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An Optimization Model for a Desert Railway Route Scheme Based on Interval Number and TOPSIS

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Abstract: The construction of desert railways inevitably destructs the environment and aggravates the wind–sand damage along the line. A reasonable railway route is an effective measure to avoid blown sand hazards, save construction costs, and reduce environmental damage. Currently, the selection methods for the railway route scheme are to analyze the qualitative indicators and quantitative indicators separately, and there are few decision-making models for the desert railway scheme. Therefore, this study aims to propose a comprehensive quantitative optimization model of the route scheme for the desert railway. Based on the design principles of hazard reduction, the evaluation index system of the desert railway route is first constructed, including railway design factors, wind-blown sand hazard factors, environmental impact factors, and operation condition factors. Subsequently, the subjective weights and objective weights are combined to obtain the comprehensive weights of the index by utilizing the principle of minimum discrimination information. Finally, the interval number is employed to quantify the linguistic fuzzy number of qualitative indicators, and the optimization model of the route scheme for the desert railway is constructed based on the technique for order preference by similarity to an ideal solution (TOPSIS). The model is verified using the Minfeng-Yuhu section in the Hotan–Ruoqiang railway as the case study. The achieved results reveal that this model enhances the accuracy and efficiency of the railway scheme decision-making and provides a theoretical basis for the optimal design and sand damage control of the desert railway.

Keywords: desert railway; route scheme; optimization model; interval number; TOPSIS; sand hazard prevention

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1. Introduction

Railways represent a crucial part of a comprehensive transportation system. Due to the unique advantages of large capacity, low freight rate, all-weather compatibility, and the high security of railways, they play an indispensable role in the social-economic development of all countries around the world [1,2]. With the large-scale construction of railways in recent years, the "four vertical and four horizontal" railway network has been completed in China. According to the National 14th Five-Year Plan and the National Comprehensive Traffic Network Plan of China, the structure and scale of the railway network in central and western China will be further developed. However, there are large areas of deserts, Gobi, and wind–sand flow areas in Northwest China [3], and most of the proposed railways directly pass through the sandy regions. The wind-blown sand hazard is the key factor restricting the construction and operation of railways in these areas.

The railway alignment design aims to determine the location of a route on the ground according to factors such as topography, geology, ecological environment, and engineering technology level [4]. Due to the complex geological conditions and fragile ecological environment in the wind-blown sandy area, the crucial concepts of geological route selection, environmental protection route selection, and hazard reduction route selection should be paid attention to in the engineering design. Commonly, blown sand hazard is the leading factor influencing the railway design in the desert region. Scientifically and reasonably designed railway routes can minimize wind–sand hazards, save construction costs, and lessen environmental damage. This kind of design represents the most economical and effective measure to reduce the damages caused by the wind–sand along the line. Therefore, it is of great significance to study the evaluation method of the desert railway route scheme and propose an optimization model to improve the levels of sand hazard prevention and ecological environment protection.

The railway route scheme selection is a complex multi-attribute decision-making problem involving qualitative and quantitative indicators. Li et al. [5] constructed a decision-making model of the railway alignment scheme in complicated and difficult mountainous areas via cloud model-cumulative prospect theory. Volkan et al. [6] determined the design scheme of the Erzincan Trabzon section in the Türkiye high-speed railway by implementing a tomographic analysis and geographic information system. Kosijer et al. [7] introduced the application of the multi-criteria decision-making method in a railway line scheme design. Based on the comprehensive route selection index and fuzzy analytic hierarchy process, Chen et al. [8] established an evaluation model for the route scheme in karst areas and then optimized the route scheme of the Guiyang–Guangzhou high-speed railway as a case study. Luo et al. [9] developed an evaluation model of the railway route scheme in earthquake-risky zones by combining the earthquake risk calculation with the traditional scheme evaluation method. The comparison and selection for railway realignment schemes are essentially concentrated in difficult and dangerous mountain areas, karst regions, and earthquake zones [10]. There is little research on the evaluation index system and quantitative decision-making method of the desert railway alignment scheme, which is not conducive to the high-quality construction of the desert railway.

The accurate quantification of the qualitative indicators and the unified calculation of all indicators are the key points for the railway scheme decision. Quantitative indicators refer to those that can be expressed in specific numerical values, such as project quantity, project investment, and land occupation. Qualitative indicators refer to those that can only be described qualitatively by linguistics, such as vegetation destruction and water pollution. Qualitative language expression has fuzziness and randomness. In the present research, the quantitative methods of qualitative indicators include expert scoring and triangular fuzzy number methods [11]. The expert scoring methodology is convenient to use, but it overlooks the fuzziness of qualitative linguistic expression. This quantitative method may make the evaluation results inconsistent with the actual results. In contrast to this approach, the method based on triangular fuzzy numbers considers fuzziness. However, in calculating the comprehensive distance between the alternative scheme and the ideal scheme, the qualitative and quantitative indexes should adopt various distance formulas, which increase the complexity and uncertainty of the calculation.

Interval numbers are defined as those numbers expressed in interval form [12]. Essentially, these all represent a set of real numbers in a closed interval. Because interval number description can realize the uncertainty of quantitative expression, interval number theory has been extensively employed in uncertain multi-attribute decision-making and uncertain mathematical programming [13,14]. The factors affecting the selection of desert railway routes include not only quantitative indicators such as railway length and proportion of bridges and tunnels, but also qualitative indicators such as environmental impact and wind–sand hazard. Therefore, the evaluation and optimization of the desert railway alignment scheme is a multi-attribute decision-making problem involving qualitative and quantitative indicators. By applying the interval number theory to the quantitative expression of qualitative indicators, the unified calculation of two types of indicators can enhance the accuracy of qualitative indicators and the efficiency of railway scheme decision-making. The technique for order preference by similarity to an ideal solution (TOPSIS) is a commonly used comprehensive evaluation methodology based on the original data information [15]. This method ranks the evaluation objects according to the proximity of the limited evaluation objects to the idealized goals. The calculated results can precisely reveal the gap between various evaluation schemes.

A brief literature survey and the explanations given above indicate that it is necessary to establish a quantitative decision-making method to optimize the desert railway alignment scheme. Let us consider the Minfeng-Yuhu section of the Hotan–Ruoqiang railway as the research object. With the aim of the technical problem of comprehensive quantification and optimization of the design of the desert railway route, the evaluation index system of the desert railway alignment plan is established. To this end, various crucial factors including railway design, wind-blown sand hazards, environmental impact, and operation condition are taken into account by analyzing the main factors affecting the design of desert railway. According to the principle of minimum discrimination information, the subjective and objective weights are appropriately combined to obtain the comprehensive weights of the index. The interval number is then exploited to realize the quantitative expression of the qualitative indexes of the railway scheme. The comprehensive distance between the alternative scheme and the ideal scheme is then evaluated based on the TOPSIS method. Additionally, the ranking and optimization of route schemes are realized by comparing the relative closeness. The present paper aims to provide a reference for desert railway alignment design and sand hazard prevention.

2. Research Methods

2.1. Main Research Framework

The main framework of this study consists of four steps (Figure 1). The first step includes the determination of the evaluation index system for the desert railway route scheme. The second step combines the analytic hierarchy process with the maximum deviation method to obtain the comprehensive weight of the indicators. The third step builds the decision-making model of the line route scheme based on the interval number theory and TOPSIS approach. The fourth step represents analysis of the application of the model to the Hotan–Ruoqiang railway, and providing appropriate suggestions for the decision-making of the route scheme.

