Construction risk assessment of green transformation of old industrial plants based on improved FMEA

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Abstract. In view of the problem that the construction process of the green transformation of the old industrial plants is easily affected by its own structure, transformation scheme, building technology and many other uncertain factors, a risk assessment model based on improved FMEA is proposed by combining fuzzy theory and D-S evidence theory. Through the data analysis of the primary indicators, 25 risk factors are screened from five aspects. On the basis of FMEA risk fuzzy evaluation matrix, Murphy’s method is introduced to correct the classical D-S evidence theory gives experts reasonable weight. The risk level is ranked according to the RPN, and the key risks factors in the construction of green transformation project of old industrial plants are determined. Finally, the model is verified by an engineering example, and the evaluation result is consistent with the actual situation.

1. Introduction
The green transformation of old industrial plants is an important way to realize the sustainable development of city memory architecture[1]. However, the reconstruction risk issues become the main cause for restricting development. There are generally problems in transformation of traditional old industrial plants[2]. As for green projects, they should be paid more attention to its technical proposal, environmental care, organizational management, etc. So, it is necessary to research the risk factors in construction of green transformation project of old industrial plants.

In order to improve the risk management levels, Fan, S.J., et al.[3] used AHP and ABC method to manage the risks on the rebuilding of old industrial plants. Liu, W.[4] made a comprehensive evaluation on the safety of old factory buildings. Wu, Q., et al.[5] identified the main risk factors for the old industrial buildings. Guo H.D., et al.[6] improved 4M1E to evaluate the construction safety risk of the recycling of old industrial buildings. Li R.P., et al.[7] discussed the emergency management of unexpected accidents in the construction process. It can be seen that the research on the reuse construction risks of old industrial plants is mainly focused on traditional projects, lack of green transformation projects. And the method cannot in advance predict the potential risks. But FMEA is considered to be the most effective preventive method, capable of identifying and analyzing various potential risk factors of the system[8]. Therefore, this paper improves the traditional FMEA method, on the base of analyzing possible potential risks, proposes risk control strategies for the key risks, so as to control the occurrence of risk events in advance.
2. Risk assessment system

2.1. Evaluation index selection
In addition to the construction risks of traditional projects, green building and other factors should also be considered in green projects. Besides, the construction risk of traditional projects has been relatively mature, which can provide reference for the green ones. Based on investigated 6 typical such projects in China, this paper divided the construction risk of green transformation of old industrial plants into five aspects: Structure reinforcement renovation, Transformation design scheme, Green construction technology, Green construction management, Energy conservation and environmental protection measures. And according to the standard T/CMCA 4001-2018, GB/T 51141-2015 and GB/T 50905-2014, obtain the primary evaluation index.

2.2. Evaluation index determination
The paper index is a qualitative index of respondents' subjective feeling. So Likert five-level scale is adopted to measure each index. During the investigation, the research group issued a total of 200 questionnaires and collected 174 valid ones, and conducted statistical analysis on the data of the recovered effective questionnaires.

- The correlation coefficient between the two items of R41 and R47 are not significant as the overall population (bilateral level of significance is less than 0.05) and low correlation (Pearson correlation coefficient is less than 0.4). Delete the two evaluation indexes.
- The appropriateness of KMO measure of sampling adequacy was 0.651>0.6 and the Battelt test value was 0.000, indicating that the scale was suitable for factor analysis. Also, it can be seen that the commonality was higher than 0.2 and the factor loading was greater than 0.5, indicating that the scale validity was good, all 25 items were retained.
- Table over the total scale item reliability analysis, Cronbach’s α coefficient is 0.941 > 0.8, which indicates that excellent scale of 25 item reliability; All subscales Cronbach’s α coefficients between 0.789 to 0.905, meet the requirements of standard. This shows that the internal consistency reliability of the scale was good, and all the 25 items are reserved.

3. Risk assessment model
The traditional FMEA method evaluates the Occurrence (O), Severity (S), Detection (D) and Risk Priority Number (RPN) to determine the relative risk ranking, then the corresponding governance measures was put forward to the greater factors in advance[9]. But the expert scoring adopted by traditional FMEA may be different in same level due to personal reasons. Therefore, combining with fuzzy theory, fuzzy language is used to replace numerical scoring. Also D-S evidence theory was introduced to allocate the expert weighting reasonably.

