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Optimization of Highway Construction Quota Determination Method Based on Fuzzy Theory

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Abstract

The determination of highway construction quota is the most important constituent part in construction management. However, given the diversified existing quota determination methods, the determined original data vary greatly with determination methods, and some may even fail to represent the normal construction level of enterprises. In this study, considering the importance of factors influencing quota determination, four first-level and 19 second-level evaluation factors were determined from four aspects, namely, natural environment, construction organization, resource allocation, and measured data. Then, a multi-level fuzzy comprehensive evaluation model was established for selecting the quota determination method to improve the accuracy and reliability of highway construction quota determination data. Next, the weights of evaluation factors at each level were allocated through the analytic hierarchy process. Subsequently, the fuzzy comprehensive evaluation method was combined to calculate the final values of evaluation factors analytically. Moreover, a reliability calculation method for the optimization evaluation model of quota determination methods was constructed on the basis of expert consultation method and system reliability theory. Finally, the model reasonability was verified with the whole construction process of the cement stabilized macadam base of Dianhong first-class highway in Shenmu City, Shaanxi Province, as an example. Results demonstrate that the established evaluation model is quite applicable to the optimization of quota determination methods in terms of high reasonability and operability. The proposed model provides evidence in evaluating the advantages and disadvantages of traditional quota determination methods with certain guiding significance for compiling supplementary quota in highway engineering.

Keywords: Highway construction quota, Determination method, System reliability, Analytic hierarchy process, Fuzzy comprehensive evaluation

1. Introduction

The determination of highway construction quota, which is an important step in deciding the validity of original data, has strict normative procedures and calculation rules [1]. The selection of determination methods not only has a bearing on the consumptions of manpower, materials, and machines in construction quota but also affect the quota compilation work of the whole project. The main methods that are currently adopted to determine highway construction quota, include realistically recording method, working-day realistic method, chronometric method, empirical estimation method, statistical analysis method, and comparative analogy method [2-7].

The realistically recording method is the most widely applied quota compilation method in terms of simple operation, easy mastery, and high accuracy. However, this method needs to input a large amount of manpower and material resources. The working-day realistic method has been extensively used in production practices with advantages of simple operation, broad application plane, and comprehensive data. However, it is of certain falsehood in determining the utilization of working hours, has a large observation workload and time consumption, and proneness to the influence of observers' subjective consciousness. The chronometric method, which is featured by high accuracy, can provide reliable data support for compiling labor quotas, but it is not applicable in studying the break time, readiness time, starting time, and ending time of field operators. The empirical estimation method is simple and feasible with a small workload and can reflect the actual field situation, but the estimated data are of poor accuracy and are restricted by the construction experience of determination personnel. The statistical analysis method refers to the statistics that are based on the original data with satisfactory persuasion, and it can truly reflect the labor efficiency and meet the requirements for fast and comprehensive quota compilation. However, this method is only applicable to quota projects that fail the field determination or secondary quota projects. The comparative analogy method, which, to some extent, improves the accuracy and balance of quota compilation, is applicable to construction quota compilation for working procedures of the same type, diversified specifications, and a small batch. In spite of this, it can be easily restricted by the comparability of similar projects, so it cannot be used extensively.

With the extensive application of emerging mathematical theories in various field, analytic hierarchy process (AHP) and fuzzy comprehensive evaluation have provided powerful theoretical support for the optimal selection of highway construction quota determination methods. Specific to factors influencing the quota of

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highway engineering construction site, numerous scholars have proposed the hierarchical structure chart of manual and mechanical magnitude difference coefficients [8], the calculation model for working-hour consumption enlargement coefficient [9], and quota determination on-site screening index system [10]. With the abovementioned systems and models, scholars have analyzed highway maintenance quota, quota magnitude differences of new projects, and determination field optimization, and achieved satisfactory results, thereby providing a theoretical foundation to deeply exploring the optimization of highway construction quota determination methods. Although quota determination methods have been applied in various fields, some commonly used quota determination or compilation methods have been mostly involved, whereas the organization contents of quota determination work and the optimization of quota determination methods have been less investigated.

On this basis, the optimization methods for highway construction quota determination were evaluated comprehensively based on fuzzy theory to provide a reasonable method for sorting highway construction quota determination methods.

