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Evaluation of Excavation Ergonomics of Drill and Blast Method Based on Game Theory G2-EW-TOPSIS Model

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Abstract: The demand for tunnel construction continues to grow by leaps and bounds. Therefore, tunnel mechanization construction is receiving more and more attention for improving excavation ergonomics. To enhance the scientific and comprehensive evaluation results of tunnel drilling and blasting method excavation ergonomics, a set of evaluation methods of tunnel drilling and blasting method excavation ergonomics based on the game theory G2-EW-TOPSIS model is proposed. From the three dimensions of drilling efficiency, construction process duration, and synergistic influence factors, a tunnel drilling and blasting construction ergonomics evaluation index system consisting of 11 indicators such as perimeter hole drilling efficiency, drilling duration, construction quality, and comprehensive cost is constructed. The subjective and objective weights of evaluation indicators are calculated by using the improved sequential relationship analysis method (G2 method) and entropy weight method, respectively, and the combination weights are carried out by using game theory method (GTM) with the Nash equilibrium as the goal. The indices are classified into five grades: excellent (I), good (II), average (III), rather poor (IV), and poor (V), according to the daily tunnel construction. The excavation ergonomics index to be evaluated is calculated using the combined weights, and the comprehensive evaluation index of excavation ergonomics to be evaluated is calculated using the technique for order preference by similarity to an ideal solution (TOPSIS). The proposed rating model was used to analyze the excavation ergonomics of the Shangtianling Tunnel in the Chizhou–Huangshan High-Speed Railway using jumbo drills (JD) and drilling machines (DM) in large- and small-mileage construction, respectively, and to obtain the excavation ergonomics rating and comprehensive evaluation rating of each evaluation object. The research results show that the established excavation ergonomics evaluation model can effectively identify the main factors affecting the excavation ergonomics of the drill and blast method, and has a certain reference value.

Keywords: tunnel; drilling and blasting method; ergonomics evaluation; TOPSIS

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1. Introduction

To meet the demand of route selection, tunneling is one of the important components of railroads. By the end of 2022, the total mileage of railroad operations in China is about 155,000 km, of which the total length of high-speed railway tunnels is about 42,000 km [1]. However, due to the complexity of the geological conditions, high construction risks, and harsh environment of tunnel engineering [2–4], tunnels are often used as the controlling project of high-speed railroad construction. Therefore, improving the tunnel construction environment and the construction ergonomics is significant in improving the construction schedule of tunnel projects [5].

With the improvement of tunnel construction requirements, the problems of tunnel excavation by the traditional manual drilling and blasting method gradually emerge, such as low mechanization, the high work intensity of construction personnel, low construction efficiency, etc., and the fact that this method is prone to environmental pollution and occupational diseases. This is contrary to the people-oriented and green development construction concept [6–8]. How do we improve the mechanization level of tunnel construction, reduce the labor intensity of construction personnel, and the comparison of mechanized construction ergonomics and manual construction ergonomics, which has been the focus of tunneling research [9–12]? Therefore, we need to establish a tunnel drilling and blasting excavation ergonomics evaluation ergonomics, and conduct a quantitative analysis and evaluation.

This paper constructs an evaluation system for the ergonomics of drilling and blasting excavation, calculates the weights of the indicators, and uses the TOPSIS method for evaluation. In the evaluation process, determining the weight of the evaluation indicators is one of the prerequisites for achieving scientific evaluation. In order to achieve a scientific evaluation, each evaluation indicator needs to be assigned an appropriate weight. Commonly used indicator weights are subjective and objective weights. Among them, the subjective weight calculation methods include the analytic hierarchy process (AHP) [13], sequential relationship analysis method (G1 method) [14], G2 method [15], Delphi method [16], etc., and the objective weight calculation methods include the entropy weight method (EWM) [17], criteria importance though intercriteria correlation method (CRITIC) [18], coefficient of variation method [19], etc. The subjective and objective weighting methods have their own advantages and disadvantages, and their effective combination can adjust the value range of the indicator weights to obtain more accurate weights. GTM can combine multiple methods to achieve the overall optimal solution by competing with each other with the goal of the Nash equilibrium. GTM has been widely applied to various fields, such as food safety [20–22], computers [23–27], management [28–30], engineering [31–34], etc.

In summary, scholars have studied the construction of the evaluation index system, the determination of index weights, and comprehensive evaluation methods. However, there are still the following shortcomings: First, the construction of the evaluation system cannot cover the whole process of the tunnel drilling and blasting method of excavation, resulting in low reliability of the evaluation results; second, the calculation of index weighting using a single assignment method causes the evaluation results to have a strong one-sided; and third, the combination of objective weights and subjective weights chosen by the method is more complex, resulting in a larger calculation workload. Therefore, in this paper, firstly, on the basis of field research, reference literature, and consultation with experts, the evaluation system of tunnel drilling and blasting excavation ergonomics is established; secondly, the subjective and objective weights of the evaluation indicators are calculated using the G2 Method and EWM, and the weights of the combination of the evaluation indicators are calculated using GTM; and finally, the TOPSIS method [35] is used to calculate the relative proximity of the excavation ergonomics of the tunnel drilling and blasting method, and the combination weights are used to calculate the grade values, which are graded according to the grade criteria. This provides a new way of thinking about the evaluation of the excavation ergonomics of the tunnel drilling and blasting method.

2. Materials and Methods

This paper establishes a game theory G2-EW-TOPSIS model based on the evaluation process of the excavation ergonomics of the drilling and blasting method, as shown in Figure 1. The steps can be described as follows:

The first step is to determine the evaluation index, build the evaluation index system of the excavation ergonomics of the drilling and blasting method, and record the relevant data in accordance with the index system to obtain the original data of the evaluation index.