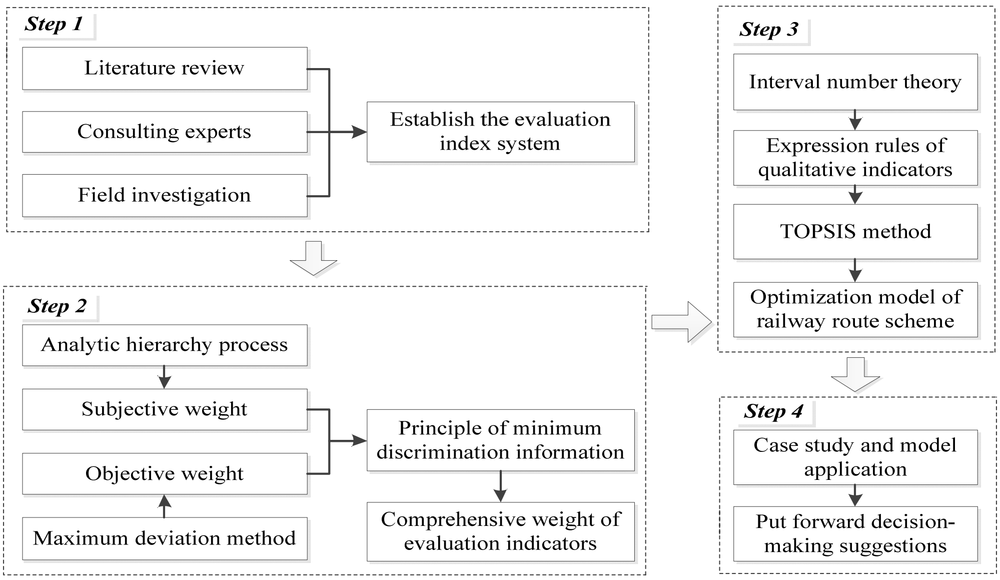

Figure 1. The research framework.

2.2. Construction of the Evaluation Index System of Desert Railway Route Scheme

2.2.1. Analysis of the Evaluation Factors

The alignment design of the desert railway is essentially limited by geological and environmental factors. The main hazard confronted by the railway in construction and operation is the wind–sand disturbance. Given the fragile ecological environment and serious geological hazards in the desert region, the design of the desert railway should follow the design principles of environmental protection and hazard reduction. During the design process, the terrain and geological conditions along the railway should be utilized to the maximum extent, avoiding areas with serious wind–sand hazards.

(1) Railway design

Railway alignment design in desert areas aims to select the best route scheme that is economically reasonable and technically feasible according to the transportation needs and natural conditions. The terrain, geology, hydrology, meteorology, and other natural conditions determine the difficulty of design and construction of railways, and then directly affect the selection of the line position [16,17]. The sand hazard should be rationally avoided and controlled during the engineering design. Due to a large number of construction sites and the wide scope of railway construction, the scale of land exploitation has grown substantially. Specifically, in wind–sand zones, the proportion of bridges and tunnels for railways is trivial, resulting in more occupied land. The original surface can be readily damaged during railway construction to form a new sand source [18]. The proportion of bridges and tunnels is closely related to earthwork, land occupation, and capital investment. Increasing this ratio can reduce land occupation, route slope, and line length, which is conducive to improving railway transportation efficiency and ensuring operational safety. The setting of bridges avoids the cutting effect on the environment on both sides of the line and facilitates the migration and foraging of wild animals [19]. Some sections with serious quicksand can also adopt the design of replacing subgrade with bridges to prevent sand damage [20]. The railway in the curvy segment is more vulnerable to the threat of sand damage. Generally, desert railways should be provided with few curves, and curves with a small radius of curvature should be avoided as much as possible. The railway in the curve section is usually designed as an embankment with the outside facing the prevailing wind direction.

(2) Wind-blown sand hazard

Wind-blown sand hazard is the main geological hazard faced by the construction and operation of the desert railway. A railway is a strip-shaped three-dimensional space entity arranged on the ground. By rationally considering the characteristics of the gas–solid two-phase flow of the wind-blown sand, appropriate engineering considerations can block its movement. The main forms of the railway sand damage are track burial, subgrade erosion, and rail abrasion [21,22]. The subgrade blocks a large amount of sand on the windward side of the railway, causing serious sand accumulation on the upper part of the track. The blocking effect strengthens with the increase in the angle between the line direction and the prevailing wind direction [23]. The local environment on both sides of the railway has a particularly prominent impact on wind–sand hazards [24]. Sand is the material basis of aeolian sand movement [25]. The more abundant the sand sources along the railway, the more likely it will suffer from wind–sand hazards. The sand control engineering of railways commonly refers to the engineering facilities set up in the sections vulnerable to sand damage, controlling the occurrence of wind erosion and altering the conditions of sand transportation. Further, sand prevention measures include engineering, vegetation, and chemical measures. Plant sand fixation in sections with good groundwater not only achieves the goal of permanent wind protection and sand stabilization, but also has a remarkably positive effect on the ecological environment along the railway.

(3) Environmental impact

The construction and operation of the railway can inevitably affect the natural environment and ecological environment along the route. Due to the sparse rainfall, low vegetation coverage, and shallow groundwater depth in the desert area, the project construction can easily damage the fragile geographical environment [26]. Ecologically sensitive areas along the railway include natural reserves, key cultural relics' protection areas, water conservation districts, and crucial ecological function zones. The noise and vibration produced by the train during the operation period will overshadow the survival of animals in protection districts [27]. Vegetation destruction is chiefly caused by the permanent occupation of forest lands, grasslands, wetlands, and temporary facilities (i.e., those in the construction stage by the railway and stations) [28]. The wildlife migration corridor plays a vital role in maintaining communities. However, the subgrade height of the railway is generally placed in the range of 2–6 m, which divides the migration activities of animals, thus affecting the reproduction and foraging of wild animals. The desert railway route should be designed to occupy less basic farmland and make use of wasteland and gravel beaches as much as possible for line development.

(4) Operating condition

Sand hazard affects the safe operation of desert railways. The track structure of railway in desert areas is usually ballasted track. Sand grains filled in the ballast reduce the damping and drainage performance of the ballast, which increases the dynamic response between wheels and rails when the train passes. In order to ensure the safe operation of the train, ballast needs to be cleaned regularly. The sand entering the track bed shortens the maintenance period and increases the maintenance cost of the ballast. The wind–sand flow reduces the visual distance of the train. The train should operate at low speed when the wind–sand flow is serious. The operation speed of train is related to the railway alignment parameters. The minimum curve radius limits the minimum speed of the train passing through the track. The more curves, the lower the passenger comfort and driving safety.

2.2.2. Construction of the Evaluation Index System

The evaluation index system is the basis of railway alignment scheme optimization. Combined with the above analyses on the railway design, wind-blown sand hazard, and environmental impact of the desert railway, an evaluation index system of a route scheme for a desert railway including three first-level indicators and fifteen second-level indicators was constructed based on the literature analysis, field investigation, and expert consultation [29,30], as presented in Table 1.

Table 1. Evaluation index system of the desert railway route.

First-Level Indicators	Second-Level Indicators	Indicator Type
Railway design (C_1)	Length of the railway line (C_{11})	Quantitative
	Land requisition amount (C_{12})	Quantitative
	Project investment (C_{13})	Quantitative
	Minimum curve radius (C_{14})	Quantitative
	The ratio of the bridges and tunnels (C_{15})	Quantitative
Wind–sand hazard (C_2)	Railway length in the moveable dune area (C_{21})	Quantitative
	The angle between the railway and the wind direction (C_{22})	Quantitative
	Temporary land occupation (C_{23})	Quantitative
	Feasibility of the plant sand control (C_{24})	Qualitative
	The scale of the sand control work (C_{25})	Qualitative
Environmental impact (C_3)	Impact on nature reserves (C_{31})	Qualitative
	Impact on the water environment (C_{32})	Qualitative
	Impact on the wildlife (C_{33})	Qualitative
	Impact on the vegetation cover (C_{34})	Qualitative
	Impact on the basic farmland (C_{35})	Qualitative
Operation condition (C_4)	Speed limit (C_{41})	Qualitative
	Track maintenance (C_{42})	Qualitative
	Operation safety (C_{43})	Qualitative

2.3. Comprehensive Weight of the Indicators

There are differences in the importance of evaluation indicators to the decision-making for railway schemes. The calculation methods of the index weight include the objective weight method and the subjective weight method. The objective weight method determines the weight according to the attribute data of the indicators, and the calculation results are not affected by human factors. However, the weight determined by this method may not conform to the actual importance of the indicator. The subjective weighting method determines the weight according to the subjective judgments of experts to each index. The weight results are commonly not affected by the value of the indicator attribute.

