Research on Application Effect Evaluation of Steel Box Girder Bridge Based on Combination Weighting

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Abstract. At present, the research on the application effect of steel box girder bridges is still only in the qualitative analysis link, and the calculation of index weights is greatly affected by personal subjective factors, and the quantitative evaluation of the application effect of steel box girder bridges has not been achieved. In this paper, we propose a combination of subjective and objective combined weighting fuzzy evaluation model, which avoids the unreasonable problem of a single weighting method in determining the weight coefficients, and makes the weight distribution results more accurate and effective. Among them, the coefficient of variation method and the AHP method are used to calculate the subjective and objective weights of the indicators, and the linear combination calculation method is used to determine the comprehensive weights of the indicators. Then, combined with the fuzzy evaluation model, a comprehensive analysis of the application effect is carried out. Finally, the effectiveness of the combined weighting evaluation model is verified with a practical project case.

1. Introduction
In recent years, with the continuous extension of our country's highway network, problems such as long construction period and many potential safety hazards of traditional cast-in-place concrete bridges have become increasingly prominent. With the continuous development of steel structure technology and large-span bridge construction, road bridge steel box girder structures with short construction period, low environmental impact, and simple maintenance have been widely used.

However, the current evaluation of the application effect of steel box girder technology is still only at the qualitative level, lacking quantitative analysis and the evaluation results are general and unobjective. Therefore, it is particularly important to comprehensively evaluate the application effects of steel box girder bridges, find out the shortcomings in project construction, and improve the evaluation level.

Domestic and foreign scholars have carried out a lot of research on the evaluation of the application effect of engineering projects, and have achieved certain results in related theories and models. Established a comprehensive evaluation model for steel box girder construction safety risks by combining triangular fuzzy number method, Bayesian theory and fuzzy comprehensive evaluation method[1]; based on the combination of BP neural network technology and fuzzy theory, the welding quality of steel box girder is evaluated effectively[2]; used the analytic hierarchy process and improved value approximation ideal solution sequencing model to evaluate the risk of the highway construction plan, and made good progress in the highway construction[3]; the coefficient of variation method and the approach to ideal point method, combined with the grey relational analysis theory to construct the safety facility evaluation model of the expressway[4]; used game theory to optimize the
fuzzy analytic hierarchy process and the critic method to establish a finite cloud model, so as to determine the risk level of each tailing pond[5].

At present, there are relatively few comprehensive evaluation studies on the application effects of steel box girder technology. The commonly used evaluation methods are mainly Delphi method and Monte Carlo simulation method. However, in view of the many influencing factors in the construction process of engineering projects, the single weighting method is more one-sided in determining the weight coefficient, and it is difficult to guarantee the accuracy and reliability of the evaluation results.

Therefore, in accordance with the idea of combining subjective and objective, this paper proposes a combined weighting model to determine the index weights based on the coefficient of variation method and the AHP method. Through the comprehensive evaluation of each section of the steel box girder bridge by using the fuzzy comprehensive evaluation method, the comprehensive evaluation grade of steel box girder bridge is obtained and the shortcomings in the project construction are pointed out, which provides an effective reference for the construction and management of steel box girder bridges. And use this model to comprehensively evaluate and analyze the application effect of a steel box girder bridge on a certain expressway in Henan, so as to verify the feasibility of this method.

2. Fuzzy Evaluation of Coefficient of Variation-AHP Combination Weighting

The single weighting method may be too subjective when determining the index weight, or only rely on data, so it cannot accurately and comprehensively reflect the importance of the index. AHP (Analytic Hierarchy Process) method of subjective weighting, coefficient of variation method objective weighting and linear combination calculation methods are used to determine the index weight coefficients. At the same time, the fuzzy comprehensive evaluation method is used to achieve quantitative analysis of fuzzy things in the evaluation process, to a certain extent, to avoid the shortcomings of a single empowerment method.