3.1. Triangular fuzzy number
Fuzzy number is a powerful tool to describe uncertain information. Because of simple structure and convenient calculation, this paper uses the triangle fuzzy number to describe the inherent meaning of fuzzy language. Besides, the triangular fuzzy number using centroid method has good robustness, so the centroid method is selected in this paper. The calculation formula is:

\[
y^* = \frac{\sum_{i=1}^{n} y \mu_{A_i}(y)}{\sum_{i=1}^{n} \mu_{A_i}(y)}
\]  (1)
3.2. D-S evidence theory

If \( \Theta \) is set as the identification framework, \( m_1 \) and \( m_2 \) are assigned to the groups of probability, the corresponding focal elements are \( A_1, A_2, \ldots, A_k \) and \( B_1, B_2, \ldots, B_l \). \( m \) is used to represent the new evidence after the combination of \( m_1 \) and \( m_2 \), then the D-S combination rule is as follows[10]:

\[
m(\Phi) = 0 \hspace{1cm} m(A) = \frac{1}{1-k} \sum_{A_i \cap B_j = \Phi} m_i(A)m_j(B) \hspace{1cm} k = \sum_{A_i \cap B_j = \Phi} m_i(A)m_j(B) \]

However, when the classical D-S evidence theory fuses highly conflicting evidence, it can produce results that deviate from reality. In this regard, Murphy's method, which is representative of the weighted fusion algorithm, is used to modify the classical D-S combination rule.

3.3. FMEA method based on fuzzy theory

In this paper, the five-level fuzzy language is selected to describe the risk factors as \( U = \{ VL, L, M, H, VH \} \). The triangular fuzzy number \( \tilde{A} = (l, m, n) \) is used to quantify the fuzzy language. The specific steps of risk assessment based on the fuzzy FMEA method are as follows:

- Identify possible risk factors through investigation and research;
- Determine the linguistic variables of risk factors and their corresponding fuzzy numbers;
- The expert team evaluates the risk factors, obtains the FMEA risk fuzzy evaluation matrix;
- The evaluation results of experts on risk factors were obtained by deblurring.

3.4. Expert weighting based on D-S evidence theory

Set up FMEA expert assessment team and complete the assessment process together with the wisdom of the group. However, there are some differences among different experts. Therefore, this paper adopts D-S evidence theory to assign expert weight. The basic steps are as follows:

- Assuming that the initial weight of the experts is \( w_0 = 1/n \), after the fuzzy evaluation matrix is defuzzified, the expectation \( \bar{P} \) for each risk factor can be obtained;
- The Euclidean measurement formula was used to calculate the evaluation deviation \( d_{ij} \):

\[
d_{ij} = \sqrt{\Delta O_i^2 + \Delta S_i^2 + \Delta D_i^2}, \hspace{1cm} \Delta O_i = O_i - \bar{O}_i, \Delta S_i = S_i - \bar{S}_i, \Delta D_i = D_i - \bar{D}_i
\]

(3)

- The evaluation deviation \( d_{ij} \) was normalized to obtain the deviation degree \( r_{ij} \):

\[
r_{ij} = d_{ij} / \sum_{i=1}^{n} d_{ij}
\]

(4)

- Calculate the evaluation confidence degree \( s_{ij} \) of each risk factor:

\[
s_{ij} = (1-r_{ij}) / [\sum_{i=1}^{n} (1-r_{ij})]
\]

(5)

- Modify the classical D-S combination rules and obtain the expert weight \( w_m \).

4. Application case analysis

4.1. Background information

Shougang desulfurization workshop renovation project, formerly known as Shi Jingshan steel making hot metal pretreatment facility, covers an area of 0.89 hectares. According to the site construction conditions and the characteristics of industrial heritage, more than 20 concrete columns are reserved. The former plant structure is transformed into east building and west building by fabricated construction, in which the east building is steel cable structure and the west is steel frame structure.
The goal is to transform the plant into a demonstration project of green ecological park, and realize the upgrading of the transformation mode of industrial heritage.

4.2. The risk assessment

This paper considering the construction characteristics and design features of the old industrial plant green transformation project, the FMEA expert evaluation team of the desulfurization workshop renovation project was established which was composed of 5 professional technicians. The experts filled in the FMEA questionnaire and the fuzzy evaluation matrix is obtained. The initial weight of experts is 1/5, and transform the fuzzy matrix into triangular fuzzy number. After the defuzzification, the expected value of risk factors of the expert group was obtained. The evaluation deviation, deviation degree and confidence degree were calculated:

\[
\begin{bmatrix}
3.40 & 7.30 & 3.40 & 7.90 & 4.20 & 6.20 & 3.40 & 4.60 & 6.20 & 4.20 & 8.50 & 5.40 & 8.20 \\
7.30 & 8.20 & 8.50 & 8.50 & 7.00 & 8.20 & 6.60 & 8.20 & 6.20 & 6.60 & 3.80 & 5.00 & 7.30 \\
7.20 & 7.60 & 5.00 & 7.30 & 1.50 & 7.60 & 8.20 & 3.80 & 4.20 & 3.90 & 2.70 & 2.40 & 3.90 \\
2.26 & 1.64 & 0.50 & 0.71 & 1.21 & 1.56 & 1.50 & 1.20 & 2.15 & 2.19 & 1.47 & 0.78 & 3.87 \\
1.87 & 1.64 & 2.06 & 1.70 & 1.03 & 1.56 & 1.50 & 1.20 & 1.50 & 3.03 & 1.72 & 1.49 & 2.64 \\
1.76 & 2.17 & 2.06 & 0.71 & 1.21 & 2.01 & 1.50 & 1.20 & 1.50 & 3.03 & 1.72 & 1.49 & 2.64 \\
1.64 & 1.04 & 2.06 & 0.71 & 1.03 & 1.28 & 1.20 & 1.96 & 1.20 & 3.23 & 2.40 & 0.78 & 1.84 \\
\end{bmatrix}
\]

The calculation formula of the improved FMEA method can be deduced as follows:

\[
\begin{align*}
RPN & = O_j \times S_j \times D_j, \\
O_j & = \sum_{i=1}^{n} w_i O_{ij}, \\
S_j & = \sum_{i=1}^{n} w_i S_{ij}, \\
D_j & = \sum_{i=1}^{n} w_i D_{ij}
\end{align*}
\]

(6)

4.3. Risk assessment results

According to the rank of RPN, the relative risk level of each risk factor was sorted (in Table 1). Finally, the key factors of the construction risk of green transformation of old industrial plants are: R12 (Dismantling of failed member), R32 (Network system refurbishment), R22 (Obstacles components), R33 (Electrical and mechanical update), R45 (Green construction cost control).

Compared with the case, it can be found that they are consistent with the actual situation.

| Item index | \( O_j \) | \( S_j \) | \( D_j \) | RPN | Rank |
|------------|-----------|-----------|-----------|-----|------|
| Structure safety testing quality (R11) | 3.48 | 7.28 | 7.76 | 196.59 | 13 |
| Dismantling of failed member (R12) | 7.28 | 8.72 | 7.80 | 495.16 | 1 |
5. Risk control strategies

**Focus on demolition works.** Lack of basic data brings difficulties to the dismantling of the invalid components. And because the mechanical balance of the original structure is disturbed by reconstruction, accidents happen from time to time. In view of the problem, before the demolition should fully understand the structural performance, determine the scientific demolition method, implement the safety technology disclosure, to ensure the smooth operation process.

**Optimized transformation scheme.** It is necessary to consider the environment, resources and climate where the project is located, so that the plan can be adapted to the conditions. In such projects, the underground pipe network system also should be re-planned in combination with the regenerative function. The original equipment and facilities can no longer meet the functional requirements of the reconstructed building, so they can be properly updated and upgraded.

**Control construction cost.** Focus should be placed on the control of construction costs, as cost overruns are a common risk for such projects. Moreover, the use of high-cost materials and technology is not significant for the green transformation of old industrial plants. Therefore, the financial plan should make full use of the existing materials and renewable energy to save the construction cost while preserving the solidified energy in existing components.

**Promoting innovative development.** There are some problems in old industrial plants, such as environmental pollution, vegetation degradation and land suitability reduction. In view of this, in the process of transformation, on the basis of monitoring and controlling the external ecological environment, concepts of "passive" and "sponge" should be integrated, ecological health evaluation should be carried out and design of "sustainable landscape" should be promoted.

6. Conclusion

Traditional plant transformation is mostly from the perspective of culture and art. Although changed the fate of the demolition. But due to the lack of consideration in terms of reducing energy consumption and creating a healthy and comfortable environment, It has not reached the development goal of meeting economic restructuring and promoting ecological cycle. Therefore, it is an inevitable
trend of current sustainable developing to optimize the transformation of old industrial plants by incorporating green ideas.

In this paper, the construction risk of green transformation of old industrial plants are divided into 5 aspects: Structure reinforcement renovation, Transformation design scheme, Green construction technology, Green construction management, Energy conservation and environmental protection measures. By introducing the fuzzy theory and D-S evidence theory to improve the traditional FMEA method, 5 key risk factors that should be paid attention to in the green transformation project of old industrial plants were identified and the corresponding risk control strategies were proposed. Based on the engineering example, it is found that the improved model is consistent with the actual situation, which is helpful for the project manager to identify and control the risks and ensure the smooth implementation of such projects.

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