The intersection of qualitative and quantitative indexes in scheme decision-making for desert railway magnifies the difficulty of index weight calculations. The accuracy of index weight affects the correctness of scheme evaluation. Given the optimization complexity of railway location schemes, any single weighting methodology may lead to inaccurate calculation results. Based on the weight combination method herein, the subjective and objective weights are considered and appropriately combined to determine the comprehensive weights of indicators. As a result, the evaluation results will be more rational and consistent with the actual situation of the railway location scheme optimization.

2.3.1. Maximum Deviation Method

The deviation maximization approach is exploited to evaluate the weight according to the dispersion of the attribute value for the indicator [31]. This method can realize the dynamic adjustment with the variation of index data, and thereby, it can be more appropriately applied to the optimization of the desert railway alignment scheme. The smaller the difference in indicator attribute values of all alternatives, the smaller the role of this indicator in scheme ranking, and conversely, the more important the index is to the evaluation results. Therefore, the index that has a large deviation from the attribute value should have a large weight value.

For the decision-making problem with m schemes and n indexes, let w_j be the weight of the jth index in the scheme such that $w_i > 0$ and satisfy the unitization constraint. The factor $V_{ij}(w)$ is introduced to represent the total deviation ($k = 1, 2, \ldots, n$) of the attribute values of scheme A_i and other schemes for the index C_j [32]. Thereby,

$$V_{ij}(w) = \sum_{j=1}^{n} \left| p_{ij}w_j - p_{jk}w_j \right| \quad (i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n) \tag{1}$$

The total deviation between an alternative scheme and other schemes can be further evaluated by:

$$V_j(w) = \sum_{i=1}^{n} V_{ij}(w) = \sum_{i=1}^{n} \sum_{k=1}^{n} \left| p_{ij} - p_{jk} \right| w_j \tag{2}$$

According to the principle of maximum deviation, the optimization model can be constructed to examine the single objective optimization problem per the following relations:

$$\begin{aligned} &\max V(w) = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{n} \left| p_{ij} - p_{jk} \right| w_j \\ &\text{s.t.} \begin{cases} w_j \geq 0 \\ \sum_{j=1}^{n} w_j = 1 \end{cases} \end{aligned} \tag{3}$$

The optimization model is then solved by utilizing the Lagrange function, provided as follows:

$$L(w, \xi) = \sum_{j=1}^{m} \sum_{i=1}^{n} \sum_{k=1}^{n} |p_{ij} - p_{ik}| w_j + \frac{1}{2}\xi(\sum_{j=1}^{n} w_j^2 - 1) \tag{4}$$

According to the first-order optimization conditions, the weighted optimal solution w_j^* obtained by Lagrange least square method is as shown in Equation (5).

$$w_j^* = \frac{\sum_{i=1}^{m}\sum_{k=1}^{n}\left|p_{ij} - p_{jk}\right|}{\sqrt{\sum_{j=1}^{n}(\sum_{i=1}^{m}\sum_{k=1}^{n}\left|p_{ij} - p_{jk}\right|)^2}} \quad (5)$$

where $\sum_{i=1}^{m}\sum_{k=1}^{n}\left|p_{ij} - p_{jk}\right|$ denotes the sum of deviations. The normalized weight w_j with a total weight value of 1 can be obtained by normalizing w_j^* as in the following form:

$$w_j = \frac{\sum_{i=1}^{m}\sum_{k=1}^{n}\left|p_{ij} - p_{jk}\right|}{\sum_{j=1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{n}\left|p_{ij} - p_{jk}\right|} \quad (6)$$

2.3.2. Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a subjective weight calculation approach that combines qualitative and quantitative analysis [33]. This method employs the experience of decision-makers to judge the relative importance of each indicator and then the weight of the index is obtained. It has the advantages of simple calculation and strong systematization. The steps for calculating the weight via the chromatography approach are given as follows:

(1) The factor set U is constructed with n indicators:

$$U = \{b_1, b_2, \cdots, b_i, b_n\} \quad (7)$$

(2) The relative important judgment matrix P is constructed according to the relative importance of each indicator:

$$P = (b_{ij})_{n\times n} \quad (8)$$

in which b_{ij} represents the relative importance value of the index b_i to the index b_j ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$), $b_{ii} = 1$, $b_{ij} = 1/b_j$, and $b_{ij} = b_{ik}/b_{kj}$. The ratio scale can be expressed by 1, 3, 5, 7, and 9 as "equally important", "slightly important", "obviously important", "strongly important", and "extremely important", respectively. The numbers 2, 4, 6, and 8 are used to indicate the scale between the two scales mentioned above.

(3) Each column b_{ij} of the judgment matrix P is normalized to obtain c_{ij}:

$$c_{ij} = \frac{b_{ij}}{\sum_{k=1}^{N} b_{ki}}, i, j = 1, 2, \cdots n \quad (9)$$

(4) Each column c_{ij} of the normalization matrix is added in rows per the following relation:

$$w_{ij} = \sum_{j=1}^{N} c_{ij}, i, j = 1, 2, \cdots, n \quad (10)$$

(5) The column vector $\overline{w} = (\overline{w}_1, \overline{w}_2, \cdots, \overline{w}_n)^T$ is normalized to arrive at the feature vector $w = (w_1, w_2, \cdots, w_n)$ as follows:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n}\overline{w_i}}, i = 1, 2, \cdots n \quad (11)$$

The random consistency ratio (CR) is employed to judge the rationality of the weights:

$$CR = \frac{CI}{RI} = \frac{(\lambda_{\max} - n)}{(n-1) \cdot RI} \tag{12}$$

where CR denotes the ratio of random consistency, $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix P, and RI represents the average random consistency index of the judgment matrix, which can be determined by the order of the judgment matrix [34]. In the case of $CR < 0.10$, the judgment matrix can be assumed to have satisfactory consistency.

2.3.3. Comprehensive Weight

In order to consider the experience and knowledge of experts and avoid the randomness of subjective weighting, this paper uses the principle of minimum discrimination information to evaluate the comprehensive weights of the subjective and objective [35]. The objective function of the comprehensive weight w_j is defined as follows:

$$\begin{cases} \min J(w) = \sum\limits_{j=1}^{n} (w_i \ln \frac{w_j}{u_j} + w_j \ln \frac{w_j}{v_j}) \\ \text{s.t.} \quad \sum\limits_{j=1}^{n} w_j = 1, w_j \geq 0 \quad j = 1, 2, \cdots, n \end{cases} \tag{13}$$

where u_j and v_j in order are the subjective and objective weights of the index.

By constructing the Lagrange function to solve the optimization model, the combined weight w_j is calculated as:

$$w_j = \frac{\sqrt{u_j v_j}}{\sum\limits_{j=1}^{n} \sqrt{u_j v_j}} \tag{14}$$

2.4. Optimization Model of the Desert Railway Route Scheme

2.4.1. Interval Number Theory

The concept of the interval number was proposed by Moore in 1965 [36]. At that time, it was mainly implemented to solve the problem of error amplification and propagation during operation. Acquiring interval numbers does not require many assumptions and prior knowledge and can be utilized to analyze the uncertain information in the data. Using interval numbers to solve uncertain problems can reduce the influence of human factors. When the original data of a problem is uncertain and included in the given boundary range, it can be expressed by interval numbers. The solution to this problem can be obtained by employing the interval number operation algorithm.