2.1. AHP (Analytic Hierarchy Process) method subjective empowerment

(1) Establish a judgment matrix

A judgment matrix is constructed by comparing the importance of each level of evaluation indicators. The importance of the indicators is determined by the scale of 1-9 proposed by Saaty[6]. The values and meanings of the judgment matrix are shown in table 1.

| Scale | \( a_{ij} \) | Meaning (\( i,j \)) |
|-------|-------------|------------------|
| 1     | \( i,j \) indicators are equally important |
| 3     | \( i \) index is slightly more important than \( j \) index |
| 5     | \( i \) index is more important than \( j \) index |
| 7     | \( i \) index is much more important than the \( j \) index |
| 9     | \( i \) index is more important than absolute \( j \) index |
| 2, 4, 6, 8 | Between the above adjacent judgment scale values |
| Reciprocal | If the judgment value of index \( i \) is compared with index \( j \) is \( a_{ij} \), then the judgment value of index \( j \) is \( 1/a_{ij} \) product. |

(2) Calculate the weight of the evaluation index

This paper uses the square root method to calculate the weight of each indicator \( B = (b_{ij})_{n \times n} \) in the criterion layer to the target layer \( A \).

\[
W_i = \sqrt[n]{\prod_{j=1}^{n} b_{ij}}, \quad W_i = \frac{W_i}{\sum_{j=1}^{n} W_j} \tag{1}
\]
That is, the weight of index \( B = (B_1, B_2, B_3, \cdots, B_n)^T \) to index A is: \( W = (W_1, W_2, W_3, \cdots, W_n)^T \).

(3) Consistency inspection

Calculate the maximum eigenvalue of the judgment matrix and judge the consistency

\[
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \left( B W \right)_i, \quad CI = \frac{\lambda_{\text{max}} - n}{n-1}
\]  

(2)

Among them, for the average random consistency index RI of the judgment matrix, whether the judgment matrix has satisfactory consistency, the RI values under different orders are shown in table 2.

| n  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9  |
|----|---|---|---|---|---|---|---|---|----|
| RI | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

When the order is greater than 2, the ratio of the consistency index CI to the average random consistency index RI is called the random consistency ratio, which is recorded as CR; at the same time, when CR<0.1, it can be judged that the judgment matrix has passed the consistency test and the evaluation result is feasible; otherwise, the judgment matrix should be adjusted appropriately.

2.2. Steps to determine the objective weight by the coefficient of variation method

In view of the one-sidedness of the single subjective weight method in determining the weight, the objective weighting of the coefficient of variation method is to further determine the coefficient of variation by calculating the ratio of the average of each evaluation index to the standard deviation. If the degree of variation of the actual calculation data is greater, the weight assigned is positively correlated; on the contrary, the weight of the indicator is smaller, which can objectively and effectively reflect the degree of differentiation of various indicators, which is an objective method of calculating weights, the main calculation steps are as follows[7]:

(1) Calculate the coefficient of variation of each index:

\[
S_j = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_j - \bar{x}_j)^2}, \quad V_j = \frac{S_j}{\bar{x}_j} \quad (3)
\]

(2) Normalize each evaluation index to calculate the weight of each index:

\[
W_j = \frac{V_j}{\sum_{j=1}^{n} V_j} \quad (4)
\]

In the formula, \( \bar{x}_j \) is the average value of the j-th evaluation index; \( V_j \) is the coefficient of variation; \( W_j \) is the evaluation index weight.

2.3. Coefficient of Variation-AHP Method Combination Weighting

In order to further improve the accuracy of the evaluation index weights, a linear combination calculation method based on subjective and objective weighting is proposed for the weights obtained by the above-mentioned coefficient of variation method and AHP method to determine the combined weights of the indicators[8]. In order to reduce the subjective and objective weight deviation and improve the reliability of the weight value, the main calculation steps are as follows:

\[
W_{ij} = \alpha W_i + (1 - \alpha) W_j \quad (5)
\]

In the formula, \( W_i \) is the weight calculated by the AHP method, \( W_j \) is the weight calculated by the coefficient of variation method, and \( \alpha \) is the proportion of the subjective weight in the combination.