2. State of the art

The optimization of highway quota determination methods has always been the emphasis of engineering management. At the end of the 19th century, domestic (Chinese) and foreign scholars have explored highway engineering quota and established a series of cost estimation models and systems. However, these studies have mainly concentrated on cost estimation, economic evaluation, and tendering and bidding analysis. For instance, Taylor proposed time quotas, namely, the labor-quota separation, and formulated systems, such as operation and tool standardization [11]. Based on Taylor's research, Frank and Lillian Gilbreth prepared an action flowchart and found the design theory of working methods [12]. Kim et al. [13] developed a cost estimation module for the follow-up maintenance and transformation of California Highway based on the cost data of Caltrans historical contracts and enhanced the automation function of RealCost developed by Federal Highway Administration. The results showed that the automatic cost calculation module could estimate the cost of each construction technology and pavement type faster. Love et al. [14] probed the differences among the budget checking, the base number estimation of a tender, contract amount, and final settlement of transportation projects and proposed the calibration process according to multiple data sources and estimation models. The results revealed that taxpayers could obtain better cost performance using the cost estimation and risk analysis methods. Margorínová et al. [15] formulated a procedure of transforming travel time on business into currency based on the social cost generated in the highway project operation stage. The results manifested that this procedure could plan the economic evaluation of road engineering effectively and reduce negative comments on roads. Elfahham [16] predicted the engineering cost index in Egypt through neural network, time series, and regression method, which could predict the cost of to-be-built projects in case of inflation accurately. Coffiee et al. [17] used construction period, budget quota, and scope change as the predictive variables upon project completion. They also developed a cost prediction model through multiple regression analysis, and the results indicated that the budget quota was a key variable, and the developed model could not only help in understanding the relationship between these factors and project completion cost better but also predict the project cost in the bid awarding stage. Chou et al. [18] developed a set of a preliminary cost estimation system, including project input information, engineering quantities prediction, and project unit price based on the cost data saved by Texas Department of Transportation, and continuously updated the data in the system through the statistical method. The results showed that the system could reduce the variability of highway engineering budgets and separate the cost of each subdivisional work in highway projects. In the abovementioned studies, cost estimation has been mainly involved, and the costs in the initial and middle project construction stages and that upon project completion have been mainly predicted, whereas engineering cost management modes and quota determination methods have not been explored. The organization contents of quota determination work should be investigated further to determine the reasonability sorting problem of quota determination methods.

With the scientific and technological progress, mathematical theories have been integrated with computer technologies to form new cost management modes in developed countries. For example, the American Government neither formulates valuation standards nor directly manages engineering costs, whereas quotas, indexes, and rates are mainly formulated by some large-scale engineering consulting companies or industry associations [19]. In Britain, the emphasis has been laid on the collection and analysis of engineering data. As early as the 1930, an enormous engineering database was established in this country [20], with the keynote lying in "quantity–price separation." To be specific, simlilar to the quota calculation method currently used in China, the information price is issued collectively by the government and relevant advisory bodies. In Japan, the quantity-price separation quota system is also used, that is, the quota calculation is managed collectively by the construction ministry. Many scholars have also explored quota determination methods. Based on field data, Chang et al. [21] established a multiple regression model and set weights to determine time quotas. They also put forward the method of determining time quotas in the production system with multiple modes and a short life cycle. Ding et al. [22] explored the applicability of determination methods for municipal-level building energy consumption quota and compiled municipal-level energy quota using the quantile method, quota level method, and linear regression method. The results reflected that the compiled supplementary quota could provide better cost services for municipal-level building energy consumption. Berljafa et al. [23] determined the acutal time consumed by the technological process of excavators through the chronometric method and then analyzed their working efficiency. Moon et al. [7] established a market price estimation model using the ETS data of European Union (EU) based on comparative analogy and then estimated the market price of carbon credits in Korea. Li et al. [24] evaluated the to-be-selected quota determination objects quantitatively through the comprehensive evaluation method. Based on multi-attribute decision-making, Ren et al. [25] constructed an evaluation model for selecting quota determination objects. The results showed that the multi-attribute decision making could compensate for the deficiencies of AHP, and the established model could help select the determination objects that conformed to the quota-level requirements.

Since being established, AHP and fuzzy comprehensive evaluation have been applied extensively in the operations management and decision evaluation in various fields. Bathrinath et al. [26] performed sorting analysis of problems on the construction site using AHP and WASPAS and put forward 18 alternative plans and 5 criteria for solving working safety and failure problems. Andreolli et al. [27] analyzed three transformation plans for single-story buildings, established a multi-criterion priority ordering model for industrial building aseismic transformation plans, and realized prefabricated parts made of reinforced concrete by means of geometric mathematics. The results showed that this model fully considered seismic analysis and engineering evaluation and was adaptable to different objectives. Furthermore, some scholars have introduced the concept of system reliability on this basis. Feng et al. [28] analyzed the reliability of unmanned aerial vehicles (UAVs) based on the staged binary decision diagram, put forward the calculation method for task reliability, and constructed an optimization model that maximized reliability. The results showed that under the guidance of importance measurement, task reliability could be improved better than random optimization, accompanied by a smaller number of UAVs needed and a more obvious optimization effect. Zhang et al. [29] established a stability evaluation model for rock-filled high embankment and analyzed the reliability of each factor index by combining reliability theory. The results indicated that the reliability of rock-filled high embankment system in China National Highway 316 Project was 0.8671, and the score of the evaluation system was 73.2, thereby belonging to a relatively stable state.

