 | Oxidation, corrosion and other goods hazards and workload proportion |
| | Flammable goods B6 | Flammable goods hazards and workload proportion |
| | Toxic or infectious goods B7 | Toxic or infectious goods hazards and workload proportion |
| | Explosives B8 | Explosives hazards and workload proportion |
| Working conditions A3 | Warning and notification B9 | Warning and notification settings condition for dangerous goods container port operations |

Figure 2. Fishbone diagram for dangerous goods container port.
3.2. Weight distribution
Using the AHP, based on the analysis of the key points and difficulties of safety management of dangerous goods container port operations, the importance of each level indicators is compared in pairs, and the same level indicators are compared in pairs to construct a judgment matrix, and the consistency check is performed until “pass” to determine the weight of each indicator in the hierarchical indicator system.

| Level | A1     | A2     | A3     | A4     | A5     | A6     | CW    | Global CI | Global RI | Global CR | Pass or not |
|-------|--------|--------|--------|--------|--------|--------|-------|-----------|-----------|-----------|-------------|
| B1    | 0.083  | 0.070  | 0.189  | 0.193  | 0.227  | 0.238  | 0.014 |           |           |           |             |
| B2    | 0.168  |        |        |        |        |        | 0.187 | 0.040     | 0.491     | 0.081     | Yes         |
| B3    | 0.371  | 0.023  |        |        |        |        | 0.315 |           |           |           |             |
| B4    | 0.371  | 0.247  | 0.247  |        |        |        | 0.031 |           |           |           |             |
| B5    | 0.446  | 0.120  | 0.120  |        |        |        | 0.008 |           |           |           |             |
| B6    | 0.371  | 0.143  | 0.143  |        |        |        | 0.027 |           |           |           |             |
| B7    | 0.446  | 0.286  | 0.286  |        |        |        | 0.054 |           |           |           |             |
| B8    | 0.187  | 0.571  | 0.571  |        |        |        | 0.054 |           |           |           |             |
| B9    | 0.446  | 0.143  | 0.143  |        |        |        | 0.028 |           |           |           |             |
| B10   | 0.286  | 0.286  | 0.286  |        |        |        | 0.055 |           |           |           |             |
| B11   | 0.187  | 0.571  | 0.571  |        |        |        | 0.108 |           |           |           |             |
| B12   | 0.446  | 0.143  | 0.143  |        |        |        | 0.028 |           |           |           |             |
| B13   | 0.571  | 0.571  | 0.571  |        |        |        | 0.110 |           |           |           |             |
| B14   | 0.286  | 0.311  | 0.311  |        |        |        | 0.044 |           |           |           |             |
| B15   | 0.667  | 0.667  | 0.667  |        |        |        | 0.159 |           |           |           |             |

*CW: Comprehensive Weight. CI: Consistency Indicator. RI: Random Consistency Indicator. CR: Consistency Ratio.
3.3. Safety risk assessment

3.3.1. Situation of evaluation object. The study is conducted by a large container terminal company in Tianjin Port, China. The company has six 100,000-ton specialized container berths with an average annual dangerous goods throughput of 35,000 TEU, including the class 2 (gases), class 3 (flammable liquids), class 4 (flammable solids, substances liable to spontaneous combustion), class 5 (oxidizing substances and organic peroxides), division 6.1 (toxic substances), class 8 (corrosive substance), class 9 (miscellaneous dangerous substances and articles, including environmentally hazardous substances). The dangerous goods container port operation process of the company is “container ship – shore container loading bridge – transport vehicle (consignor)”. The dangerous goods containers are not stored in the on-site terminal and yard. The equipment is 23 sets of 65t/66m shore container loading bridges. There are more than 550 related personnel on site, complete with terminal safety facilities, auxiliary production system safety facilities, fire safety facilities and safety signs. Details of the site refer to Figure 3.

![Figure 3. Dangerous goods container port operation site.](image)

3.3.2. Fuzzy evaluation process. Set the comment set \( V = \{ \text{good, better, medium, poor, unacceptable} \} \) \((n=5)\), invite 100 experts in the field of port security management to judge the 19 2nd-level evaluation indicators of dangerous goods containers port operations of the above companies. And obtain the fuzzy mapping relationship and fuzzy matrix \( R_1 \sim R_6 \) of the 2nd-level evaluation indicator of dangerous goods container port operations.

According to the fuzzy matrix of the 2nd-level evaluation indicator, the fuzzy matrix of the 1st-level indicator of dangerous goods container port operations of the company is calculated by using the comprehensive weight vector in Table 3 as matrix \( R \).

\[
R = \begin{bmatrix}
0.054 & 0.102 & 0.357 & 0.361 & 0.028 \\
0.100 & 0.374 & 0.350 & 0.176 & 0.000 \\
0.157 & 0.320 & 0.486 & 0.000 & 0.000 \\
0.072 & 0.257 & 0.443 & 0.228 & 0.000 \\
0.000 & 0.082 & 0.230 & 0.397 & 0.167 \\
0.333 & 0.500 & 0.167 & 0.000 & 0.000
\end{bmatrix}
\]
From Equation 10, the final FCE vector can be derived as:

\[ B = \omega \cdot R = (0.134, 0.283, 0.323, 0.176, 0.04) \]

3.3.3. Quantitative embodiment and analysis of assessment results. In this study, in order to better quantify the security risk level of dangerous goods container port operations, a clear score set \( C \) is set for the fuzzy mapping relationship of the evaluation indicators proposed above, and build a set of safety risk level commentary interval table, as shown in Table 8. Using the mapping relationship between the evaluation vector of the 1st-level and the 2nd-level indicators to the comment set can quantitatively reflect the security risk.

### Table 4. Comprehensive evaluation risk level.

| Comment set | Best | Better | Medium | Poor | Unacceptable |
|-------------|------|--------|--------|------|--------------|
| Fuzzy mapping score \( C \) | 95   | 85     | 75     | 65   | 30           |
| Safety risk comment set score interval | \([100, 90]\) | \((90, 80]\) | \([80, 70]\) | \((70, 60]\) | \((60, 0]\) |

Using the results of the above table, we can calculate the quantitative value of the safety risk level of dangerous goods container port operations of the company. Normalize the safety risk assessment vector \( B' \) to:

\[ B' = \left[ \frac{0.134}{0.956}, \frac{0.283}{0.956}, \frac{0.323}{0.956}, \frac{0.176}{0.956}, \frac{0.04}{0.956} \right] = (0.14, 0.295, 0.338, 0.185, 0.042) \]

The evaluative quantitative scores is:

\[ F = B' \cdot C = 95 \times 0.14 + 85 \times 0.295 + 75 \times 0.338 + 65 \times 0.185 + 30 \times 0.042 = 77.0 \]

4. Conclusions

This study proposes a comprehensive safety risk assessment method that can be applied to port operations of dangerous goods containers, and conducts a case study on a container terminal company in Tianjin Port, China. The research results show that the combination of AHP and fuzzy evaluation can establish an effective risk assessment method, which can be preferably applied to the identification and assessment of safety risks in the dangerous goods container port operations. Through the evaluation results, the risk management and control measures are proposed in a targeted manner, thereby effectively reducing the safety risk of the operation process.

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