The second step is the data standardization process, including data consistency and dimensionless processing.

The third step is the use of G2 method and EWM to calculate the evaluation index system of the subjective weights and objective weights, combined with GTM calculations to obtain a comprehensive weight of the evaluation index system.

The fourth step is the calculation of the drilling and blasting method excavation ergonomics index for the tunnel to be evaluated, and analysis of evaluation results.

The following four aspects will be introduced from the evaluation index system, evaluation model and method, TOPSIS evaluation method, and evaluation criteria.

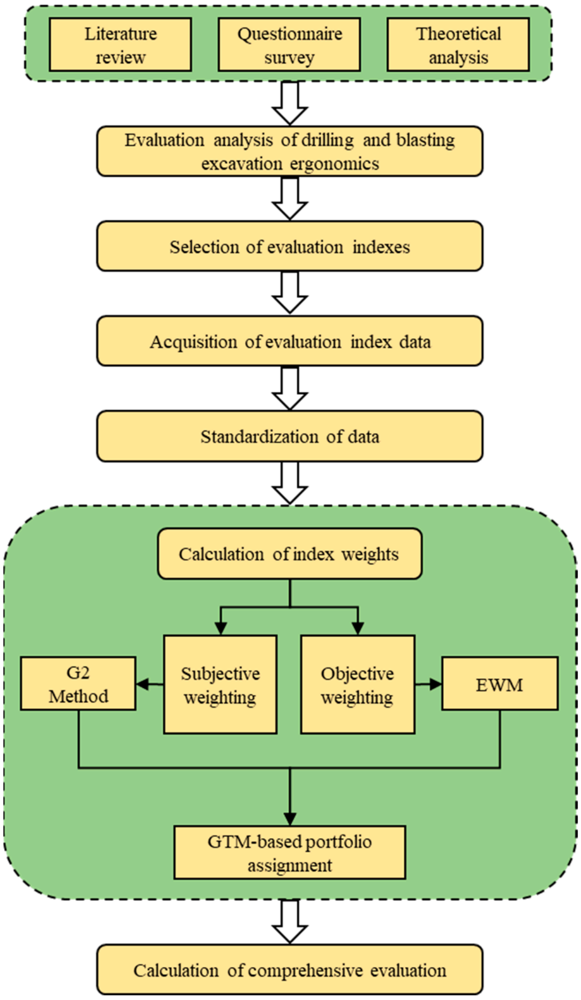

Figure 1. Tunnel drilling and blasting method excavation ergonomics evaluation process.

2.1. Evaluation Index System

There are many factors affecting the excavation ergonomics of tunnel drilling and blasting method, such as drilling efficiency, construction time, and construction quality, and there is a complex non-linear relationship between the factors. Therefore, it is important to choose a reasonable evaluation index system for tunnel drilling and blasting method excavation ergonomics. The establishment of a systematic and complete evaluation index system is the basis for scientific evaluation; in the construction of tunnel drilling and blasting method of excavation ergonomics evaluation index system, this should follow the principles of being scientific, systematic, and comprehensive. In this paper, based on the review of relevant standards, literature, and field research [36–42], a tunnel drilling and blasting method excavation ergonomics evaluation index system containing three primary indicators and 11 secondary indicators was established, as shown in Figure 2.

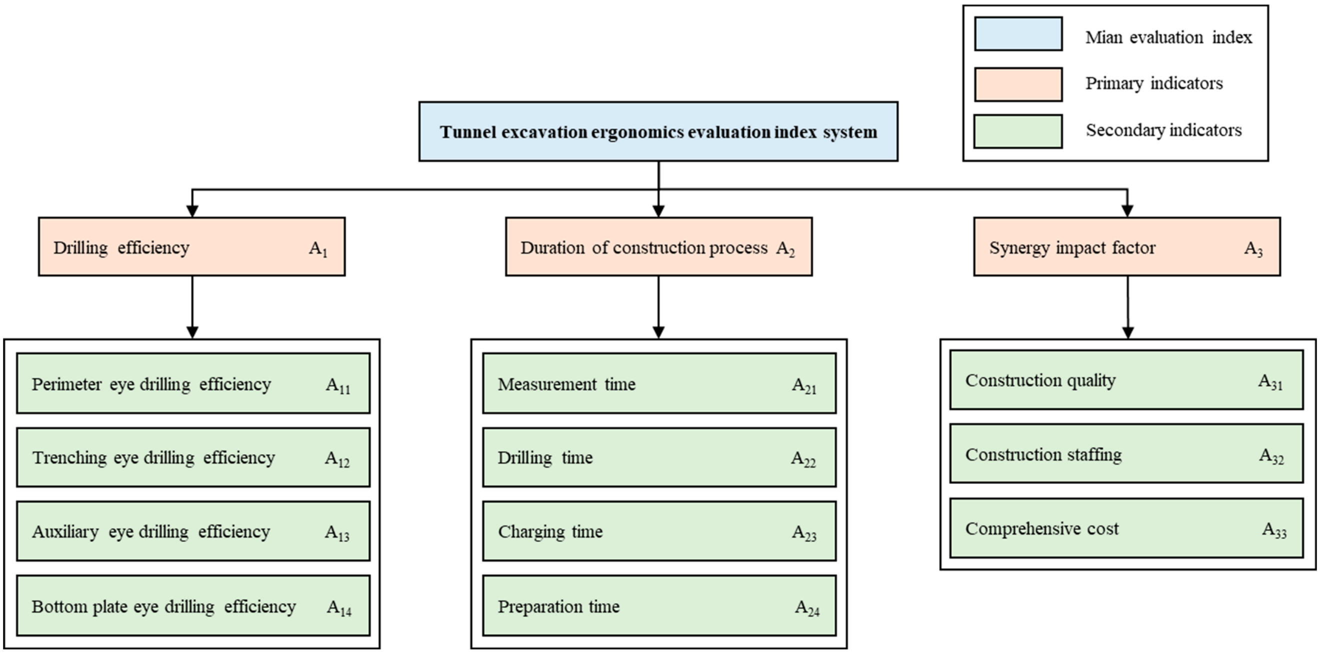

Figure 2. Tunnel drilling and blasting method excavation ergonomics evaluation system.