Definition 1. *Let $a = [a^L, a^U] = \{x \mid 0 < a^L \leq x \leq a^U; a^L, a^U \in R\}$, where a^L and a^U stand for the upper and lower bounds of interval numbers, respectively, and a denotes the interval number [37]. Obviously, in the special case of $a^L = a^U$, the interval number a is transformed into an ordinary real number.*

Let $a = [a^L, a^U]$, $b = [b^L, b^U]$ be interval numbers, then a and b follow the following interval number algorithm.

(1) $a = b \rightarrow a^L = b^L, a^U = b^U$;
(2) $a + b = [a^L + b^L, a^U + b^U]$;
(3) $\lambda a = [\lambda a^L, \lambda a^U], \lambda > 0$;
(4) $ab = [a^L b^L, a^U b^U]$;

Definition 2. *Let $a = [a^L, a^U]$, $b = [b^L, b^U]$ be two positive interval numbers, then $D(a, b) = \frac{\sqrt{2}}{2}\sqrt{(a^L - b^L)^2 - (a^U - b^U)^2}$ is stated as the distance between two interval numbers [38].*

2.4.2. Interval Quantification of the Qualitative Indicators

Using interval numbers to describe qualitative indexes can help overcome the deficiencies of fuzziness and randomness. For the decision-making problem of the route alignment scheme, the linguistic value with the uncertain attribute can be converted between qualitative concept and quantitative expression by the interval number. This method is helpful to improve the accuracy of linguistic quantification. The qualitative indicators include benefit indicators and cost indicators. According to the engineering information of each scheme, experts should employ linguistic fuzzy numbers to evaluate the qualitative indicators in the quantitative transformation. According to the characteristics of the qualitative indicators [39], the scale of linguistic fuzzy numbers is appropriately divided into seven levels. The linguistic scale set of cost indicators is represented by S_1 = {Very small, Smaller, Small, Average Large, Larger, Very large}, while the linguistic scale set of benefit indicators is specified by S_2 = {Very bad, Worst, Bad, Average, Good, Better, Very good}.

According to the representation rules of interval numbers and the characteristics of railway schemes, the total range of interval numbers used to describe qualitative indicators is given by [0, 10]. Then, based on the linguistic scale and the total range of interval numbers, the width of each interval is about 1.43 for the equally divided case. In order to enhance the convenience of employing interval numbers, the range of each interval is further adjusted based on equal division by mixing the index level, interval number range, and fuzzy linguistic rules. The corresponding relationship between the linguistic scale and the interval number of qualitative indicators is provided in Table 2.

Table 2. Conversion rule between linguistic scales and interval numbers.

Cost Indicators	Benefit Indicators	Interval Range
Very small	Very bad	[0, 1.5]
Smaller	Worst	[1.5, 3]
Small	Bad	[3, 4.5]
Average	Average	[4.5, 5.5]
Large	Good	[5.5, 7]
Larger	Better	[7, 8.5]
Very large	Very good	[8.5, 10]

2.4.3. TOPSIS Method

TOPSIS is a suitable approach to solving mixed multi-attribute decision-making problems with the advantages of simple calculation and a wide application range [40]. The optimization of railway alignment schemes is a multi-level and multi-factor decision-making process involving qualitative and quantitative indicators. Therefore, TOPSIS can be effectively employed for the evaluation of railway schemes. The decision-making problem is commonly solved by sorting the positive and negative ideal solutions of the scheme. The basic steps for analyzing unknown problems are provided as follows:

Step 1: Construct the evaluation matrix for the railway route scheme.

If there are m railway schemes and n evaluation indexes, the scheme set can be stated by $A = \{A_1, A_2, \ldots, A_m\}$, and the indicators set can be expressed as $C = \{C_1, C_2, \ldots, C_n\}$, where the factors C_1~C_k represent the quantitative indicators with an accurate value, and C_{k+1}~C_n stand for the qualitative indicators associated with the interval numbers. The values of the quantitative and qualitative indexes of the scheme A_i for the index C_i are denoted by x_{ij} and given as $x_{ij} = [x_{ij}^L, x_{ij}^U]$ (i = 1, 2, . . . , m; j = 1, 2, . . . , n). Subsequently, the original evaluation matrix A_1 of the railway alignment scheme is calculated as follows:

$$A_1 = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{k1} & x_{k2} & \cdots & x_{kn} \\ [x_{(k+1)1}^L, x_{(k+1)1}^U] & [x_{(k+1)2}^L, x_{(k+1)2}^U] & \cdots & [x_{(k+1)n}^L, x_{(k+1)n}^U] \\ \vdots & \vdots & \ddots & \vdots \\ [x_{m1}^L, x_{m1}^U] & [x_{m2}^L, x_{m2}^U] & \cdots & [x_{mn}^L, x_{mn}^U] \end{bmatrix} \quad (15)$$

According to the interval numbers theory, the accurate numbers used to describe the quantitative indicators are converted into interval numbers. The evaluation matrix A_2 composed of interval numbers is as follows:

$$A_2 = \begin{bmatrix} [x_{11}^L, x_{11}^U] & [x_{12}^L, x_{12}^U] & \cdots & [x_{1n}^L, x_{1n}^U] \\ [x_{21}^L, x_{21}^U] & [x_{22}^L, x_{22}^U] & \cdots & [x_{2n}^L, x_{2n}^U] \\ \vdots & \vdots & \ddots & \vdots \\ [x_{m1}^L, x_{m1}^U] & [x_{m2}^L, x_{m2}^U] & \cdots & [x_{mn}^L, x_{mn}^U] \end{bmatrix} \quad (16)$$

Step 2: Normalization of the original decision matrix.

Since each indicator has distinct units and dimensions, the consisting ones cannot be compared uniformly. In order to eliminate the influence of the data dimension on the calculation results, Equations (17)–(20) are utilized to normalize the index data, and then the normalization matrix $Y = (y_{ij})_{m\times n}$ is obtained, where $y_{ij} = [y_{ij}^L, y_{ij}^U]$ (i = 1, 2, . . . , m; j = 1, 2, . . . , n).

The benefit indicator is a particular index whose value is larger and better for decision-making. The normalization procedure of benefit indicators is presented in the following:

$$y_{ij}^L = x_{ij}^L / \sqrt{\sum_{i=1}^{m} (x_{ij}^U)^2} (i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots,\ n) \quad (17)$$

$$y_{ij}^U = x_{ij}^U / \sqrt{\sum_{i=1}^{m} (x_{ij}^L)^2} (i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots,\ n) \quad (18)$$

The cost indicator is an index whose value is smaller and better for decision-making. The normalization approach of cost indicators has been demonstrated as follows:

$$y_{ij}^L = (1/x_{ij}^U) / \sqrt{\sum_{i=1}^{m} (1/x_{ij}^L)^2} (i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots,\ n) \quad (19)$$

$$y_{ij}^U = (1/x_{ij}^L) / \sqrt{\sum_{i=1}^{m} (1/x_{ij}^U)^2} (i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots,\ n) \quad (20)$$

Step 3: Construct the weighted normalized decision matrix.

The construction of the weighted normalized decision matrix is explained in the following. To this end, the index weight calculated by the weighting method is as $w = [w_1, w_2, \ldots, w_n]^T$ ($0 < w_j < 1$, and $\sum_{j=1}^{n} w_j = 1$). The weighted normalization matrix can be expressed by $Z = (z_{ij})_{m\times n}$, where $z_{ij} = w_j \times y_{ij}$ (i = 1, 2, . . . , m; j = 1, 2, . . . , n).