According to existing research findings, the optimization of quota determination methods has been scarcely investigated considering the varying domestic and foreign pricing methods of highway projects, and quota determination methods can be easily affected by many uncertain factors. , However, fuzzy theory is capable of priority ordering of traditional quota determination methods, thereby solving this problem very well. Directing at the existing research deficiencies, therefore, the factors that influence quota determination methods were analyzed in this study under the background of the whole construction process of Dianhong first-class highway in Shenmu City, Shaanxi Province. Then, a multi-level fuzzy comprehensive evaluation model was constructed, expecting to break through the unicity of original quota determination methods, provide a basis for reasonably selecting determination methods, and render reliable sample data for compiling construction and budget quotas.

The remainder of this study was organized as follows. Section 3 expounds fuzzy theory. Section 4 analyzes and discusses the evaluation results. Section 5 summarizes the study and provides relevant conclusions.

3. Methodology

3.1 Establishment of evaluation indexes for quota determination methods

3.1.1 Influencing factors of construction quota determination methods

Construction quota determination methods are influenced by many factors, and the factors that cannot be analyzed quantitatively or qualitatively with a small influence degree may be neglected. Hence, the main influencing factors of the following four aspects were finally selected by reference to expert opinions:

(1) Natural environmental factors. The highway engineering construction site is subjected to complicated environment and various influencing factors, such as the geological conditions and soil quality, climatic characteristics, hydrological characteristics, and traffic conditions of the site. Hence, the optimal determination method should be selected according to the actual site conditions.

(2) Construction organization factors. Construction organization management is an indispensable part in the operation and management of construction enterprise, which runs through the management mode of the whole enterprise and plays a role of strategic deployment and tactical adjustment. The reasonable deployment of construction organization directly decides whether the construction unit can organize the site operation orderly. Meanwhile, it will also impact the quota determination result indirectly.

(3) Resource allocation factors. In practical observation, since one project involves multiple sections, each of which is operated simultaneously by different construction teams, and the market price of materials fluctuates greatly due to the epidemic, the use conditions of workers, mechanical equipment, and materials will influence the selection of quota determination methods directly.

(4) Measured data factors. The data precision varies with the determination method used, thereby leading to the great differences in determination results, which will not only affect the precision of quota data but also reduce the quota quality considerably. Therefore, an appropriate determination method should be chosen by combining data precision and quota quality.

To sum up, an evaluation factor model of quota determination methods was established through AHP and fuzzy theory based on four-aspect (e.g., natural environment, construction organization, resource allocation, and measured data) factors. Finally, a total of 19 second-level evaluation indexes were determined (Fig. 1).

3.1.2 Evaluation factors of quota determination methods

A total of A_i (i = 1, 2, …, n) factors that influence quota determination methods were set, where n stands for the number of factors. Through investigation and analysis, the factors influencing the selection of quota determination methods were determined as natural environmental factor A_1, construction organization factor A_2, resource allocation factor A_3, and measured data factor A_4. The first-level evaluation factor set is expressed as: $A = \{A_1, A_2, A_3, A_4\}$.

m subfactors exist in the first-level evaluation factor A_i, where m represents the number of subfactors that correspond to each influencing factor at the factor layer, thus constituting the second-level evaluation factor set $A_i = \{C_{i1}, C_{i2}, C_{i3}, \ldots, C_{im}\}$, i = 1, 2, …, n. For instance, the second-level factor set of natural environmental factor A_1 is $A_1 = \{C_{11}, C_{12}, C_{13}, C_{14}\}$={site geological conditions and soil quality, climatic characteristics, hydrological characteristics, site traffic conditions}. The other evaluation factors sets could be obtained in a similar fashion.