The objective function is used to find the optimal value of \( \alpha \), so as to obtain the optimal combination weighting value.
Through the objective function calculation, the optimal solution is 0.5.

2.4. Fuzzy comprehensive evaluation

As a quantitative evaluation method for fuzzy things, the fuzzy comprehensive evaluation method is conducive to the realization of quantitative analysis of fuzzy things on the basis of qualitative analysis.

For the evaluation index system, establish multiple evaluation index factor sets \( U = [u_1, u_2, u_3, \ldots, u_n] \), and based on the single factor evaluation results, establish the corresponding evaluation set \( V = [v_1, v_2, v_3, \ldots, v_m] \) and the degree of membership \( r_{ij} \), this paper adopts the triangular distribution function and establishes the corresponding membership function, and constructs the membership function formula according to the corresponding index.

\[
B = W \cdot R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix} \quad (7)
\]

In the formula, \( r_{ij} \) represents the degree of membership of the index factor \( u_i \) and the evaluation set \( v_j \); \( W \) is the importance weight set; \( R \) is the evaluation matrix; \( B \) is the corresponding fuzzy comprehensive evaluation set.

3. Example application

This article uses the construction of a steel box girder project of an expressway in Henan as the research background. Divide it into 4 sections and use the actual test data as the analysis sample to verify the coefficient of variation-AHP method in expressway steel box girder. Effectiveness in the comprehensive evaluation of the application effect of beam technology.

The comprehensive evaluation of the application effect of steel box girder technology is mainly conducted from five aspects that affect the quality, schedule, safety, cost and environmental impact factors of project management. The evaluation system is divided into target level: comprehensive evaluation index for the application effect of steel box girder technology; criterion level: engineering quality, project progress, engineering safety, engineering cost and engineering environment regarding the application effect of steel box girder technology; index level: evaluation of specific indicators for relevant elements in the application process of steel box girder technology in the criterion layer, so as to construct a comprehensive evaluation system for the application effect of steel box girder bridges and the details are shown in table 3.

At the same time, according to the relevant specifications for the application of expressway steel box girder technology, this article divides the index levels into four application effect evaluation levels, namely first level (excellent), second level (good), third level (medium), and fourth level (poor), the critical value of each index is determined according to relevant specifications.

| Table 3. Comprehensive evaluation index system of application effect of steel box girder bridge |
|---------------------------------------------|
| Target level | criterion level | index level |
| Engineering quality B1 | Steel quality C1 | Geomtry size of beam C2 |
| Weld quality C3 | Anti-rust coating C4 |
| Linear error C5 | Interference in the production process C6 |
| Project progress B2 | Interference during transportation C7 |
### Comprehensive evaluation index of application effect of steel box girder bridge

- **Engineering safety** (B3)
  - Interference of welding assembly (C8)
  - Interference of hoisting erection (C9)
  - Human unsafe behavior (C10)

- **Integrity rate of machinery and equipment** (C11)
- **Construction environment interference** (C12)
- **Traffic Guarantee Plan** (C13)
- **Engineering cost** (B4)
  - Additional material fee (C14)
  - Additional labor cost (C15)
  - Additional station fee (C16)
- **Engineering environment** (B5)
  - Wastewater pollution (C17)
  - Solid waste pollution (C18)
  - Civilized Construction (C19)

### 3.1. Calculation of combined weight of steel box girder

The subjective weight is obtained by the AHP method through formula (1)–(2); at the same time, according to the measured value data of the indicators, from formula (3)–(4) uses the coefficient of variation method to obtain the objective weight W; finally, Matlab is used to obtain the combination weight W of the indicators according to the equations (5) ~ (6); the relevant indicator combination weight values are shown in Table 4.