Step 4: Determine positive and negative ideal solutions

The positive ideal solution Z^+ and the negative ideal solution Z^- of the decision scheme are determined according to the following relations:

$$Z^+ = (z_1^+, z_2^+, \cdots, z_n^+) = (\max_i [z_{ij}^L, z_{ij}^U]) \tag{21}$$

$$Z^- = (z_1^-, z_2^-, \cdots, z_n^-) = (\max_i [z_{ij}^L, z_{ij}^U]) \tag{22}$$

in which $z_{ij}^+ = [\max_i \left\{ z_{ij}^L \right\}, \max_i \left\{ z_{ij}^U \right\}]$, $z_{ij}^- = [\max_i \left\{ z_{ij}^L \right\}, \max_i \left\{ z_{ij}^U \right\}]$.

Step 5: Determine the distance between the alternative and the ideal

The distance D^+ from each alternative to the positive ideal solution and the distance D^- from the negative ideal solution are, respectively, calculated using the following relations:

$$D^+ = \sqrt{\sum_{j=1}^{n} (z_{ij}^+ - Z_j^+)} = \left(\sum_{j=1}^{n} \frac{\sqrt{2}}{2} \sqrt{(z_{ij}^L - Z_j^L)^2 - (z_{ij}^U - Z_j^U)^2} \right)^{1/2} \tag{23}$$

$$D^- = \sqrt{\sum_{j=1}^{n} (z_{ij}^- - Z_j^-)} = \left(\sum_{j=1}^{n} \frac{\sqrt{2}}{2} \sqrt{(z_{ij}^L - Z_j^L)^2 - (z_{ij}^U - Z_j^U)^2} \right)^{1/2} \tag{24}$$

Step 6: Calculate relative closeness

The design schemes are sorted according to the value of relative closeness. The smaller value of D_i indicates that the scheme is better, which is calculated as follows:

$$D_i = \frac{D_i^+}{D_i^+ + D_i^-} \tag{25}$$

3. Case Study

3.1. Project Overview

The Hotan–Ruoqiang railway is a single-track railway with a design speed of 120 km/h connecting Hotan to Ruoqiang in Xinjiang, China. The total length of its trunk line is 825.5 km. This railway extends from west to east along the piedmont proluvial plain at the northern foot of the Kunlun Mountain and the southern fringe of the Taklimakan Desert. It is another convenient network for Xinjiang to connect with other external regions. The corresponding geographical location has been illustrated in Figure 2. The areas along the Hotan–Ruoqiang railway are characterized by drought, sparse vegetation, and fragile ecology. It is difficult for the railway to avoid all environmentally sensitive areas and wind-blown sand districts along the route. Therefore, the wind–sand hazards and ecological environment are the key factors restricting railway construction.

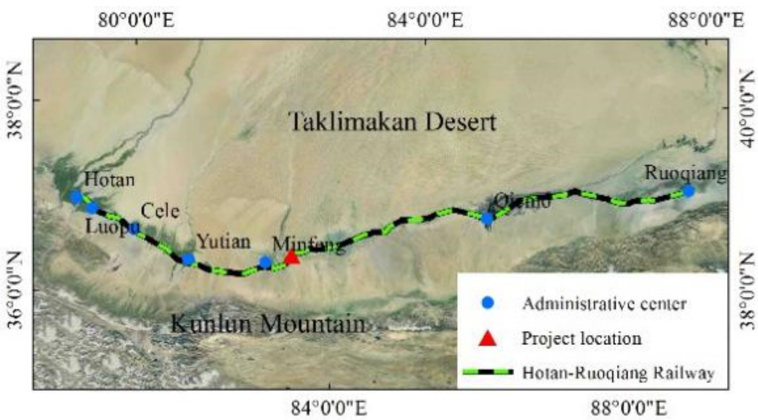

Figure 2. Location of the Hotan–Ruoqiang railway.

The main influencing factors of the alignment design in the Minfeng-Yuhu section of the Hotan–Ruoqiang railway are the Niya National Wetland Park and moving dunes. This park has been spread from the Kunlun Mountain and ends in the hinterland of the Taklimakan Desert, an important local environmental protection barrier. In order to lessen the damage of the railway construction to the sandy zones and the environment, accounting for the park scope, sand hazard distribution, and topographic condition, the railway engineer examined Schemes A–C (Figure 3).

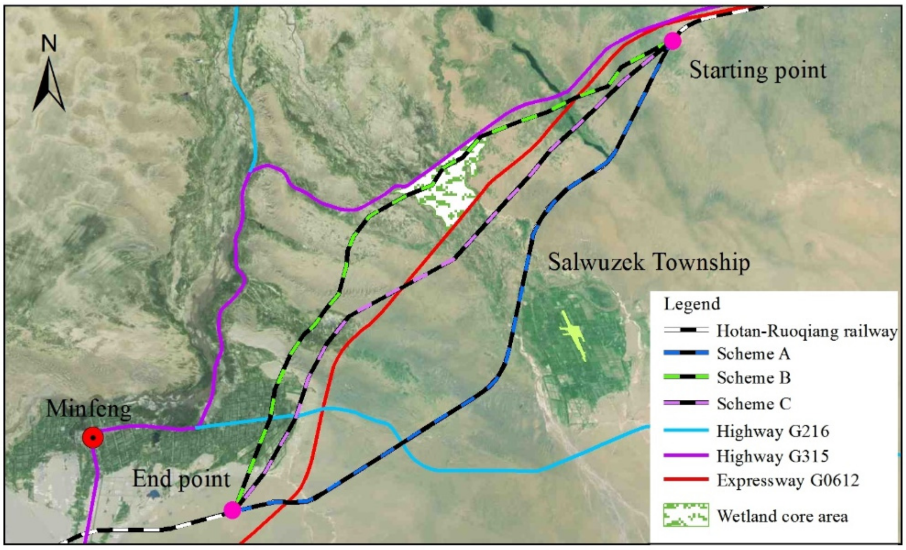

Figure 3. Schematic representation of the railway scheme.

Scheme A: The route turns to the southeast from the starting point of the comparison and passes through the moving dunes on the eastern side of the Yuhu. It then goes southward along the western edge of the Salwuzek Township and turns west to cross a 9.3-kilometre super bridge over a serious section of moving sandy dunes in the Minfeng East. Finally, after crossing the highway G215, this railway reaches the endpoint of the comparison. Scheme A completely bypasses the Niya National Wetland Park, passing only 11.87 km of the wetland and oasis, with the best environmental benefits. However, the railway crossing the moving dunes is the longest, which leads to the highest project investment and sand control work among the alternatives.

Scheme B: The route starts from the starting point of the comparison and crosses the wetland protected area of the Niya National Wetland Park to the south. After crossing the G215 expressway, the route runs southward parallel to the national road G315, partially passing through flowing sand dunes. At last, it turns west and crosses the Tullekanrik River to the end of the comparison. The length of Scheme B is the shortest, and the corresponding project investment is less than that of Scheme A. The length of the railway that passes through the wetland oasis and the wetland park is about 18.5 km and 7.53 km, respectively, which has apparent environmental damage.

Scheme C: The route starts from the comparison starting point, passes through the wetland conservation area of the Niya National Wetland Park, and runs southward along the southern side of the expressway. The route then crosses through the moving dunes and the expressway under construction by bridges and turns south. Finally, it turns west and crosses the Tullekanrik River to the comparison endpoint. Scheme C exhibits the largest railway length, but the corresponding engineering investment and protection quantities are the least. The railway passes through 22.1 km of wetland oasis and 11.88 km of wetland park, causing great damage to the ecological environment.

From the analyses given above, it can be seen that the three route schemes have their own advantages and disadvantages in alignment design, wind–sand hazard, environmental impact, and operation condition, and it is difficult to determine what is optimal. Since the influencing factors include both qualitative and quantitative indicators, it is necessary to conduct multi-attribute comparison studies of route schemes to realize the optimal design of the desert railway. Therefore, the optimization model constructed in this paper is exploited to assess the line scheme. The data values of quantitative indicators are obtained from the engineering data in this section. The data of qualitative indicators are also obtained after consulting with the design experts participating in the project. The engineering information of the alignment design scheme has been presented in Table 3.