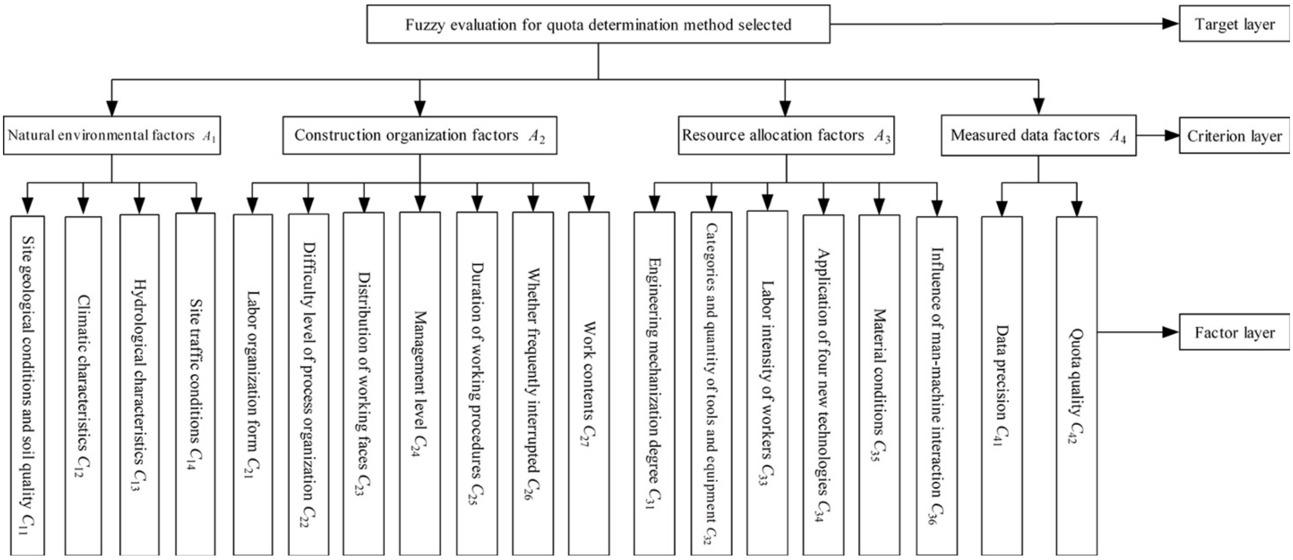

Fig. 1. Evaluation factor model of quota determination methods

3.2 System reliability

In the evaluation system for the optimal selection of quota determination methods, many influencing factors influenced each other. Fig. 1 shows that the optimization of evaluation indexes has been implemented according to the top-level design principle, and two subsystems were available, where the criterion layer included 4 factors, and the factor layer included 19 subfactors, all of which belonged to the criterion layer.

(1) Reliability of criterion layer
The four factors at the criterion layer were in series by default. In case that any factor was invalid, the whole criterion layer system would also be invalid, that is, the whole evaluation system for the selection of quota determination methods was also considered invalid. The reliability of the basic factor i at the criterion layer was set as Q_i, and the four factors at the criterion layer were assumed to be mutually independent. The reliability Q_s of the criterion layer is expressed as follows:

$$Q_s = \prod_{i=1}^{4} Q_i \tag{1}$$

(2) Reliability of factor layer
In the default factor layer, the 19 index factors were parallelly associated, namely, the whole factor layer would not be invalid because of the invalidity of one factor. The criterion-layer system was invalid only when all factors in the factor layer became invalid, thereby further leading to the failure of the whole evaluation system for the optimal selection of construction quota determination methods. The unreliability of the factor j among second-level evaluation factors was set as Q_j. The 19 indexes at the factor layer were assumed to be mutually independent, and the reliability Q_s of the factor layer is expressed as follows:

$$Q_s = 1 - \prod_{j=1}^{m} Q_j \tag{2}$$

According to the above reliability calculation principle of indexes at all levels, the reliability of the evaluation model for the optimal selection of highway construction quota determination methods was the reliability of the criterion layer, in which the reliability of each basic factor was the reliability of the corresponding factor layer. Through the simultaneous Eqs. (1) and (2), the reliability of the whole evaluation model for the optimal selection of highway construction quota determination methods could be solved.

3.3 Determination of index weights

AHP is a hierarchical weight decision analysis method that decomposes a complex system into multiple objectives or criteria [30]. Then, the weight vector and the maximum eigenvalue of evaluation factors at each level in the model were obtained through calculation and analysis according to the association degree and membership between factors.

3.3.1 Construction of judgment matrix

After constructing a comprehensive evaluation index model (Fig. 1), the quantitative scales were generally given using 1–9 and the corresponding reciprocals (Table 1). Every two of second-level evaluation factors were compared, and the following judgement matrix A_k could be obtained according to the relative importance of the former to the latter:

$$A_k = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & A_{ii} & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix} \tag{3}$$

where A_{ij} stands for the importance degree of the factor i to the factor j. For each factor in the judgment matrix, $A_{ii} = 1$, $A_{ij} = 1/A_{ji}$ ($i, j = 1, 2, \ldots, n$; and $i \neq j$).

