A Selection Method for Pipe Network Boosting Plans

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Abstract. Based on the fuzzy mathematics theory, a multi-objective fuzzy comprehensive evaluation method used for selection of pipe network boosting plans was proposed by computing relative membership matrix and weight vector for indexes. The example results show that the multi-objective fuzzy comprehensive evaluation method combining the indexes and the fuzzy relationship between them is suited to realities and can provide reference for decision of pipe network boosting plan.

1. Introduction
It can be beneficial to the efficient development of the gas field by boosting the ground station and the gas gathering pipeline[1,2]. During the selection of pipe network boosting plans, it is necessary to take into account the technical and economic indexes such as the additional value of recoverable reserves, pipeline pressure drop, financial internal rate of return. The relationship between these indexes is contradictory as well as interdependent, moreover, the advantages and disadvantages of each index are relative and fuzzy. It is not proper to define the entire pipe network boosting plan based on one single economic or technical index. In this paper, a multi-objective fuzzy comprehensive evaluation method is applied to the pipe network boosting plans to get the optimal plan considering all indexes.

2. Basic principle of multi-objective fuzzy comprehensive evaluation method
There are n plans to be evaluated, and the set of decision domain is \( U = \{u_1, u_2, \ldots, u_n\} \). Each program contains m indexes involved in the evaluation, expressed as \( X = \{x_1, x_2, \ldots, x_n\} \). Using \( d_{ij} \) to express the \( x_i \) index of the \( u_j \) plan, the decision matrix \( D \) can be expressed as:

\[
D = \begin{bmatrix}
    d_{11} & d_{12} & \cdots & d_{1n} \\
    d_{21} & d_{22} & \cdots & d_{2n} \\
    \cdots & \cdots & \cdots & \cdots \\
    d_{m1} & d_{m2} & \cdots & d_{mn}
\end{bmatrix}
\]  (1)

According to the fuzzy set theory, the relative membership matrix \( R \) corresponding to the decision matrix \( D \) can be calculated according to the membership degree. And \( r_{ij} \) represents the evaluation value of the index \( x_i \).
The weights of each index in X are written in vector form, \( \mathbf{w} = \{w_1, w_2, \ldots, w_m\} \), where \( \sum_{i=1}^{m} w_i = 1 \).

Using fuzzy relation operation, the multi-objective fuzzy comprehensive evaluation model is:

\[
\mathbf{B} = \mathbf{W} \cdot \mathbf{R} = \{b_1, b_2, \ldots, b_n\}
\]

According to the principle of maximum membership, the corresponding plan of \( \text{Maxmum}\{b_1, b_2, \ldots, b_n\} \) is the optimal value plan for comprehensive evaluation\(^{[3,4]}\).

Therefore, the steps of fuzzy comprehensive evaluation method include: (1) Collect basic information about the target to be evaluated. (2) Determine its technical and economic indexes. (3) Establish the relative membership matrix \( \mathbf{R} \) of the plans and the evaluation indexes. (4) Determine the weight vector \( \mathbf{W} \) of each index. (5) Evaluate the optimal selection according to the comprehensive evaluation model.

### 2.1. The calculation of relative membership matrix \( \mathbf{R} \)

According to different indexes, how to determine the membership degree of each plan relative to the ideal plan is the key to use multi-objective fuzzy comprehensive evaluation method. In the ideal plan, \( c_i \ (i = 1, 2, \ldots, m) \) is the optimal value of the index \( x_i \). The maximum and minimum values of the indexes \( x_i \) in the plan are represented by \( d_i^+ = \max(d_{i1}, d_{i2}, \ldots, d_{ij}) \) and \( d_i^- = \min(d_{i1}, d_{i2}, \ldots, d_{ij}) \).

The evaluation indexes are usually divided into three types: benefit indexes, cost indexes, and moderate indexes, each have different calculation method of membership degree \( r_{ij} \)\(^{[5]}\).

1. **The benefit indexes**, also known as positive indexes, that is, the larger the index value, the better the plan.

\[
r_{ij} = \begin{cases} 
0 & d_{ij} < d_i^- \\
\frac{d_{ij}-c_i}{d_i^+-d_i^-} & d_i^- \leq d_{ij} < d_i^+ \\
1 & d_{ij} \geq d_i^+
\end{cases}
\]

2. **The cost indexes**, also known as the negative index, that is, the smaller the index value, the better the plan.

\[
r_{ij} = \begin{cases} 
0 & d_{ij} \geq d_i^+ \\
\frac{c_i-d_{ij}}{d_i^+-d_i^-} & d_i^- \leq d_{ij} < d_i^+ \\
1 & d_{ij} < d_i^-
\end{cases}
\]

3. **The moderate indexes**, the closer the index value is to the \( c_i \) value, the better the plan.

\[
r_{ij} = \begin{cases} 
\frac{d_{ij}-d_i^-}{c_i-d_i^-} d_i^- \leq d_{ij} < c_i \\
\frac{d_i^+-d_{ij}}{c_i-d_i^-} & c_i \leq d_{ij} < d_i^+ \\
1 & d_{ij} < d_i^- \text{ or } d_{ij} \geq d_i^+
\end{cases}
\]

If it is better that the index value is closer to the interval \([a, b]\), then
From the above calculation method, the relative membership matrix is \( R = (r_{ij})_{m \times n} \).