Table 3. Engineering information of route schemes.

Indicators.	Scheme A	Scheme B	Scheme C
Length of the railway line (km)	39.50	40.97	38.88
Land requisition amount (hec)	115.4	122.1	137.5
Project investment ($million)	172.29	162.91	156.71
Minimum curve radius (m)	2000	2200	2500
The ratio of the bridges and tunnels (%)	28.59	10.42	20.33
Railway length in the moveable dune area (km)	31.952	28.558	27.452
The angle between the railway and the wind direction)/°	26.70	16.10	18.30
Temporary land occupation (hec)	1202.0	1399.0	1513.0
The scale of the sand control work	Larger	Large	Small
Feasibility of plant sand control	Bad	Average	Better
Impact on nature reserves	Smaller	Large	Larger
Impact on the water environment	Average	Large	Large
Impact on the wildlife	Average	Larger	Large
Impact on the vegetation cover	Smaller	Large	Larger
Impact on the basic farmland	Small	Average	Small
Speed limit	Small	Large	Average
Track maintenance	Average	Small	Small
Operation safety	Average	Good	Good

3.2. Index Weight Calculation

3.2.1. Weight of the AHP Method

According to the evaluation index system established in this paper, six experts from design and construction are invited to utilize the AHP approach to analyze the relative importance of the indexes. The judgment matrix of the secondary indicators has been summarized in Table 4.

The subjective weights of the indicator are calculated by using Equations (7)–(12). Each judgment matrix should pass the consistency test.

The indicators that have the largest weight are length of the railway line, impact on nature reserves, and project investment, among which the length of the railway line has the greatest influence on the scheme decision-making. This is because the railway divides the original surface of the desert area. The longer the route mileage, the more noticeable the damaging effect. Increasing the length of the railway also increases the investment and the risk of sand damage. The Niya National Wetland Park not only has a strong function in regulating groundwater, but also can purify sewage and regulate regional climate. As a result, the geographical environment is very sensitive to the project construction, and the cost of recovery after the damage is very high. Due to the large scale of the railway project investment, the railway design scheme should achieve economic rationality by ensuring performance and advanced technology.

Table 4. The judgment matrix of the second-level index.

C_1	Sub-Criteria	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_{11}	Length of the railway line	1	4	2	5	3
C_{12}	Land requisition amount	1/4	1	1/3	2	1/2
C_{13}	Project investment	1/2	3	1	4	2
C_{14}	Minimum curve radius	1/5	1/2	1/2	1	1/3
C_{15}	The ratio of the bridges and tunnels	1/3	2	1/2	3	1
				CR = 0.0152		
C_2	**Sub-Criteria**	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}
C_{21}	Railway length in the moveable dune area	1	4	3	2	5
C_{22}	The angle between the railway and the wind direction	1/4	1	1/2	1/3	2
C_{23}	Temporary land occupation	1/3	2	1	1/2	3
C_{24}	Feasibility of the plant sand control	1/2	3	2	1	4
C_{25}	The scale of the sand control work	1/5	1/2	1/3	1/4	1
				CR = 0.0152		
C_3	**Sub-Criteria**	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
C_{31}	Impact on nature reserves	1	2	4	3	9/2
C_{32}	Impact on the water environment	1/2	1	3	2	5/2
C_{33}	Impact on the wildlife	1/4	1/3	1	1/2	1
C_{34}	Impact on the vegetation cover	1/3	1/2	2	1	3/2
C_{35}	Impact on the basic farmland	2/9	2/5	1	2/3	1
				CR = 0.0060		
	Sub-Criteria	C_{41}	C_{42}	C_{43}		
C_{41}	Speed limit	1	2/3	2/5		
C_{42}	Track maintenance	3/2	1	2/3		
C_{43}	Operation safety	5/2	3/2	1		
				CR = 0.0010		

3.2.2. Weight of the Maximum Dispersion Method

According to the standardized interval number decision matrix and the maximum deviation method, the objective weight of the indicators is obtained by using Equations (1)–(6). The results are shown in Table 5.

The ratio of bridges and tunnels, impact on nature reserves, and impact on the vegetation cover have the largest weight among the secondary indicators evaluated by the dispersion approach. The ratio of bridges and tunnels in Scheme A is 28.59%, which is 1.41 times that of Scheme C (i.e., the smallest one). Compared with the subgrade, the excavation volume and land area of the bridge are commonly smaller, which reduces the damage of the railway construction with respect to the surface. The wind-blown sand flow can pass under the bridge to avoid the problem of railway sand damage [41]. The Hotan–Ruoqiang railway is a single-track railway that employs diesel locomotives to provide power. During operation, the locomotive directly discharges CO, SO_2, and other exhaust gases into the areas along the line. These pollutants can damage the biological diversity and water safety in the wetland park.

Table 5. The weights of evaluation indicators.

Evaluation Indicators	Subjective Weight	Objective Weight	Comprehensive Weight
Length of the railway line	0.1806	0.0068	0.0417
Land requisition amount	0.0422	0.0227	0.0367
Project investment	0.1139	0.0124	0.0446
Minimum curve radius	0.0266	0.0293	0.0331
The ratio of the bridges and tunnels	0.0693	0.1128	0.1050
Railway length in the moveable dune area	0.0745	0.0196	0.0454
The angle between the railway and the wind direction	0.0174	0.0617	0.0389
Temporary land occupation	0.0286	0.0303	0.0350
Feasibility of the plant sand control	0.0470	0.0916	0.0779
The scale of the sand control work	0.0110	0.0930	0.0379
Impact on nature reserves	0.1067	0.1118	0.1296
Impact on the water environment	0.0626	0.0302	0.0516
Impact on the wildlife	0.0221	0.0587	0.0428
Impact on the vegetation cover	0.0364	0.1118	0.0757
Impact on the basic farmland	0.0238	0.0507	0.0412
Speed limit	0.0276	0.0754	0.0542
Track maintenance	0.0430	0.0507	0.0554
Operation safety	0.0667	0.0303	0.0534

3.2.3. Comprehensive Weight

The subjective weights evaluated by the AHP method and the objective weights calculated by the maximum deviation method are substituted into Equations (13) and (14) to arrive at the comprehensive weight of the evaluation index. The achieved results have been presented in Table 5.

Among the secondary indicators, impact on nature reserves, the ratio of bridges and tunnels, and feasibility of the plant sand control have the first three ranks. The wetland park not only has abundant resources, but also has enormous ecological regulation functions and environmental benefits. The Niya National Wetland Park is a crucial part of maintaining the ecological balance in the region. The wetland is the significant foundation of water resource protection and the main source of freshwater resources. It plays a vital role in impounding water, regulating runoff, replenishing groundwater, and maintaining regional water balance. In the section with particularly serious sand damage, the bridge is employed to replace the subgrade for allowing the wind-blown sand to pass under the bridge, which can remarkably reduce the threat of wind–sand along the line. Therefore, the final weights of the indicators are consistent with their actual importance.