Table 1. 1–9 scaling method

Scale	Meaning
1	For two factors, the former is as important as the latter
3	For two factors, the former is slightly more important than the latter
5	For two factors, the former is obviously more important than the latter
7	For two factors, the former is much more important than the latter
9	For two factors, the former is absolutely more important than the latter
2, 4, 6, 8	Median between the above adjacent judgments

3.5 Single hierarchical arrangement and consistency check

It was assumed that there was one n-order normal vector w, and the approximate value of eigenvector w and maximum eigenvalue $\lambda_{\max}$ could be solved through the equality $Aw = \lambda_{\max}w$ and square root method, with the following calculation steps [31, 32]:

a. Calculate the weight of each index:

$$w_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{4}$$

b. Calculate the normalized weight vector:

$$\overline{w_i} = \frac{w_i}{\sum_{j=1}^{n} w_j} \tag{5}$$

c. Calculate the maximum eigenvalue:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(w_i A)_i}{n w_i} \tag{6}$$

d. Calculate the consistency index:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{7}$$

e. Calculate the random consistency ratio:

$$CR = \frac{CI}{RI} \tag{8}$$

where n denotes the order of judgment matrix, and $i, j = 1, 2, \ldots, n$. RI stands for the average consistency index of the matrix (Table 2). If $CR < 0.1$, then the judgment matrix conformed to the consistency check, otherwise, the judgment matrix should be corrected until $CR < 0.1$, and only under this circumstance could the consistency check be passed.

Table.2. Mean randonm consistency index

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

3.4 Multi-level fuzzy comprehensive evaluation

For a multilayer system with excessive factor-layer indexes and different layer systems between such indexes, if the single-layer fuzzy evaluation is adopted, then the obtained comprehensive evaluation result will lack reliability. Hence, single-factor evaluation must be performed using six quota determination methods to solve the fuzzy matrix B, followed by the second-level evaluation of fuzzy matrix B. The calculation formula is expressed as follows [33]:

a. Single-factor fuzzy comprehensive evaluation:

The fuzzy matrix of single-layer factors was obtained by the established single-factor evaluation matrix R_i and the weight vector w_i of judgment matrices.

$$B = \begin{pmatrix} w_1 \bullet R_1 \\ w_2 \bullet R_2 \\ \vdots \\ w_n \bullet R_n \end{pmatrix} = \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{pmatrix} \tag{9}$$

b. Second-level evaluation:

$$L = wB = [b_1 \; b_2 \; b_3 \cdots b_n] \tag{10}$$

c. Principle of maximum membership:

In this study, the above second-level evaluation results were finally evaluated according to the principle of maximum membership, the numerical values in the multi-level evaluation vector were sorted successively in a descending order, and the maximum value was considered the optimal determination method.

$$b_r = \max_{1 \le j \le n} \{b_j\} \tag{11}$$

4. Results analysis and discussion

4.1 Determination of index weights

To verify the accuracy and applicability of the above fuzzy evaluation model of quota determination methods, the construction site of Dianhong first-class highway in Shenmu City, Shaanxi Province, was evaluated and determined. From Fig. 1 in combination with Eqs. (4)–(8), the weights of evaluation factors at each level were calculated, namely, the judgment matrix (Table 3) of the first-level evaluation factors. The judgment matrices of the factor layers subordinate to the first-level evaluation factor A_i are listed in Tables 4–7.

Table 3. Judgment matrix and weights of first-level evaluation factors

Index	A_1	A_2	A_3	A_4	Weight
A_1	1	1/7	1/4	1/3	0.0636
A_2	7	1	2	4	0.5184
A_3	4	1/2	1	2	0.2676
A_4	3	1/4	1/2	1	0.1504

$\lambda_{\max} = 4.0299$, $CR = 0.0111 < 0.1$, pass the consistency check.

Table 4. Judgment matrix and weights of natural environmental factors

Index	C_{11}	C_{12}	C_{13}	C_{14}	Weight
C_{11}	1	1/3	3	1/5	0.1302
C_{12}	3	1	2	1/4	0.2009
C_{13}	1/3	1/2	1	1/7	0.0720
C_{14}	5	4	7	1	0.5969

$\lambda_{\max} = 4.2393$, $CR = 0.0886 < 0.1$, pass the consistency check.