2.1.1. Drilling Efficiency

The drilling efficiency of tunnel drilling and blasting method is further subdivided into four indicators, including: perimeter eye drilling efficiency A_{11}, trenching eye drilling efficiency A_{12}, auxiliary eye drilling efficiency A_{13}, and bottom plate eye drilling efficiency A_{14}. Drilling efficiency refers to the construction process of a single-hole drilling time. Obviously, the smaller its value, the higher the corresponding drilling efficiency. Let T indicate the drilling time and N indicate the number of holes drilled at that time; then, the drilling efficiency can be expressed as follows:

$$A = \frac{T}{N} \tag{1}$$

2.1.2. Duration of Construction Process

The duration of construction process is further subdivided into four indicators, specifically: measurement time A_{21}, drilling time A_{22}, loading time A_{23}, and preparation time A_{24}. Duration of construction process is the time consumed from the beginning to the end of the tunnel construction using the drilling and blasting method. Obviously, the smaller its value, the higher the construction efficiency. Let T_1 indicate the start moment and T_2 indicate the end moment; then, the duration of construction process can be expressed as follows:

$$A = T_2 - T_1 \tag{2}$$

2.1.3. Synergy Impact Factor

1. Construction quality

The construction quality during the construction of tunnel drilling and blasting method can be considered in terms of the over-under-excavation situation, residual rate of blast holes, and blasting accuracy [43]. In this paper, the over-under-excavation situation is selected to measure the construction quality. Obviously, the smaller the value of over-excavation, the higher the corresponding construction quality.

2. Construction staffing

The construction personnel include the on-site construction personnel and the lead personnel. On-site construction personnel specifically include operators, support workers, handymen, and charging personnel. Obviously, the smaller the value of construction staffing, the more concentrated and reasonable the human resources ratio.

3. Comprehensive cost

Tunnel drilling and blasting method of construction in the process of the composition of the comprehensive cost is more complex; this paper mainly selected seven items with a greater impact, including: mechanical depreciation, labor costs, electricity, water, pyrotechnic supplies, accessories' wear and tear costs, and machinery maintenance costs. Obviously, the smaller the value of comprehensive cost, the better the corresponding construction method. Let M (yuan) and L (m) denote the total cost and total mileage of the drilling and blasting method of construction over a period of time, respectively; the comprehensive cost can be expressed as follows:

$$A_{33} = \frac{M}{L} \tag{3}$$

In summary, around the whole process of tunnel drilling and blasting excavation operations, this paper establishes a drilling and blasting excavation ergonomics evaluation model. From the three aspects of drilling efficiency, the duration of construction process time, and synergistic impact factors, 11 indicators were selected to evaluate the drilling and blasting ergonomics system, including perimeter eye drilling efficiency, trenching eye drilling efficiency, auxiliary eye drilling efficiency, bottom plate eye drilling efficiency, measurement time, drilling time, charging time, preparation time, construction quality, construction staffing, and comprehensive cost.

2.2. Evaluation Models and Methods

The commonly used methods for calculating index weights are subjective assignment and objective assignment. Among them, subjective assignment method relies excessively on experts' experience, while objective assignment method relies heavily on the sample. It can be seen that a single assignment method has strong subjectivity or objectivity, and an effective combination of subjective and objective weights can further improve the accuracy of model weights. Therefore, in this paper, in order to improve the reliability of the evaluation results, GTM is selected to calculate the comprehensive weights of the evaluation indices, and TOPSIS method is used to achieve a comprehensive evaluation of the excavation ergonomics of tunnel drilling and blasting method. The specific steps are shown in Figure 3:

1. Standardization of the original data of evaluation indicators using the extreme difference method;
2. The use of G2 method and EWM to calculate the evaluation indicators, respectively;
3. Calculate the weight of the combination of evaluation indices based on GTM;
4. Construct a weighted judgment matrix and use TOPSIS method to conduct a comprehensive evaluation of the evaluation object.

