Application of Fuzzy Analytic Hierarchy Process and Three-Dimensional Terrain Model in Traffic Routes Selection

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Abstract. The selection of a road route plan is an essential preliminary task. The choice of the route greatly influences its function, role in the road network, economic development of the areas along the route, and the return on investment. In this paper, qualitative analysis and evaluation of the details of the proposed route options in terms of ecological environment and engineering economy are carried out through fuzzy hierarchical analysis, based on the route data from Bushang to Bizhou, to combine the principles of the routes and develop several route options. Among the pre-determined route options, screening and comparison are carried out, and Option II is proposed as the recommended route.

Keywords: routes selection; fuzzy analytic hierarchy method; evaluation system.

1. Introduction (Heading 1)

The improvement of social living standards depends on economic development, while economic growth largely depends on the development of transportation. At present, most of the development of Chinese transportation is composed of highway construction. Choosing a reasonable route is an important issue that needs to be considered in the preliminary design of highways. On the other hand, route design is determined by the quality of the route, technical merits, and the maintenance cost and safety at the later stage. However, the current route planning is still carried out traditionally, that is, the advantages and disadvantages of different schemes are compared with indicators such as national economy and finance. With the development of the national economy and the renewal of contemporary road design concepts, it has been unable to meet the new requirements. The requirements of construction are up to date. Therefore, it is necessary to consider more reasonable mathematical methods to enhance the actual benefits of highway construction further.

At present, the selection of route plans is mainly based on modern models for reasoning and decision-making on the relevant relationships in the route selection factors. Quantitative decision-making models are studied to ensure a reasonable and objective route method. Yihu Wu [1] used the hierarchical analysis method for route comparison of mountain road routes and found that the method could reduce the subjective and one-sided limitations of route comparison and determine the optimal target route plan. Based on the current ecological environment assessment index system along the road, Lei Guan [2] adopted a pressure-state response model. A more applicable route ecological environment assessment index system is proposed. Yu Zhang [3] established a BIM three-dimensional terrain model and carried...
out route selection in a three-dimensional terrain environment. Jie Yao [4] and others studied the design scheme of highway routes based on green road construction. Bozhao Shen [5] proposed a terrain, geological and environmental protection alignment selection method based on BIM+GIS technology. Bin Wang [6] established the interaction matrix between the landslide hazard subsystem and the route scheme subsystem.

The above research is about the evaluation of motorway route options. However, the analytical hierarchy process has its own limitations. The internal factors of the layers are not related and cannot control each other. There is no interaction between the upper and lower levels and there is no direct relationship between the levels, but rather an indirect influence. The GIS technology is not very mature. The traditional GIS model is an unnatural division and abstraction of the geographic space of the objective world according to the computer method, which makes it difficult to express complex geographic entities and meet the requirements of the overall characteristics of the objective world as people's cognitive model of geographic space cannot form a good correspondence with the data model in the computer. However, BIM requires many participants from different departments and the lack of a common data processing method will make information exchange difficult.

Therefore, an integrated and comprehensive approach is needed to evaluate the routes. In this case, a fuzzy hierarchical evaluation model is used for route planning comparison and decision making. By combining the respective advantages of the hierarchical process and the fuzzy comprehensive evaluation method, not only the influence of the individual indicators of route planning comparison and selection on the subordinate indicators is considered, but also qualitative and quantitative analyses are carried out.

2. Road Overview

The section of Provincial Road 102 from Bushang to Bizhou is located beside the river bend section. Topographical characteristics of this section: the river bend stretches, the concave bank is steep, the convex bank has a mountain leg prominently, and there is a saddle in the middle. The old road follows the natural topography of the riverbank, around the mouth of the mountain and the river bend. The route is 3.5 km long, the radius of the bend is small, and its technical standard can only reach the low limit standard of general grade 3 highway in the mountainous and heavy hill area. The section of Provincial Road 102 in Mingxi needs to be transformed into a general Grade 2 highway in the mountainous and hilly area. During the survey, the topography of this section is thoroughly investigated and studied. Two options, including using the old road to improve the standard (Option II) and using two river crossings to take a straight route (Option I) are compared and discussed in depth at the same time. The data is obtained from Liu Weiguo, Fujian Forestry Survey and Design Institute [7], and the technical and economic justification is shown in Table 1.