Table 5. Judgment matrix and weights of construction organization factors

Index	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}	Weight
C_{21}	1	1/6	4	1/3	1/2	1	3	0.0876
C_{22}	6	1	8	2	3	5	7	0.3731
C_{23}	1/4	1/8	1	1/7	1/5	1/2	1/2	0.0311
C_{24}	3	1/2	7	1	2	4	6	0.2401
C_{25}	2	1/3	5	1/2	1	3	5	0.1587
C_{26}	1	1/5	2	1/4	1/3	1	2	0.0678
C_{27}	1/3	1/7	2	1/6	1/5	1/2	1	0.0416

$\lambda_{\max} = 7.1811$, $CR = 0.0229 < 0.1$, pass the consistency check.

Table 6. Judgment matrix and weights of resource allocation

Index	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	Weight
C_{31}	1	2	1/2	1/3	1	3	0.1337
C_{32}	1/2	1	1/3	1/5	1/2	2	0.0764
C_{33}	2	3	1	1/2	2	4	0.2265
C_{34}	3	5	2	1	3	6	0.3805

C_{35}	1	2	1/2	1/3	1	3	0.1337
C_{36}	1/3	1/2	1/4	1/6	1/3	1	0.0492

λ_{max} = 6.0493, CR =0.0079 < 0.1, pass the consistency check.

Table 7. Judgment matrix and weights of measured data factors

Index	C_{41}	C_{42}	Weight
C_{41}	1	3	0.75
C_{42}	1/3	1	0.25

λ_{max} = 2, when n = 2, RI = 0, pass the consistency check.

4.2 Single-factor judgment matrix

In this study, the to-be-selected construction quota determination methods were used as the evaluation set $U = \{u_1, u_2, u_3, u_4, u_5, u_6\}$, namely, U = {comparative analogy method, statistical analysis method, empirical estimation method, chronometric method, working-day realistic method, realistically recording method}. To mitigate the subjectivity of expert consultation method and improve the accuracy of evaluation results, at least five consultant experts should be invited for AHP decision-making, and the 10–16-expert reviews could achieve a relatively ideal accuracy. In this study, a total of 12 relevant experts were invited to form an evaluation group, and each index (determination method) was evaluated by the number of votes for this determination method, with the evaluation results listed in Table 8.

The voting results shows that the single-factor judgment matrices for the six quota determination methods are as follows:

$$R_1=\begin{pmatrix} 1/12 & 1/6 & 1/6 & 1/12 & 1/4 & 1/4 \\ 1/12 & 1/12 & 1/6 & 0 & 1/3 & 1/3 \\ 1/12 & 1/6 & 1/6 & 0 & 1/6 & 5/12 \\ 0 & 1/12 & 1/12 & 1/12 & 5/12 & 1/3 \end{pmatrix}$$

$$R_2=\begin{pmatrix} 1/12 & 1/6 & 1/12 & 1/4 & 1/6 & 1/4 \\ 0 & 1/12 & 1/12 & 1/4 & 1/4 & 1/3 \\ 1/6 & 1/3 & 1/4 & 1/12 & 1/12 & 1/12 \\ 1/12 & 1/6 & 1/3 & 1/12 & 1/6 & 1/6 \\ 0 & 1/3 & 1/3 & 1/12 & 1/6 & 1/12 \\ 1/12 & 1/6 & 1/12 & 1/3 & 1/12 & 1/4 \\ 0 & 1/6 & 1/3 & 1/12 & 1/6 & 1/4 \end{pmatrix}$$

$$R_3=\begin{pmatrix} 1/12 & 1/12 & 1/6 & 1/6 & 1/4 & 1/4 \\ 1/12 & 1/4 & 1/12 & 0 & 1/4 & 1/3 \\ 1/12 & 5/12 & 1/3 & 0 & 1/12 & 1/12 \\ 1/6 & 1/12 & 0 & 1/4 & 1/6 & 1/3 \\ 1/12 & 1/12 & 1/6 & 1/6 & 1/4 & 1/4 \\ 1/12 & 1/6 & 1/3 & 1/3 & 0 & 1/12 \end{pmatrix}$$

$$R_4=\begin{pmatrix} 0 & 1/12 & 1/12 & 1/3 & 1/4 & 1/4 \\ 1/12 & 1/12 & 1/12 & 1/4 & 1/4 & 1/4 \end{pmatrix}$$