3.3. Railway Route Scheme Optimization

According to the quantitative method of qualitative indicators and the attribute data in Table 3, the linguistic fuzzy number of the route scheme is converted into an interval number. The interval number decision matrix can be evaluated as follows:

$$A_1 = \begin{bmatrix} [39.5, 39.5] & [40.97, 40.97] & [38.88, 38.88] \\ [115.4, 115.4] & [122.1, 122.1] & [137.5, 137.5] \\ [172.29, 172.29] & [162.91, 162.91] & [156.71, 156.71] \\ [2000, 2000] & [2200, 2200] & [2500, 2500] \\ [28.59, 28.59] & [10.42, 10.42] & [20.33, 20.33] \\ [31.952, 31.952] & [28.558, 28.558] & [27.452, 27.452] \\ [26.7, 26.7] & [16.1, 16.1] & [18.3, 18.3] \\ [1202, 1202] & [1399, 1399] & [1513, 1513] \\ [7.0, 8.5] & [5.5, 7.0] & [3.0, 4.5] \\ [3.0, 4.5] & [4.5, 5.5] & [7.0, 8.5] \\ [1.5, 3.0] & [5.5, 7.0] & [7.0, 8.5] \\ [4.5, 5.5] & [5.5, 7.0] & [5.5, 7.0] \\ [4.5, 5.5] & [7.0, 8.5] & [5.5, 7.0] \\ [1.5, 3.0] & [5.5, 7.0] & [7.0, 8.5] \\ [3.0, 4.5] & [4.5, 5.5] & [3.0, 4.5] \\ [3.0, 4.5] & [5.5, 7.0] & [4.5, 5.5] \\ [4.5, 5.5] & [3.0, 4.5] & [3.0, 4.5] \\ [4.5, 5.5] & [5.5, 7.0] & [5.5, 7.0] \end{bmatrix}^T$$

Then, the index data is normalized according to Equations (17)–(20), and the normalized decision matrix (A_2) is given by:

$$A_2 = \begin{bmatrix} [0.5811, 0.5811] & [0.5602, 0.5602] & [0.5903, 0.5903] \\ [0.6205, 0.6205] & [0.5864, 0.5864] & [0.5207, 0.5207] \\ [0.5482, 0.5482] & [0.5798, 0.5798] & [0.6027, 0.6027] \\ [0.5149, 0.5149] & [0.5663, 0.5663] & [0.6436, 0.6436] \\ [0.7812, 0.7812] & [0.2847, 0.2847] & [0.5555, 0.5555] \\ [0.5266, 0.5266] & [0.5891, 0.5891] & [0.6129, 0.6129] \\ [0.4124, 0.4124] & [0.6840, 0.6840] & [0.6017, 0.6017] \\ [0.6497, 0.6497] & [0.5582, 0.5582] & [0.5161, 0.5161] \\ [0.2801, 0.4968] & [0.3521, 0.6322] & [0.5478, 1.0000] \\ [0.2708, 0.5087] & [0.4062, 0.6218] & [0.6318, 0.9609] \\ [0.4724, 1.0000] & [0.2025, 0.4769] & [0.1667, 0.3747] \\ [0.5350, 0.8176] & [0.4204, 0.6689] & [0.4204, 0.6689] \\ [0.5669, 0.8566] & [0.3668, 0.5506] & [0.4455, 0.7008] \\ [0.4724, 1.0000] & [0.2025, 0.4769] & [0.1667, 0.3747] \\ [0.4264, 0.9181] & [0.3489, 0.6121] & [0.4264, 0.9181] \\ [0.5051, 1.0000] & [0.3174, 0.5669] & [0.4133, 0.6929] \\ [0.3489, 0.6121] & [0.4264, 0.9181] & [0.4264, 0.9181] \\ [0.3974, 0.6121] & [0.4857, 0.7790] & [0.4857, 0.7790] \end{bmatrix}^T$$

Then, the weighted normalized decision matrix (A_3) is obtained by multiplying the index weight and the normalized decision matrix.

$$A_3 = \begin{bmatrix} [0.0242, 0.0242] & [0.0234, 0.0234] & [0.0246, 0.0246] \\ [0.0228, 0.0228] & [0.0215, 0.0215] & [0.0191, 0.0191] \\ [0.0244, 0.0244] & [0.0258, 0.0258] & [0.0269, 0.0269] \\ [0.0170, 0.0170] & [0.0188, 0.0188] & [0.0213, 0.0213] \\ [0.0820, 0.0820] & [0.0299, 0.0299] & [0.0583, 0.0583] \\ [0.0239, 0.0239] & [0.0267, 0.0267] & [0.0278, 0.0278] \\ [0.0160, 0.0160] & [0.0266, 0.0266] & [0.0234, 0.0234] \\ [0.0227, 0.0227] & [0.0195, 0.0195] & [0.0180, 0.0180] \\ [0.0218, 0.0387] & [0.0274, 0.0492] & [0.0427, 0.0779] \\ [0.0103, 0.0193] & [0.0154, 0.0236] & [0.0240, 0.0364] \\ [0.0612, 0.1296] & [0.0262, 0.0618] & [0.0216, 0.0486] \\ [0.0276, 0.0422] & [0.0217, 0.0345] & [0.0217, 0.0345] \\ [0.0243, 0.0367] & [0.0157, 0.0236] & [0.0191, 0.0300] \\ [0.0358, 0.0757] & [0.0153, 0.0361] & [0.0126, 0.0284] \\ [0.0176, 0.0378] & [0.0144, 0.0252] & [0.0176, 0.0378] \\ [0.0274, 0.0542] & [0.0176, 0.0307] & [0.0224, 0.0375] \\ [0.0193, 0.0339] & [0.0236, 0.0509] & [0.0236, 0.0509] \\ [0.0212, 0.0327] & [0.0259, 0.0416] & [0.0259, 0.0416] \end{bmatrix}^T$$

Based on the weighted normalized decision matrix, the positive ideal solution Z^+ and the negative ideal solution Z^- of the decision scheme can be, respectively, determined by Equations (21) and (22):

$$Z^+ = \begin{bmatrix} [0.0246, 0.0246] \\ [0.0228, 0.0228] \\ [0.0269, 0.0269] \\ [0.0213, 0.0213] \\ [0.0820, 0.0820] \\ [0.0278, 0.0278] \\ [0.0266, 0.0266] \\ [0.0227, 0.0227] \\ [0.0427, 0.0779] \\ [0.0240, 0.0364] \\ [0.0612, 0.1296] \\ [0.0276, 0.0422] \\ [0.0243, 0.0367] \\ [0.0358, 0.0757] \\ [0.176, 0.0378] \\ [0.0274, 0.0542] \\ [0.0236, 0.0509] \\ [0.0259, 0.0416] \end{bmatrix}^T, Z^- = \begin{bmatrix} [0.0234, 0.0234] \\ [0.0191, 0.0191] \\ [0.0244, 0.0244] \\ [0.0170, 0.0170] \\ [0.0299, 0.0299] \\ [0.0239, 0.0239] \\ [0.0160, 0.0160] \\ [0.0180, 0.0180] \\ [0.0218, 0.0387] \\ [0.0103, 0.0193] \\ [0.0216, 0.0486] \\ [0.0217, 0.0345] \\ [0.0157, 0.0236] \\ [0.0126, 0.0284] \\ [0.0144, 0.0252] \\ [0.0176, 0.0307] \\ [0.0193, 0.0339] \\ [0.0212, 0.0327] \end{bmatrix}^T$$

The distance between each alternative scheme and the positive ideal scheme or the negative ideal scheme is evaluated by using Equations (23) and (24). The calculation results are shown in Table 6.

Table 6. Scheme comparison.

Evaluation Scheme	D^-	D^+	Relative Closeness
Scheme A	0.0937	0.0398	0.2979
Scheme B	0.0237	0.0887	0.7891
Scheme C	0.0498	0.0794	0.6145

The presented results in Table 6 display that the comprehensive distance of Scheme A is 0.2979, which is smaller than that of Schemes B and C. Therefore, Scheme A is the most recommended scheme for the railway alignment design.

3.4. Analysis of Evaluation Results

Scheme A is located at the southern edge of the Niya National Wetland Park, neglecting the core area and buffer zone sensitive to biodiversity, and minimizing the resulting impacts on the structure, overall function, and ecosystem of the reserve. The predicted results by the proposed calculation model in this paper are consistent with the results obtained by the design experts through quantitative calculation and qualitative analysis.