| Table 1. Comparison table of the route plan from Bushang to Bizhou |
|---------------------------------------------------------------|
| Project                                      | Unit             | Option I | Option II |
| Mileage                                      | km               | 1.585    | 3.480     |
| Planar Crossing                              |                  | 3        | 10        |
| Minimum curve radius                         | m/one            | 200/1    | 80/1      |
| Maximum longitudinal slope                   | %/m              | 2.95/595 | 6/350     |
| Drainage protection works                    | m³               | 2147     | 4811      |
| Cement pavements                            | m²               | 11790    | 28800     |
| Culvert                                      | one              | 6        | 13        |
| Bridge                                       | m/seat           | 229.99/2 |          |
| Power communication poles                    | pole             | 32       | 40        |
| Occupy farmland                             | km²              | 1.41     | 2.50      |
| Subgrade earthwork volume                    | km³              | 11.095   | 467.804   |
| Estimated total amount                       | 10000 ¥          | 1352.084 | 1789.1273 |
| Cost per kilometer                          | 10000 ¥          | 853.0498 | 559.1023  |
3. Model Building

3.1. Model introduction

Fuzzy Analytic Hierarchy Process (FAHP) and Computational Process Analytic Hierarchy Process (AHP) are qualitative and quantitative systematic analysis methods proposed by Professor T.L. Saaty of American Operations Research in the 1970s. The problem with the analytic hierarchy process is that when there are too many evaluation indicators at a certain level, its consistency is difficult to guarantee. In this case, the Fuzzy Analytic Hierarchy Process (FAHP) will solve this problem well. Its basic ideas and steps are the same as those of AHP, but there are different in two aspects.

(1) The established judgment matrix is different: in AHP, the judgment consistency matrix is established through the pairwise comparison of elements, while in FAHP, the fuzzy consensus judgment matrix is established through the pairwise comparison of elements.

(2) The method to calculate the weight of each element in the matrix is different: Fuzzy Analytic Hierarchy Process (FAHP) improves the problems of the traditional Analytic Hierarchy Process, and FAHP is based on the fuzzy consistency matrix, which enhances the reliability of decision-making.

Table 2. The meaning of the quantitative scale in the scaling method

| Scale | Definition               |
|-------|--------------------------|
| 0.5   | Equally important        |
| 0.6   | Weakly important         |
| 0.7   | Important                |
| 0.8   | A lot more important     |
| 0.9   | Extremely important      |
| 0.1, 0.2 | Inverse comparison      |

The basic idea for the Fuzzy Analytic Hierarchy Process is to decompose the problem itself according to the level, the nature and overall goal of the multi-objective evaluation problem, forming a bottom-up hierarchical structure. Therefore, when using AHP to make decisions, it can be roughly divided into the following four steps:

(1) Analyze the problem, determine the causal relationship between various factors in the system, and establish a multi-level (multi-level) hierarchical structure model for various elements of the decision-making problem.

(2) Compare the elements of the same level (level) with the higher-level elements as criteria and determine their relative importance according to the evaluation scale, and finally establish a fuzzy judgment matrix based on this.

(3) Determine the relative importance of each element through certain calculations.

(4) By calculating comprehensive importance, all alternatives are prioritized to provide a scientific decision-making basis for decision-makers to choose the best plan.

When the fuzzy analytic hierarchy process is adopted, the relative importance of a certain factor compared with other factors is generally used to make a quantitative judgment on the importance of two factors. A fuzzy judgment matrix can be obtained by comparing all factors pair by pair to judge whether it has the following properties:

(1) $a_{ij} = 0.5, i = 1, 2, ..., n$;

(2) $a_{ij} + a_{ji} = 1, i = 1, 2, ..., n; j = 1, 2, ..., n$;

Suppose the judgment matrix satisfies the above property requirements. In that case, this matrix is called a fuzzy complementary judgment matrix, which is used to describe the relative importance of the indicators accurately and quantitatively. The commonly used method is to use the 0.1-0.9 scaling method in Table 3.1 to calibrate the relative importance of the indicators. Take the above numbers as the scale basis, compare $a_1, ..., a_n$ and other factors to obtain the fuzzy complementary matrix, as shown in formula 3.1.
Suppose fuzzy complementary matrix \( R = (r_{ij})_{n \times n} \), satisfying \( \forall i, j, \)

\[
r_{ij} = r_{ik} - r_{jk} + 0.5
\]  

Then \( R \) is a matrix satisfying fuzzy complementary consistency.