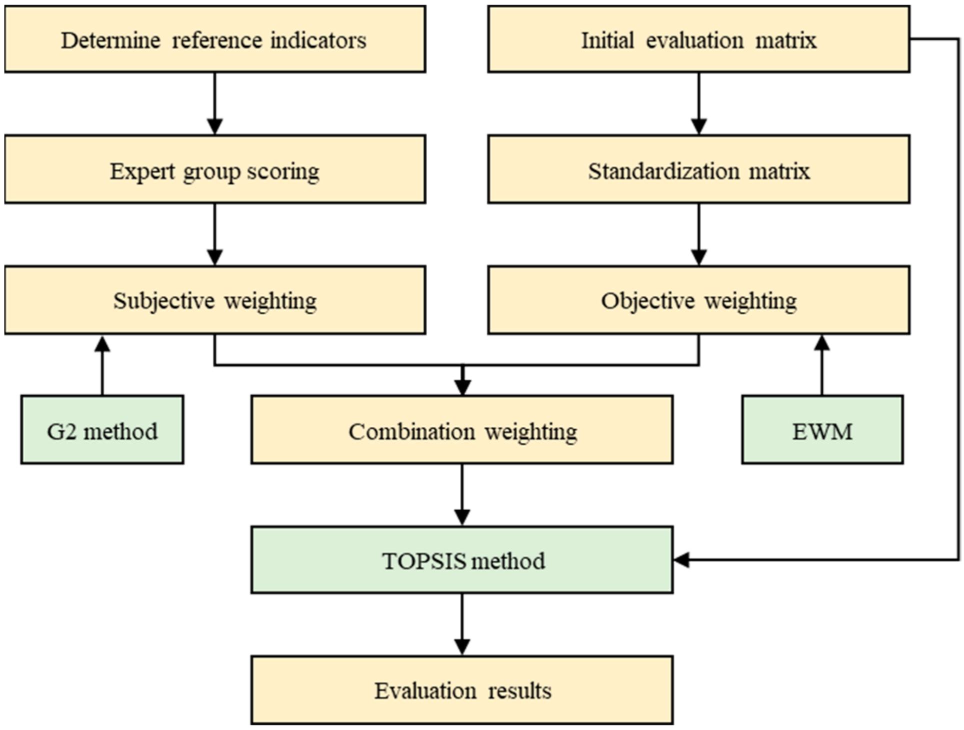

Figure 3. Step-by-step diagram of the tunnel drilling and blasting method excavation ergonomics evaluation model.

2.2.1. Subjective Empowerment Method—G2 Method

The G2 method is a concise and effective subjective assignment method without the need for consistency testing. The G2 method is a more complete weight calculation method based on the G1 method, which can be used for interval assignment instead of point assignment to further improve the accuracy of subjective assignment, and its calculation steps are as follows:

Step 1: Determine reference indicators

Assuming that the set of evaluation indicators $\{x_1, x_2, x_3, \ldots, x_n\}$ are n indicators of the same level in the indicator system and $n \geq 2$, the indicator sequential relationships are determined according to the following steps in conjunction with expert opinions:

1. The expert selects the least important one of the evaluation indicators in the set $\{x_1, x_2, x_3, \ldots, x_n\}$, noted as y_n;
2. The least important indicator y_n is taken as the only reference, and the experts assign an interval of importance ratios to the remaining indicators relative to y_n.

Step 2: Determine the weight interval of the remaining indicators with reference to the indicator y_n

The importance of the evaluation indicators y_m (m= 1, 2, ..., $n-1$) and y_n were quantified according to Table 1 and can be expressed as follows:

$$r_k = \frac{\alpha_m}{\alpha_n} \tag{4}$$

where r_k denotes the relative importance ratio between evaluation indices y_m and y_n; the value range of k is $[1, n-1]$; and α_m and α_n denote the weights of evaluation indices y_m and y_n. A table of r_k assignments based on the 9-level tone operator [44] is established, which is shown in Table 1.

Table 1. r_k assignment reference table.

r_k	r_k Assignment Description
1.0	y_m is as important as y_n
1.2	y_m is slightly more important than y_n
1.4	y_m is significantly more important than y_n
1.6	y_m is strongly more important than y_n
1.8	y_m is extremely more important than y_n
1.1, 1.3, 1.5, 1.7	The median of two adjacent judgments above

Step 3: Calculation of indicator weights

Referring to the weight assignment in Table 1, a range of values is assigned to the weights of the evaluation indicators:

$$r_k \triangleq D_k = [d_{1k}, d_{2k}], (k = 1, 2, \ldots, n-1) \tag{5}$$

where $d_{1k} \leq d_{2k}$.

At this point, the weight of the evaluation index y_m is obtained from the following equations:

$$\alpha_m = \frac{n(D_k) + \varepsilon e(D_k)}{\sum_{i=1}^{n} n(D_i) + \varepsilon e(D_i)}, (i = 1, 2, \ldots, n) \tag{6}$$

$$n(D_k) = \frac{d_{1k} + d_{2k}}{2} \tag{7}$$

$$e(D_k) = d_{2k} - d_{1k} \tag{8}$$

where $n(D_k)$ is the midpoint of the interval; $e(D_k)$ is the length of the interval; and ε is the risk attitude factor. The range of ε values varies according to the type of experts. Conservative experts take $-1/2 \leq \varepsilon < 0$; neutral experts take $\varepsilon = 0$; and risky experts take $0 < \varepsilon \leq 1/2$.

In turn, the subjective weight vector ω of the set of evaluation indicators for the excavation ergonomics of the tunnel drilling and blasting method can be obtained as:

$$\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_n) \tag{9}$$

where α denotes the weight vector corresponding to the original set of evaluation indicators.

2.2.2. Objective Empowerment Method—EWM

Entropy, originally a concept in thermodynamics, was first introduced into information theory by Shannon to measure the uncertainty of a system, and information entropy quantitatively describes how much information a message contains [45]. The EWM starts from the target itself and determines the weight based on the information entropy of the evaluation index. The EWM is an objective evaluation method based on the actual data of the evaluation index, and the calculation steps are as follows:

Step 1: Raw data pre-processing

The initial evaluation matrix is established based on the evaluation indices and the raw data obtained from the evaluation objects, as shown in Equation (10):

$$B = \left(b_{ij}\right)_{m \times n} = \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{bmatrix} \tag{10}$$

where B denotes the initial evaluation matrix; b_{ij} denotes the raw data of the jth indicator of the ith evaluation object, whose value is obtained from the excavation statistics of the tunnel over a period of time; m denotes the number of evaluation objects; and n denotes the number of evaluation indicators.