In terms of railway design, Scheme A is about 1.472 km shorter than Scheme C and 0.62 km longer than Scheme B. The desert railway design is attempted to avoid causing sections with serious wind-blown sand hazards. The ratio of bridges and tunnels in Scheme A is 28.59%, being the largest among the three schemes. Due to the setting of the sand crossing bridge, the project investment of Scheme A increases by USD 9.38 million and USD 15.58 million, respectively, compared with Schemes B and C, but the amounts of increase are still acceptable. The bridge will not substantially grow the area of sand-blown land, nor will it pose a serious threat to the structure and function of the wetland ecosystem along the line. Scheme C is close to the National Highway 315 and makes use of the existing access roads in the construction area. In general, the traffic conditions for railway construction, operation, and maintenance are good.

In terms of wind-blown sand hazards, the three schemes will be affected by variously applied levels of wind–sand hazards. The project is located in the dry–warm temperate continental climate, with dry climate and little rain, sparse surface vegetation, and obvious land desertification. Crescent dunes have been developed in the understudied area. Strong winds and widely distributed quicksand will have adverse effects on the constructional and operational works of the railway. Since Scheme A completely bypasses the Niya National Wetland Park, it passes through a large area of moving dunes on the eastern side of Minfeng. The total length of the wind-blown sand section is about 31.952 km. Some parts of the lines in Schemes B and C are located in the protected area of the wetland park. The vegetation coverage along the railway is high and the quicksand distribution is small, so the possibility of wind–sand damage is low. The degree of sand hazard and the scale of the protection project for Scheme A are higher than those of the other two schemes.

Concerning the ecological environment, Scheme A completely bypasses the wetland park, and the land occupied by the project mainly presents a small amount of forest land and shrubs, which does not affect the ecological diversity of the wetland park. Both Schemes B and C cross the Niya National Wetland Park three times, with a length of 11.875 km and 7.525 km, respectively. In addition, railway stations are reserved within the conservation area in these two schemes. The sustainability of biodiversity and water environment of the wetland park in desert areas are very weak. Scheme B crosses the wetland conservation area of the park by 4.44 km in the form of bridges and subgrade. Scheme C passes through the wetland conservation area of the wetland park by 2.095 km in the form of a subgrade. The lands occupied by the two schemes are mostly forest land, shrub forest, and river water surface. Due to the temporary and permanent lands required in the project construction, some natural vegetation, surface microorganisms, and some wild animals will inevitably be destroyed, and the number of these species in the wetland park will be reduced in a short time. The railway construction will also damage the closeness and safety of the water source of the Niya River National Wetland Park. From the point of view of the ecological environment, Scheme A is superior to Schemes B and C.

The sandstorm environment reduces the operating conditions of the railway. When the sand damage is serious, the train speed needs to be reduced to ensure the safety of the operation. The route length of Scheme A in the mobile sand dune area is the largest among the three schemes. Although sand prevention works have been set up, sand particles cannot be prevented from depositing on the track. Schemes B and C have good vegetation cover and weak wind–sand flow. Therefore, the track maintenance cycle and operation safety of Scheme A are the worst.

The evaluation results of the railway alignment scheme of the Niya National Wetland Park section are consistent with those of the selected scheme for the project construction. It confirms the scientificity and validity of the decision-making model in this paper. This park plays a crucial role in mitigating local climate change and maintaining regional ecosystem balance. If the railway passes through the wetland park, it will affect its ecological environment. The obtained results reveal that the evaluation results are consistent with the actual project. The 4-year construction of Scheme A demonstrates that the wind–sand hazard of the line has been effectively controlled, with good environmental benefits and good operating conditions. Therefore, Scheme A is a successful case of railway route selection in desert areas. This evaluation model is a scientific and effective method for optimizing the railway alignment scheme and can provide a solid decision-making basis for optimizing the railway scheme in desert areas.

4. Discussion

The evaluation and optimization of the railway alignment scheme is a multi-attribute decision-making problem. First, we should establish an indicator system for project evaluation, but there is no unified standard. There is also little information about comparing and choosing the schemes of the desert railway route. The influencing factors on the route selection are tightly related to the cost, benefit, technology, safety, and surrounding environment [42]. Due to the fragile ecological environment and frequent geological hazards in desert zones, the geographical environment is very sensitive to engineering construction. The railway cuts off the movement path of the wind–sand flow on the surface, thus intensifying the imposition of sand damage and the destruction of the natural environment. Due to the long construction period and many crossing areas for the railway, the unreasonable route scheme will reduce its traffic efficiency, even leading to environmental and social problems. Once the environment in the desert area is destroyed, it is very difficult and expensive to recover [43]. The construction of the evaluation index system of the alignment scheme should not only consider the railway construction itself, but also focus on the ecological environment factors and sand hazards. Therefore, 18 indicators from the alignment design, blown sand hazard, environmental impact and operation condition are selected to establish the evaluation index system for railway alignment schemes in desert zones. The control factors of the railway route in the gale environment and the Gobi sandstorm environment are different from those in the desert areas. The index system developed in this paper has certain limitations. In practical application, the evaluation index system of the route scheme can be adjusted according to the characteristics of these sandy areas.

In the current exploration, the subjective and objective weight methods are appropriately employed to determine the comprehensive weight of the evaluation index. A slight change in the index weight can have a remarkable impact on the evaluation results of the scheme. Because there are some qualitative indicators in the evaluation index system, it is difficult to evaluate the weight by employing the objective weighting method. At present, the analytic hierarchy process is commonly utilized to evaluate the index weight in the comparison and selection of railway route schemes; however, the calculation results are noticeably disturbed by human factors. The maximum deviation method determines the objective weight of the indicator based on the variance of the original data, which reflects the importance of the indicator from the data itself. Using interval numbers to quantify qualitative indicators also makes it more convenient to obtain objective weights. The comprehensive weight not only reflects the objective information of the decision-making, but also reduces the influence of subjective factors on the decision-making results.

The optimal design of the alignment scheme for the railway is an important measure to reduce the environmental impact of railway engineering and wind–sand hazards in desert areas. Currently, the comprehensive evaluation of railway schemes often discusses qualitative and quantitative indicators separately. Through the calculation of quantitative indicators, combined with the qualitative analysis of qualitative indicators by experts, comprehensive evaluation results are achieved. These approaches do not realize the unified calculation of qualitative and quantitative indicators. The tedious calculation and complicated model reduce the efficiency and accuracy of railway scheme selection. Linguistic fuzzy numbers have some uncertainties. The quantification of the qualitative indicators through accurate numbers may lead to an incomplete expression of expert opinions, and ultimately the evaluation results do not conform to the actual situation of the project. The interval number theory can represent and solve uncertainty problems within a given range. Employing interval numbers to quantify qualitative indicators can realize the effective conversion from qualitative linguistic to quantitative expression, which considers the fuzziness of the conversion. Compared with the traditional triangular fuzzy number method and the accurate number method, it improves the efficiency and accuracy of calculations.

5. Conclusions

This paper proposed a quantitative evaluation model of the route scheme for the desert railway. The factors affecting the railway design from the aspects of alignment design, sand hazard and environmental impact were analyzed, and the evaluation index system was constructed by selecting the major factors. The comprehensive weights of the index were obtained by combining subjective weights and objective weights. The quantitative method of the qualitative index using interval number was designed. An optimization model of the railway route scheme in desert areas based on interval number and TOPSIS was established. The model was verified by using a case study of the Hotan–Ruoqiang railway. The following conclusions can be drawn:

(1) The comprehensive weights reflect the actual importance of each index. Compared with the single weighting method, the combination weighting method takes into account both the attribute characteristics of the index and the experience and knowledge of experts.
(2) The quantification of qualitative indicators based on interval number reduces the impact of subjective reasons on the evaluation results. The interval number takes into account the fuzziness and uncertainty in the quantitative transformation. The index operation expressed in interval number improves the convenience and reliability of the scheme decision.
(3) The proposed method is an effective evaluation method for the railway route scheme. The obtained results reveal that the evaluation results are consistent with the actual project. This model can provide quantitative theoretical support for the decision-making of the desert railway route scheme.

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