Table 8. Expert evaluation of quota determination methods

Criterion layer	Factor layer	Comparative analogy method	Statistical analysis method	Empirical estimation method	Chronometric method	Working-day realistic method	Realistically recording method
Natural environmental factors	C_{11}	1	2	2	1	3	3
	C_{12}	1	1	2	0	4	4
	C_{13}	1	2	2	0	2	5
	C_{14}	0	1	1	1	5	4
Construction organization factors	C_{21}	1	2	1	3	2	3
	C_{22}	0	1	1	3	3	4
	C_{23}	2	4	3	1	1	1
	C_{24}	1	2	4	1	2	2
	C_{25}	0	4	4	1	2	1
	C_{26}	1	2	1	4	1	3
	C_{27}	0	2	4	1	2	3
Resource allocation factors	C_{31}	1	1	2	2	3	3
	C_{32}	1	3	1	0	3	4
	C_{33}	1	5	4	0	1	1
	C_{34}	2	1	0	3	2	4
	C_{35}	1	1	2	2	3	3
	C_{36}	1	2	4	4	0	1
Measured data factors	C_{41}	0	1	1	4	3	3
	C_{42}	1	1	1	3	3	3

4.3 Single-layer fuzzy evaluation matrix

The following could be obtained according to Tables 4–7:

$$w_1=\left[0.1302\ \ 0.2009\ \ 0.0720\ \ 0.5969\right]$$

$$w_2=\left[0.0876\ \ 0.3731\ \ 0.0311\ \ 0.2401\ \ 0.1587\ \ 0.0678\ \ 0.0416\right]$$

$$w_3=\left[0.1337\ \ 0.0764\ \ 0.2265\ \ 0.3805\ \ 0.1337\ \ 0.0492\right]$$

$$w_4=\left[0.75\ \ 0.25\right]$$

Then, a comprehensive evaluation was implemented by combining fuzzy theory. According to Eq. (9), the following single-layer fuzzy evaluation matrix could be obtained:

$$B=\begin{pmatrix} 0.0336 & 0.1002 & 0.1169 & 0.0606 & 0.3602 & 0.3285 \\ 0.0381 & 0.1672 & 0.1986 & 0.1772 & 0.1895 & 0.2294 \\ 0.1150 & 0.1757 & 0.1428 & 0.1562 & 0.1682 & 0.2421 \\ 0.0209 & 0.0833 & 0.0833 & 0.3125 & 0.2500 & 0.2500 \end{pmatrix}$$

4.4 Second-level evaluation

Table 3 suggests that the weight allocation of the first-level evaluation factor A_i is: w = [0.0636 0.5184 0.2676 0.1504]. Next, the second-level evaluation vector was calculated through Eq. (10):

$$L = wB = \begin{bmatrix}0.0636 & 0.5184 & 0.2676 & 0.1504\end{bmatrix}$$
$$\begin{bmatrix}0.0336 & 0.1002 & 0.1169 & 0.0606 & 0.3602 & 0.3285\\ 0.0381 & 0.1672 & 0.1986 & 0.1772 & 0.1895 & 0.2294\\ 0.1150 & 0.1757 & 0.1428 & 0.1562 & 0.1682 & 0.2421\\ 0.0209 & 0.0833 & 0.0833 & 0.3125 & 0.2500 & 0.2500\end{bmatrix}$$
$$= \begin{bmatrix}0.0558 & 0.1526 & 0.1611 & 0.1845 & 0.2038 & 0.2422\end{bmatrix}$$

According to the principle of maximum membership and Eq. (11), $b_r = 0.2422$, namely, the optimal method was “realistically recording method.” The comprehensive score of the evaluation model for the optimal selection of highway construction quota determination methods is as follows:

$$E = LD^T = \begin{bmatrix}0.0558 & 0.1526 & 0.1611 & 0.1845 & 0.2038 & 0.2422\end{bmatrix}$$
$$\begin{bmatrix}20 & 40 & 60 & 80 & 100 & 120\end{bmatrix}^T = 81.09$$

The system reliability $Q = R\, D^T/120$ was calculated by combining Eqs. (1) and (2) (Table 9).

Table 9. Scoring results of evaluation system reliability

Criterion layer	Factor layer	Reliability of criterion layer	Reliability of factor layer	Overall system reliability
A_1	C_{11}	0.9953	0.67	0.92
	C_{12}		0.74	
	C_{13}		0.71	
	C_{14}		0.81	
A_2	C_{21}	0.9992	0.67	
	C_{22}		0.78	
	C_{23}		0.47	
	C_{24}		0.60	
	C_{25}		0.56	
	C_{26}		0.65	
	C_{27}		0.67	
A_3	C_{31}	0.9977	0.69	
	C_{32}		0.68	
	C_{33}		0.47	
	C_{34}		0.69	
	C_{35}		0.69	
	C_{36}		0.54	
A_4	C_{41}	0.9275	0.75	
	C_{42}		0.71	