For positive indicators, the normalization is given by:

$$c_{ij} = \frac{b_{ij} - \min\limits_{1 \le i \le m}\{b_{ij}\}}{\max\limits_{1 \le i \le m}\{b_{ij}\} - \min\limits_{1 \le i \le m}\{b_{ij}\}} \quad (11)$$

For negative indicators, their normalization is given by:

$$c_{ij} = \frac{\max\limits_{1 \le i \le m}\{b_{ij}\} - b_{ij}}{\max\limits_{1 \le i \le m}\{b_{ij}\} - \min\limits_{1 \le i \le m}\{b_{ij}\}} \quad (12)$$

where c_{ij} represents the standardized evaluation index data, which, in turn, leads to the tunnel excavation ergonomics standardization matrix as:

$$C = (c_{ij})_{m \times n} = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{m1} & \cdots & c_{mn} \end{bmatrix} \quad (13)$$

where C denotes the standardized matrix of excavation ergonomics of the tunnel drilling and blasting method.

The normalization of the elements of the normalized matrix is performed, and the calculation procedure is shown in Equation (14):

$$p_{ij} = \frac{c_{ij}}{\sum_{i=1}^{m} c_{ij}} \quad (14)$$

where p_{ij} denotes the normalized value of the jth indicator of the ith rated object.

Step 2: Calculate the information entropy of evaluation indices:

$$e_j = -\frac{1}{ln(m)} \sum_{i=1}^{m} p_{ij} ln(p_{ij}) \quad (15)$$

where e_j denotes the information entropy of the jth evaluation index.

Step 3: Calculate the entropy weight of evaluation index

$$\beta_j = \frac{1 - e_j}{n - \sum_{i=1}^{n} e_j} \quad (16)$$

where β_j denotes the jth evaluation index entropy weight, which in turn can be obtained from the objective weight vector β of the tunnel drilling and blasting method excavation ergonomics evaluation index set as:

$$\beta = (\beta_1, \beta_2, \ldots, \beta_n) \quad (17)$$

where $0 \le \beta_j \le 1$ and $\beta_1 + \beta_2 + \ldots + \beta_n = 1$.

2.2.3. Portfolio Empowerment Method—GTM

In the evaluation of multiple indicator items, evaluation weights play a decisive role. In the same evaluation, if different weight values are used, it may cause great differences. Therefore, how to correctly determine the weights in the evaluation is a key factor in improving the evaluation. In practice, the role of evaluation factors is objective, and many indicators are now also determined by subjective will. Therefore, the weights of subjective and objective factors must be considered comprehensively so that their importance can be fully reflected [46–48].

The GTM is used to study the role of subjective and objective allocation methods in reconciling conflicts, taking into account subjective and objective weights and enhancing the science of allocation. The specific implementation of the index is as follows: the G2 method and the EWM are used to assign subjective and objective weights to the indicators. Nash equilibrium is used as the synergistic goal to derive a combined weight that reflects the will of the decision maker and the attributes of the indicator [49].

The steps of the GTM-based portfolio assignment are as follows:

Step 1: Construct the set of weights

The weight values calculated by the above G2 method and EWM are used to construct a new weight set $u = \{\alpha, \beta\}$, and the linear combination of these two weight sets at each level is a possible set of weights, which is calculated as follows:

$$u_j = \sum_{i=1}^{2} a_i u_{ij}^T \tag{18}$$

where u_j denotes the set of combined weights of the jth indicators based on GTM, a_i denotes the weight coefficients of GTM, and u_{ij} denotes the set of weights of the jth indicators of the ith method.

Step 2: Construct the optimal response model

The response model is:

$$Min\left\|\sum_{k=1}^{2} a_k u_{kj}^T - u_{i1}^T\right\|_2, (i = 1, 2) \tag{19}$$

From matrix differentiability, the first-order optimal inverse of Equation (19) is:

$$\sum_{k=1}^{2} a_k u_{ij} u_{ij}^T = u_{ij} u_{ij}^T, (i = 1, 2) \tag{20}$$

This leads to the system of linear equations corresponding to Equation (20):

$$\begin{bmatrix} u_{1j}u_{1j}^T & u_{1j}u_{2j}^T \\ u_{2j}u_{1j}^T & u_{2j}u_{2j}^T \end{bmatrix} \begin{bmatrix} a_{1j} \\ a_{2j} \end{bmatrix} = \begin{bmatrix} u_{1j}u_{1j}^T \\ u_{2j}u_{2j}^T \end{bmatrix} \tag{21}$$

Step 3: Solve the percentage of combined weights of G2 method and EWM

Using MATLAB software, the above corresponding system of linear equations is solved and normalized to the following equation:

$$\mu_{ij} = \frac{a_{ij}}{\sum_{i=1}^{2} a_{ij}} \tag{22}$$

where μ_{ij} denotes the normalized value of the weight share of the indicator of jth of the ith method.

Step 4: Solve for the weights of the optimal combination based on GTM

The final game combination weights of each indicator are obtained and calculated by the equation:

$$u_j = \sum_{i=1}^{2} \mu_{ij} u_{ij}^T \tag{23}$$

2.3. TOPSIS Evaluation Methodology

The TOPSIS method is a comprehensive rating method based on raw data and is suitable for the comparative analysis of multiple evaluation objects. The basic idea of the method is to calculate the distance between the evaluation results of multiple objects to be evaluated and the idealized target. Then, the ranking is performed according to the distance. This method can be used for both rating evaluation and program preference and effect evaluation [50–53]. The algorithm steps are as follows:

Step 1: Original matrix orthogonalization

The initial evaluation matrix is established based on the evaluation indices and the raw data obtained from the evaluation objects, as shown in Equation (24):

$$X = (x_{ij})_{m\times n} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{24}$$

where X denotes the initial evaluation matrix, x_{ij} denotes the original data of the jth index of the ith evaluation object, m denotes the number of evaluation objects, and n denotes the number of evaluation indices.

The so-called normalization of the original matrix is the unified conversion of all indicator types into extremely large indicators, and the four most common types of indicators are shown in Table 2.

Table 2. Types and characteristics of indicators.