The formula mentioned above is a general formula for fuzzy complementary consistency judgment. Due to a large amount of calculation, this paper uses the formula to solve the fuzzy complementary judgment matrix to calculate the weight:

\[
r_i = \sum_{k=1}^{n} a_{ik}, (i = 1, 2, ..., n),
\]

Perform the following mathematical substitutions:

\[
r_{ij} = \frac{r_i - r_j}{2(n-1)} + 0.5
\]  

This leads to a fuzzy complementary consistency matrix \( R = (r_{ij})_{n \times n} \), and the expression of sorting vector \( w = (w_1, w_2, ..., w_n)^T \) is as follows.

\[
W = \frac{\sum_{i=1}^{n} a_{ij} + n - 1}{n(n-1)}, i = 1, 2, ..., n
\]

3.2. Consistency check method

Judgment consistency is to observe whether the judgment matrix is completely consistent, to judge the reasonableness of the resulting weight values. At the same time, it is to conduct consistency tests. When the offset consistency is too large, it indicates that the calculation result is not correct. One can use the compatibility of the fuzzy judgment matrix to determine the consistency of the matrix.

Set the set of all \( n \)-order fuzzy complementary judgment matrices as \( G_n \). Let \( A = (a_{ij})_{n \times n} \) and \( B = (b_{ij})_{n \times n} \in G_n \). It is considered that \( A \) and \( B \) are compatible; In particular, if \( \rho(A, B) = 0 \) and \( \forall i, j \in N \), then, we have \( a_{ij} = b_{ij} \). Let \( FC_{(AB)} = \sum_{i=1}^{n} \sum_{j=1}^{n} |a_{ij} + b_{ij} - 1| \), say the compatibility of the AB matrix. The compatibility index of \( A \) and \( B \) is \( CI(A, B) = \frac{1}{n^2} \rho(A, B) \).

Define \( w = (w_1, w_2, ..., w_n)^T \) as the weight vector of matrix \( A \), \( \sum_{i=1}^{n} w_i = 1, w_i \geq 0 (i = 1, 2, ..., n) \), let \( w^*_i = \frac{w_i}{w_i + \frac{1}{w^*_j}} (\forall i, j = 1, 2, ..., n) \). The characteristic matrix of judgment matrix \( A \) is \( w^* = (w^*_i)_{n \times n} \). If the ratio of the compatibility index \( I \) to the attitude of the decision-maker is \( I(A, W^*) \leq \alpha \), then call the judgment matrix sign satisfactory consistency. The smaller the value of \( \alpha \), the higher the requirements of decision-makers for the consistency of the fuzzy matrix. In general, \( \alpha \) can be taken as 0.1.

In terms of actual engineering, multiple (suppose \( k, k=1, 2, ..., m \)) expert evaluation factors \( x \) are generally used to construct a complementary judgment matrix.

\[
A_k = (a_{ij}^{(k)})_{n \times n}, k = 1, 2, ..., m
\]

The above formulas are all fuzzy judgment matrices, and the formulas for calculating the weights are as follows:

\[
W^k = (w_1^{(k)}, w_2^{(k)}, ..., w_n^{(k)})^T, k = 1, 2, ..., m
\]
When conducting a consistency check, the following two properties need to be judged:

1) Test the satisfactory consistency of matrices \( A_k \)

\[
I(A_k, W^{(k)}) \leq \alpha, k = 1,2, \ldots, m
\]  \hspace{1cm} (7)

2) Test the satisfactory compatibility of the judgment matrix.

\[
I(A_k, A_i) \leq \alpha, k = 1,2, \ldots, m
\]  \hspace{1cm} (8)

Table 3. Indicator system for evaluating route options

| The target level of indicator system A | Index system target layer B | Index system index level C |
|---------------------------------------|-----------------------------|---------------------------|
|                                       | Economic indicators \( B_1 \) | Subgrade earthwork volume \( C_1 \) |
|                                       | Budgeted costs \( C_2 \)     |
|                                       | Bridge-to-tunnel ratio \( C_3 \) |
|                                       | Technical indicators \( B_2 \) | Minimum curve radius \( C_4 \) |
|                                       | Maximum longitudinal slope \( C_5 \) |
|                                       | Planar Crossing \( C_6 \) |
|                                       | Social and environmental indicators \( B_3 \) | Social impact analysis \( C_7 \) |
|                                       | Ecological impact \( C_8 \) |
| Route comprehensive evaluation system A | Project impact index \( B_4 \) | Construction conditions and degree of difficulty \( C_9 \) |
|                                       |                             | Geological conditions \( C_{10} \) |