#### Table 4. Weight values of each index

| Evaluation index | Subjective weight | Objective weight | Comprehensive weight |
|------------------|-------------------|------------------|---------------------|
| C1               | 0.023             | 0.001            | 0.012               |
| C2               | 0.009             | 0.010            | 0.010               |
| C3               | 0.006             | 0.002            | 0.004               |
| C4               | 0.012             | 0.004            | 0.008               |
| C5               | 0.003             | 0.027            | 0.015               |
| C6               | 0.015             | 0.095            | 0.055               |
| C7               | 0.076             | 0.142            | 0.109               |
| C8               | 0.045             | 0.142            | 0.094               |
| C9               | 0.026             | 0.177            | 0.102               |
| C10              | 0.015             | 0.113            | 0.064               |
| C11              | 0.053             | 0.071            | 0.062               |
| C12              | 0.01              | 0.026            | 0.018               |
| C13              | 0.033             | 0.018            | 0.026               |
| C14              | 0.075             | 0.006            | 0.041               |
| C15              | 0.03              | 0.013            | 0.022               |
| C16              | 0.16              | 0.009            | 0.085               |
| C17              | 0.07              | 0.046            | 0.058               |
| C18              | 0.213             | 0.080            | 0.147               |
| C19              | 0.124             | 0.017            | 0.071               |

It can be seen from Table 4 that the combination weighting method is used to calculate the index weight value, and the coefficient of variation method is combined with the traditional AHP method, which can avoid the shortcomings of a single method in calculating weights, and can more accurately reflect each the degree of influence of the evaluation index in the project evaluation.

Among the combined weights, the weight value of solid waste pollution (C18) is 0.147, which is the highest weight, indicating that strengthening the control of solid waste pollution during the construction of steel box girder bridges plays an important role in the overall evaluation effect; the weight values of interference (C7) and interference (C9) of hoisting erection are 0.109 and 0.102,
respectively, which account for a higher weight, indicating that the control of the transportation and hoisting progress of steel box girder in the construction of steel box girder bridges is the result of comprehensive evaluation of impact Important factor.

According to the characteristics of steel box girder technology application, a three-level index system was constructed. In the evaluation study based on the combination of coefficient of variation-AHP method, it was found that the index weights of the three calculation methods are significantly different. As a subjective weighting method, the AHP method is affected by subjective experience factors, which makes the gap between the indicator weights larger, and it is difficult to reflect the true evaluation results. The weighting calculation of the comparative analysis method of the coefficient of variation is more objective, but when the average value of the indicator is close to Small disturbances at 0 will cause deviations in the value of the coefficient of variation, thereby reducing the reliability of the calculation and analysis results. Therefore, this paper adopts the combined weighting method to further highlight the important influencing factors on the basis of maintaining the objectivity of the evaluation, so that the weight value of the evaluation index is more scientific and effective.

3.2. Evaluation grade of steel box girder technology application
By bringing the quantified value of the project evaluation index into the membership function, the membership level of the steel box girder technology application evaluation index is further obtained. Here, the index layer of the "engineering quality" element is taken as an example for comprehensive calculation.

By constructing the evaluation index set and evaluation matrix of the "engineering quality" elements, according to the above-mentioned coefficient of variation-AHP method, the comprehensive weight is $W_i = (0.012, 0.01, 0.004, 0.008, 0.015)$, and the comprehensive evaluation result is $B_i = (0.004, 0.010, 0.036, 0.011)$. Therefore, according to the principle of maximum degree of membership, it can be known that the quality of steel box girder bridge project quality is "medium".

In the same way, the fuzzy comprehensive evaluation results of other index levels can obtained respectively: $B_2 = (0.034, 0.254, 0.072, 0)$; $B_3 = (0, 0.092, 0.078, 0)$; $B_4 = (0.081, 0.067, 0, 0)$; $B_5 = (0.069, 0.133, 0.074, 0)$.