Indicator Name	Indicator Characteristics
Extremely large (efficiency-based) indicators	The bigger (more), the better
Extremely small (cost-type) indicators	The smaller (less), the better
Intermediate indicators	The closer to a certain value, the better
Interval-type indicators	It is best to fall in a certain range

1. Conversion of very small indicators to very large indicators, which is expressed as:

$$x'_{ij} = \max_{1\le i\le m}\left\{x_{ij}\right\} - x_{ij} \tag{25}$$

If all elements are positive, the following formula can also be used for calculation:

$$x'_{ij} = \frac{1}{x_{ij}} \tag{26}$$

where x'_{ij} denotes the value of the indicator after forwarding.

2. Conversion of intermediate indicators to very large indicators, which is expressed as:

$$\begin{cases} M = \max_{1\le i\le m}\left\{\left|x_{ij} - x_{best}\right|\right\} \\ x'_{ij} = 1 - \frac{\left|x_{ij} - x_{best}\right|}{M} \end{cases} \tag{27}$$

where x_{best} represents the best value within the metric.

3. Conversion of interval-type indicators to very large indicators, which is expressed as:

$$\begin{cases} M = \max_{1\le i\le m}\left\{a - \min_{1\le i\le m}\left\{x_{ij}\right\}, \max_{1\le i\le m}\left\{x_{ij}\right\} - b\right\} \\ x'_{ij} = \begin{cases} 1 - \frac{a - x_{ij}}{M}, x < a \\ 1, a \le x \le b \\ 1 - \frac{x_{ij} - b}{M}, x > b \end{cases} \end{cases} \tag{28}$$

where a denotes the upper limit of the optimal interval, and b denotes the lower limit of the optimal interval.

Step 2: Normalization of the forwarding matrix

To remove the effect of the magnitude, the matrix that completes the normalization is normalized as shown in Equation (29) and the matrix Y is obtained.

$$y_{ij} = \frac{x'_{ij}}{\sqrt{\sum_{i=1}^{m} {x'_{ij}}^2}} \tag{29}$$

$$Y = (y_{ij})_{m\times n} = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{30}$$

Step 3: Construct a weighted judgment matrix

$$S = YU = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \begin{bmatrix} u_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & u_n \end{bmatrix} = \begin{bmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{m1} & \cdots & s_{mn} \end{bmatrix} \tag{31}$$

where S denotes the weighted judgment matrix, U denotes the evaluation index weight matrix, u_j denotes the combination weight of index, and s_{ij} denotes the jth-index weighted value of the ith evaluation object.

Step 4: Determine the "positive ideal solution S^+" and "negative ideal solution S^-"

$$\begin{cases} S^+ = \max\limits_{1\le i\le m} s_{ij} = \left(s_1^+, s_2^+, \ldots, s_n^+\right) \\ S^- = \min\limits_{1\le i\le m} s_{ij} = \left(s_1^-, s_2^-, \ldots, s_n^-\right) \end{cases} \tag{32}$$

where j = 1, 2, ... , n, S^+ denotes "positive ideal solution", S^- denotes "negative ideal solution", and s_j^+ and s_j^- denote the "positive ideal solution" and "negative ideal solution" of the jth evaluation index, respectively".

Euclidean spatial distance of the ith evaluation object from the "positive ideal solution S^+":

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(s_j^+ - s_{ij}\right)^2}, (i = 1, 2, \ldots, m) \tag{33}$$

Euclidean spatial distance of the ith evaluation object from the "negative ideal solution S^-":

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(s_j^- - s_{ij}\right)^2}, (i = 1, 2, \ldots, m) \tag{34}$$

where D_i^+ and D_i^- denote the Euclidean spatial distances of the ith object to be evaluated from the "positive ideal solution S^+" and the "negative ideal solution S^-", respectively.

Step 4: Calculate the relative proximity

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{35}$$

where C_i denotes the relative proximity of the ith object to be evaluated. Obviously, $0 \le C_i \le 1$, the larger the C_i, and the better the object is evaluated.

3. Case Study

3.1. Project Overview

The new Chihuang High-speed Railway Shangtianling Tunnel starts from the west side of Yixin Village, Yixian County, Anhui province, China, County Road X030 to the south through the Tachuan National Geological Forest Park to Xidi Town, Tamkou Village, Yuanyang Valley scenic spot. The tunnel import mileage is DK102+727.765, the export mileage is DK113+573.89, with the total length of 10,846.125 m, Pingkou cross-hole length of 945 m, large machine work area length of 3320 m, cross-hole 3 work area 1370 m, and Class III Enclosure, using the full section method of construction.

In this tunnel construction, it was divided into large–mileage and small–mileage at the same time, and the construction was carried out by alternating the use of JD drilling and DM drilling. In large–mileage construction, the JD was used for drilling from DK110+952 to DK111+487, while manual drilling was used from DK111+491 to DK112+023. In small–mileage construction, DM drilling was used from DK109+742 to DK110+452, and drilling was carried out with the JD from DK108+310.5 to DK109+738.

3.2. Data Statistic

This paper relies on the construction project of the drilling and blasting method in Shangtianling Tunnel. Field research is carried out to obtain actual construction data according to the index system established in this paper.

1. Drilling efficiency includes: perimeter eye drilling efficiency, trenching eye drilling efficiency, auxiliary eye drilling efficiency, and bottom plate eye drilling efficiency. The drilling efficiency of drilling and blasting excavation construction by JD and drilling and blasting excavation construction by DM drill is shown in Table 3.

Table 3. Drilling efficiency statistics.