It can be shown that if the consistency of the fuzzy judgment matrix \( A_k \) is acceptable, then the consistency of the composite judgment matrix is equally acceptable. If both of the properties mentioned above are satisfied, it makes sense to use the average of the \( m \) weight sets as the assignment vector for \( X \) of the factor set, where the weight vector can be expressed in the following form:

\[
W = (W_1, W_2, \ldots, W_n)
\]  \hspace{1cm} (9)

\[
W_i = \frac{1}{n} \sum_{k=1}^{m} W_i^{(k)}, \ i = 1,2, \ldots, n
\]  \hspace{1cm} (10)

A comprehensive evaluation system for the route is shown in table3.2. They are quantitative indicators, such as budgetary costs, and qualitative indicators, including geological conditions' ecological and environmental impact. They are used to avoid an evaluation system that produces too strong subjective indicators, into ten evaluation indicators, considering both the program and the economic and technical and its relationship with the natural environment and harmony, considering the linear choice of fundamental technology and economy.

3.3. Indicator assignment

The lower the indicator for the volume of soil and rock on the roadbed, the better the solution. The values assigned to such indicators are exchanged to assess the route solution in table 3.3.
3.4. Calculation of indicator weights
In this work, a weighting method for economic, environmental, engineering impact, and technical aspects is proposed by Li Shibing [8], according to which criteria the weights are calculated.

1) Target layer - sub-target layer judgment matrix

\[
A = \begin{bmatrix}
0.5 & 0.6 & 0.7 & 0.6 \\
0.4 & 0.5 & 0.4 & 0.4 \\
0.3 & 0.6 & 0.5 & 0.6 \\
0.4 & 0.6 & 0.4 & 0.5 \\
\end{bmatrix}
\]  \hspace{1cm} (11)

The weight vector is calculated as \( W = (0.283 \ 0.225 \ 0.250 \ 0.242) \), while A and W compatibility index is calculated as \( I(A,W) = 0.065, < 0.1 \), so A is satisfactorily consistent and the weight W is correctly assigned.

3.5. Sub-objective level-indicator level judgment matrix

3.5.1. The economic fuzzy judgment matrix is

\[
B_1 = \begin{bmatrix}
0.5 & 0.3 & 0.3 \\
0.7 & 0.5 & 0.6 \\
0.7 & 0.4 & 0.5 \\
\end{bmatrix}
\]  \hspace{1cm} (12)

The weight vector is calculated as \( W_1 = (0.267 \ 0.383 \ 0.350) \). Also, the result of the calculation of \( B_1 \) and \( W_1 \) compatibility index: \( I(B_1,W_1) = 0.071, < 0.1 \), so \( B_1 \) is satisfactorily consistent and the weight \( W_1 \) is correctly assigned.

3.5.2. The technical fuzzy judgment matrix is

\[
B_2 = \begin{bmatrix}
0.5 & 0.6 & 0.6 \\
0.4 & 0.5 & 0.6 \\
0.4 & 0.4 & 0.5 \\
\end{bmatrix}
\]  \hspace{1cm} (13)

The weight vector is calculated as \( W_2 = (0.367 \ 0.333 \ 0.3) \). Meanwhile \( B_2 \) and \( W_2 \) compatibility index is calculated as \( I(B_2,W_2) = 0.044, < 0.1 \), so \( B_2 \) is satisfactorily consistent and the weight \( W_2 \) is correctly assigned.

3.5.3. The fuzzy judgment matrix of social and environmental evaluation indicators is

\[
B_3 = \begin{bmatrix}
0.5 & 0.6 \\
0.4 & 0.5 \\
\end{bmatrix}
\]  \hspace{1cm} (14)

The weight vector is calculated as \( W_3 = (0.55 \ 0.45) \). Also, the result of the calculation of the \( B_3 \) and \( W_3 \) compatibility index: \( I(B_3,W_3) = 0.025, < 0.1 \), so \( B_3 \) is satisfactorily consistent and the weight \( W_3 \) is correctly assigned.

3.5.4. The fuzzy judgment matrix of the engineering impact indicators is

\[
B_4 = \begin{bmatrix}
0.5 & 0.7 \\
0.3 & 0.5 \\
\end{bmatrix}
\]  \hspace{1cm} (15)