### 2.2. The calculation of weight vectors

Analytic Hierarchy Process which combines qualitative analysis with quantitative analysis is one of the commonly used methods for calculating the weight of indexes. Firstly, the indexes were compared in pairs, and the Numbers 1~9 were used to quantify them [6]. And then use the appropriate mathematical method to obtain the multifactor comparison judgement matrix \( A: A = (a_{ij})_{m \times n} \) from the results of all the pairwise comparison.

| Qualitative results                  | Quantitative results |
|-------------------------------------|----------------------|
| Ai has the same influence as Aj     | \( a_{ij} = 1 \)     |
| Ai has a slightly stronger influence than Aj | \( a_{ij} = 3 \)     |
| Ai has a stronger influence than Aj | \( a_{ij} = 5 \)     |
| Ai has an apparently influence than Aj | \( a_{ij} = 7 \)     |
| Ai has a absolutely influence than Aj | \( a_{ij} = 9 \)     |
| Intermediate values between the two adjacent judgments | \( a_{ij} = 2, 4, 6, 8 \) |
| Ai and Aj have the opposite influence | \( a_{ij} = 1, 1/2, \ldots, 1/9 \) |

Through the judgment matrix, the eigenvector corresponding to the maximum eigenvalue can be calculated as its initial weight vector. After normalization, the weight vector \( W \) is obtained.

### 3. Application and Discussion

Take the pipe network boosting plan in the literature [1] as an example, the multi-objective fuzzy comprehensive evaluation method is applied to optimize selection.

| Plan  | Plan2 | Plan3 | Plan4 | Plan5 | Plan6 | Plan7 | Plan8 | Plan9 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| The additional value of recoverable reserves (10^8m³) | 1.342 | 1.141 | 1.146 | 1.147 | 1.145 | 1.143 | 1.144 | 1.148 | 1.148 |
| Average pressure drop per unit length of pipeline (MPa.km⁻¹) | 0.098 | 0.092 | 0.08 | 0.123 | 0.08 | 0.108 | 0.093 | 0.07 | 0.06 |
| Pressure of the pipe network in the well area (MPa) | 2.39 | 2.23 | 2.2 | 2.4 | 1.85 | 1.88 | 1.89 | 1.3 | 1.34 |
| The total power required for the compressor (kW) | 570 | 530 | 545 | 550 | 445 | 470 | 465 | 380 | 430 |
| Total investment (Ten thousand yuan) | 2437.07 | 2175.25 | 2169.6 | 1832.86 | 2598.96 | 1493.86 | 1647.99 | 2409.16 | 1443.06 |
| Financial internal rate of return (%) | 18.12 | 15.86 | 15.96 | 30.89 | 19.71 | 48.66 | 42.17 | 24.26 | 22.4 |

From the results, Plan 8 has the highest financial internal rate of return, followed by Plan 4 and Plan 7. Plan 9 has the lowest financial internal rate of return. Therefore, Plan 8 is the optimal choice.
According to equation (4) ~ (7), the relative membership matrix \( R \) is calculated as:

\[
\begin{bmatrix}
1 & 0 & 0.025 & 0.03 & 0.02 & 0.01 & 0.015 & 0.035 & 0.035 \\
0.397 & 0.492 & 0.683 & 0 & 0.683 & 0.238 & 0.476 & 0.841 & 1 \\
0.009 & 0.155 & 0.182 & 0 & 0.5 & 0.473 & 0.464 & 1 & 0.964 \\
0 & 0.211 & 0.132 & 0.105 & 0.658 & 0.526 & 0.553 & 1 & 0.737 \\
0.14 & 0.367 & 0.371 & 0.663 & 0 & 0.956 & 0.823 & 0.164 & 1 \\
0.069 & 0 & 0.003 & 0.458 & 0.117 & 1 & 0.802 & 0.256 & 0.199 \\
0.075 & 0 & 0.003 & 0.461 & 0.118 & 1 & 0.803 & 0.257 & 0.2 \\
0.126 & 0 & 0.005 & 0.637 & 0.158 & 1 & 0.893 & 0.377 & 0.298 \\
\end{bmatrix}
\]

The initial weight of each index is determined by Analytic Hierarchy Process, \( W_0 = (0.5589, 0.2795, 0.3323, 0.1662, 0.3952, 0.47, 0.235, 0.1976) \)

After normalization, the weight vector is obtained, \( W = (0.2121, 0.1061, 0.1261, 0.0631, 0.15, 0.473, 0.464, 1, 0.964) \)

The results of multi-objective fuzzy comprehensive evaluation are:

\[
B = W \cdot R = (0.3048, 0.14, 0.1658, 0.283, 0.2245, 0.6062, 0.5521, 0.4074, 0.5073)
\]

According to the maximum optimal principle, the optimal result is plan 6 > plan 7 > plan 9 > plan 8 > plan 1 > plan 4 > plan 5 > plan 3 > plan 2. Plan 6 is the best option, followed by plan 7, plan 9, plan 8, plan 1, and the other four plans are inferior, which should not be adopted.

The order of the plan obtained by multi-objective fuzzy decision analysis is basically the same as the order of the plan obtained by the single index method, but there are still differences. For example, although the internal rate of return of plan 4 is relatively high, it should not be used because the comprehensive evaluation is worse when using multi-objective decision making method.

4. Conclusion

(1) The multi-objective fuzzy comprehensive evaluation method takes into account the index information and the fuzziness of the indexes. Therefore, the results are more realistic and provide a reliable reference for the selection of pipe network boosting plans.

(2) When using Analytic Hierarchy Process to determine the weight, the survey opinions of several experts should be integrated to evaluate the comparison of two indexes, so as to improve the accuracy of the results.
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