Construction Objects	Construction Method	Average Single−Hole Drilling Time (min)			
		Perimeter Eye	Trenching Eye	Auxiliary Eye	Bottom Plate Eye
Large mileage	JD excavation	2.7	3.0	2.7	2.7
	DM excavation	15	15	17	15
Small mileage	JD excavation	2.7	3.0	2.7	2.7
	DM excavation	15	15	17	15

2. The total time of excavation by the drilling and blasting method in Shangtianling Tunnel includes: measurement time, preparation time, drilling time, and charging time. The statistics of the construction cycle time for large mileage are shown in Figure 4a,b, and the statistics of the construction cycle time for small mileage are shown in Figure 4c,d.

Among them, each of measurement time, drilling time, charging time, and preparation time were counted. In the construction of the large–mileage JD drilling and blasting method, mileage DK111+042~DK111+487 was selected from 28 September 2021 to 13 January 2022, and the statistics of 110 sets of data are shown in Figure 5. In the construction of the large–mileage DM drilling and blasting method, mileage DK111+632~DK112+023 was selected from 26 April 2022 to 14 August 2022, and the statistics of 110 sets of data are shown in Figure 6. In the construction of the small–mileage JD drilling and blasting method, mileage DK109+285~DK109+734 was selected from 16 January 2022 to 29 April 2022, and the statistics of 110 sets of data are shown in Figure 7. In the small–mileage DM drilling and blasting method construction, we selected the DK109+742~DK110+169 mileage, from 2 October 2021 to 11 January 2022, and the statistics of 110 sets of data are shown in Figure 8.

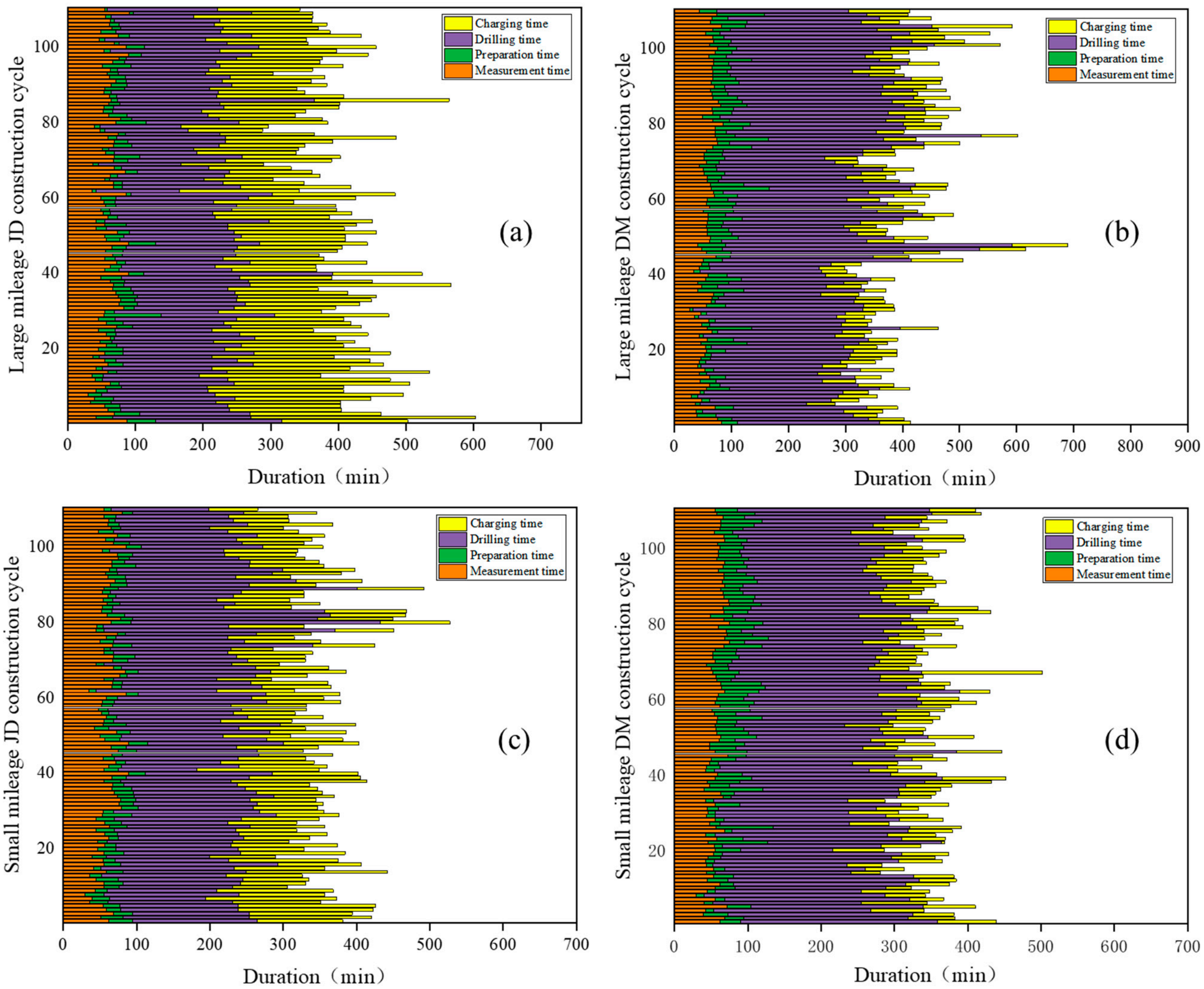

Figure 4. Drilling and blasting method excavation cycle statistics time: (**a**) the statistics of the large–mileage JD construction cycle time; (**b**) the statistics of the large–mileage DM construction cycle time; (**c**) the statistics of the small–mileage JD construction cycle time; and (**d**) the statistics of the small–mileage DM construction cycle time.

In summary, the average time for each phase of the drilling and blasting excavation is shown in Table 4.

Table 4. Average time spent in each phase of tunnel construction by drilling and blasting method.