According to the principle of maximum degree of membership, the comprehensive evaluation results of the application effect of steel box girder bridges are determined, as shown in table 5.

| Evaluation grade | Evaluation result |
|------------------|-------------------|
| Level 1 (Excellent) | 0.055 |
| Level 2 (Good) | 0.124 |
| Level 3 (Medium) | 0.052 |
| Level 4 (Poor) | 0.001 |

| Evaluation result |
|-------------------|
| Level 2 (Good) |

3.3. Evaluation results
In summary, through the evaluation model of coefficient of variation and combined weight of AHP method, the comprehensive evaluation result of the application of steel box girder bridge in an expressway in Henan is level 2 "good", and the best evaluation result of cost control effect is level 1 "excellent". The evaluation result of engineering quality control, engineering progress management and engineering safety is level 2 "good", while the evaluation result of engineering quality is generally the third level "medium".

Therefore, it is necessary to further strengthen the inspection and management of steel quality in the subsequent construction of related projects, and further improve the evaluation level of project
quality. The evaluation result is consistent with the actual situation of the project, which verifies the effectiveness of the method in the comprehensive evaluation of the application effect of steel box girder bridges.

4. Conclusion
In this study, by combining the whole application process of steel box girder bridges, 19 main factors influencing the application effect of steel box girder bridges in 5 categories were found. For the first time, a comprehensive analysis of the application effect of steel box girder bridge is carried out by combining the fuzzy evaluation model of composite weighting, and the main control links and critical control points in the construction process are further defined, which enriches the index system and evaluation model of the application evaluation of steel box girder bridge.

The fuzzy comprehensive evaluation model of the coefficient of variation-AHP method effectively avoids the one-sidedness of a single method in determining the index weight, reduces the influence of subjective factors, and further improves the accuracy of the evaluation results. However, due to the current steel box girder technology just a few researches on the appraisal of the application, the index system established in this article still has certain shortcomings, and there is a certain degree of subjectivity for the expert scoring in the AHP method. Therefore, in the follow-up research, it is necessary to further improve the selection of indicators and the optimization of evaluation methods.

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References
[1] Hongyun Xue, Fengkun Cui, Xu Dong, Baoqun Wang, Wei Lu, Kai Wang. (2020) Safety Risk Analysis and Control for Construction of Two-way Jacking Steel Box Girder Based on Hybrid Algorithm [J]. Highway, 65 (11): 124-129.
[2] Hongfei Xu, Yunfei Xian, Baisheng Wu. (2020) Welding Quality Evaluation Method of Steel Box Girder Based on Fuzzy BP Neural Network [J]. Science Technology and Industry, 20(12): 233-236.
[3] Haopeng Jiang, Jiancheng Sun, Wenwei Yang, et al. (2020) Risk Evaluation of Highway Construction Scheme Based on AHP and Improved TOPSIS Weight Algorithm [J]. Journal of Wuhan University (Engineering Science), 53(08): 698-703.
[4] He Gao, Huicong Zhou. (2014) Evaluation of Highway Safety Facilities Based on Grey Approximation Ideal Point [J]. Forest Engineering, 30(06): 124-128.
[5] Yixuan Dong, Hongwen Zhou. (2020) Risk assessment of tailings pond dam break based on game theory-finite cloud model [J]. Hydropower and Energy Science, 38(12): 75-78+168.
[6] SAATY T L. (1977) A scaling method for priorities in hierarchical structures [J]. Journal of Mathematical Psychology, 15(3): 234-281.
[7] Peng Huiwu, Angui Li, et al. (2020) Evaluation system of distributed energy system based on IAHP- coefficient of variation method [J]. Journal of Xi 'an University of Architecture and Technology (Natural Science Edition), 52(04): 572-578.
[8] Ping Zhuang, Yanxi Li. (2011) An Empirical Study on the Risk Assessment Model of Enterprise Investment Based on G1-Coefficient of Variation [J]. Soft science, 25(10): 107-112+120.