4.5 Analysis of measurement results

To prove the reasonability of the above results, the manual and mechanical construction quota data in the working procedure of “cement stabilized macadam base” were recorded using three methods, namely, chronometric method, working-day realistic method, and realistically recording method. Then, the consumption of budget quota was calculated according to the manual and mechanical magnitude difference coefficients [34]. Given that the estimation method is adopted by the three other methods and the obtained data precision is poor, the statistical analysis method, empirical estimation method, and comparative analogy were excluded. The determined budget quota data are listed in Table 10:

Table 10 suggests that the consumption data determined by the realistically recording method is the most reasonable, followed by that determined through working-day realistic method. Compared with the working-day realistic method, the realistically recording method was applicable in determining the labor consumption of each subitem or category, with a smaller input of manpower and material resources. Hence, the realistically recording method was the optimal determination method for the whole construction process of cement stabilized macadam bases.

Table 10. Comparision of budget quota data determined by different determination methods

Quota determination methods	Labor consumption/(work-day)	Stabilized soil spreading machine within 7.5 m/(machine-team)	Vibratory roller within 30 t/(machine-team)	12-15 t smooth-wheel roller/(machine-team)	8000 L sprinkler truck/(machine -team)
chronometric method	1.9×1.06=2.01	0.44×1.21=0.53	0.62×1.2=0.74	0.05×1.2=0.06	0.2×1.18=0.24
working-day realistic method	2.32×1.06=2.46	0.34×1.21=0.41	0.41×1.2=0.49	0.11×1.2=0.13	0.12×1.18=0.14
realistically recording method	2.55×1.06=2.70	0.27×1.21=0.33	0.35×1.2=0.42	0.08×1.2=0.10	0.17×1.18=0.20
Budget quota consumption relevant code	2.8	0.31	0.41	0.08	0.19

Note: The manual magnitude difference is 1.06. The magnitude differences of 7.5 m spreading machine, 30 t vibratory roller, 12-15 t smooth-wheel roller, and 8000 L sprinkler truck are 1.21, 1.2, 1.2, and 1.18, respectively.

5. Conclusions

To make a rapid and effective evaluation for the optimal selection of highway construction quota determination methods, an evaluation index system for the selection of quota determination methods was established on the basis of fuzzy theory. Then, the comprehensive evaluation vector of quota determination methods was acquired using AHP and fuzzy comprehensive evaluation. Moreover, the reliability analysis was performed for the evaluation model. Finally, the following conclusions were drawn:

(1) Given the fuzziness of quota determination methods, a relatively comprehensive multilayer evaluation model for the optimal selection of quota determination methods is established by combining relevant study results and actual engineering conditions. On this basis, the final comprehensive evaluation vector of highway engineering construction quota determination methods is obtained as [0.1526, 0.1611, 0.0558, 0.1845, 0.2422, 0.2038], and the optimal method is determined as the realistically recording method.

(2) The factors that influence construction quota determination methods and their mutual relations were investigated. Moreover, AHP and fuzzy theory were combined with the system reliability theory, an evaluation model for the optimal selection of quota determination methods was established, and the calculation method of the evaluation model for the optimal selection of quota determination methods was constructed to obtain the reliability of each factor and the whole system.

(3) The evaluation model is applied to the cement-stabilized macadam base project of Dianhong first-class highway in Shenmu City, Shaanxi Province. Its reliability is 0.92, and the final score of the evaluation system is 81.09, which indicate that the construction sample data measured by the realistically recording method, chronometric method, and working-day realistic method were reasonable and accurate. The evaluation method is basically consistent with the actual investigation scheme. The investigation results showed that the determination method determined by the comprehensive evaluation method is feasible, the measured data is of high precision, and a favorable actual measurement effect is harvested.

In a word, a multi-scheme optimal selection system for quota determination is constructed, expecting to break through the limitations of traditional construction quota determination methods. The measured sample data at the construction site can reflect the production level of the construction site and the highway cost management level, thereby providing more real and reliable theory and data support of highway engineering with subsequently compiling supplementary quota or maintenance quota. Meanwhile, the evaluation model constructed in this study can also be used to optimize the selection of field determination objects and even the selection of construction quota determination methods for highway reconstruction and extension projects or maintenance projects. However, the environment and climate vary from region to region, so the selection of index layer, the planning of factor layer, and the weight calculation of each factor during the fuzzy comprehensive evaluation should be confirmed, improved, and perfected according to the construction technology of actual measurement projects.

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