The weight vector is calculated as \( W_4 = (0.6 \ 0.4) \). At the same time \( B_4 \) and \( W_4 \) compatibility index calculation results: \( I(B_4,W_4) = 0.025, < 0.1 \), so \( B_4 \) is satisfactory consistent, the weight \( W_4 \) is correctly assigned.
Table 4. Total ranking weights for level C

| Sub-target layer | Indicator layer | Overall ranking |
|------------------|----------------|----------------|
|                  |                 |                |
| \( B_1 \) 0.283 | \( c_1 \) 0.267 | 0.076          |
|                  | \( c_2 \) 0.383 | 0.108          |
|                  | \( c_3 \) 0.350 | 0.099          |
| \( B_2 \) 0.225 | \( c_4 \) 0.367 | 0.083          |
|                  | \( c_5 \) 0.333 | 0.075          |
|                  | \( c_6 \) 0.300 | 0.067          |
| \( B_3 \) 0.250 | \( c_7 \) 0.550 | 0.138          |
|                  | \( c_8 \) 0.450 | 0.112          |
| \( B_4 \) 0.242 | \( c_9 \) 0.600 | 0.145          |
|                  | \( c_{10} \) 0.400 | 0.097 |

In summary, the overall ranking at C level is shown in the figure, with the largest weight of 0.283 for economic indicators in the target tier, followed by social and environmental indicators at 2.50, and the smallest being the weight of technical indicators at 0.225. In the indicator layer, the weight of structure, structure and difficulty in the indicator layer is the highest at 0.145, followed by social impact analysis at 0.138, and the smallest is the plane crossing at 0.67, as shown in Table 4.

Table 5. Comprehensive evaluation table of route options

| Economic indicators | Technical indicators | Environmenta l index | Project impact index |
|---------------------|----------------------|----------------------|----------------------|
|                     |                      |                      |                      |
| Subgrade earthwork volume /(/1000 m³) | Budgeted costs /1000 ¥ | Bridge-to-tunnel ratio /(m·km⁻¹) | Minimum curve radius /m | Maximum longitudinal slope /% | Planar Crossing | Social impact analysis | Ecol ogeical impact analysis | Construction conditions | Geological conditions |
| p_1                 | 0.404                | 0.68                 | 0.71                 | 0.19                 | 0.5            | 0.6                    | 0.6                     | 0.3                    | 0.5                      |
| p_2                 | 0.608                | 0.32                 | 0.29                 | 0.81                 | 0.5            | 0.4                    | 0.4                     | 0.7                    | 0.5                      |

3.6. Program Comparison

The combined assessment table of route options is fuzzy judged, and the scoring table of the two options is obtained.
Table 6. Comparison table of scheme scores

| Basic layer indicators | Level c sort | Option I | Option II |
|------------------------|-------------|----------|-----------|
| C1                     | 0.076       | 0.404    | 0.608     |
| C2                     | 0.108       | 0.43     | 0.56      |
| C3                     | 0.099       | 0.68     | 0.32      |
| C4                     | 0.083       | 0.71     | 0.29      |
| C5                     | 0.075       | 0.19     | 0.81      |
| C6                     | 0.067       | 0.5      | 0.5       |
| C7                     | 0.138       | 0.6      | 0.4       |
| C8                     | 0.112       | 0.6      | 0.4       |
| C9                     | 0.145       | 0.3      | 0.7       |
| C10                    | 0.097       | 0.5      | 0.5       |

According to the above table, we can see that Option II has a higher score for Subgrade earthwork and Budgeted costs, which means that Option II is superior in terms of financial spending. In terms of Minimum curve radius and Maximum longitudinal slope, both options have one good and one bad score, which means that there is not much difference between the two options in terms of technology. In terms of socio-environmental indicators, Option I is higher than Option II, which means that Option I has a lower impact on the environment and ecology. However, in terms of project impact indicators, Option II scores higher than Option I, indicating that Option II is less challenging to construct. Finally, we can see that the final score for Option I is 0.4931 and Option II is 0.5069, which are similar, but Option II is better. Therefore, Option II can be used as the final route selection option.

4. Conclusion
This paper takes the road from Bushang to Bizhou as the research object, combining the project construction conditions in the area where the project is located. The basic geological information, such as the natural geography along the route, is presented. A comparison study on the route selection scheme is carried out through qualitative analysis and fuzzy hierarchical analysis method. The main conclusions are as follows:

1. The fuzzy comprehensive evaluation method is used to compare route options at the feasibility study stage of highway engineering, and the comparison is made by combining numerical quantification and scoring. It can reduce the subjective judgment of human factors and produce evaluation results intuitively, which can provide a reference for comparing route options of the same type of highway.

2. The recommended route selection scheme has considered various factors such as economic, technical, safety, and environmental factors, focusing on the consideration of environmentally sensitive points, adapting to the environment's adaptability, and considering the economic aspects of engineering technology and construction funding.

3. Based on the results of the evaluation system, Option II will be the recommended route option.

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