Construction Objects	Construction Method	Average Duration (min)			
		Measurement Time	Measurement Time	Measurement Time	Measurement Time
Large mileage	JD excavation	59.2	160.7	165.2	18.6
	DM excavation	58.1	258.3	62.9	32.3
Small mileage	JD excavation	60.1	173.1	103	17.2
	DM excavation	57.2	211.0	60	30.3

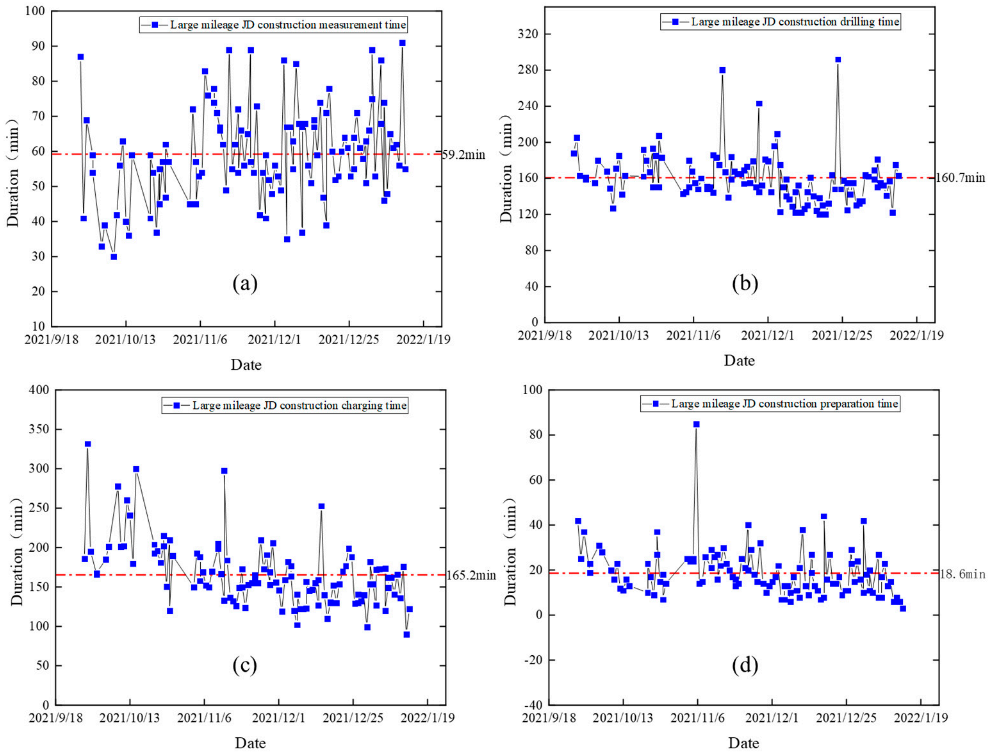

Figure 5. Duration statistics of excavation by JD at large mileage: (**a**) the measurement time of large–mileage JD construction; (**b**) the drilling time of large–mileage JD construction; (**c**) the charging time of large–mileage JD construction; and (**d**) the preparation time of large–mileage JD construction.

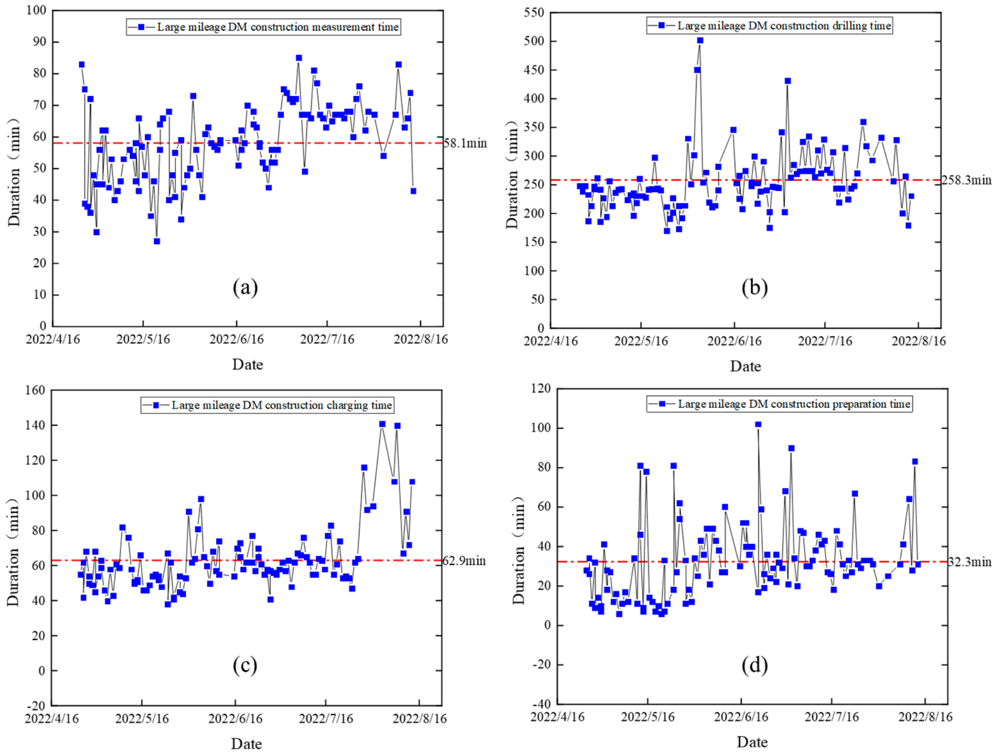

Figure 6. Duration statistics of excavation by DM at large mileage: (**a**) the measurement time of large–mileage DM construction; (**b**) the drilling time of large–mileage DM construction; (**c**) the charging time of large–mileage DM construction; and (**d**) the preparation time of large–mileage DM construction.

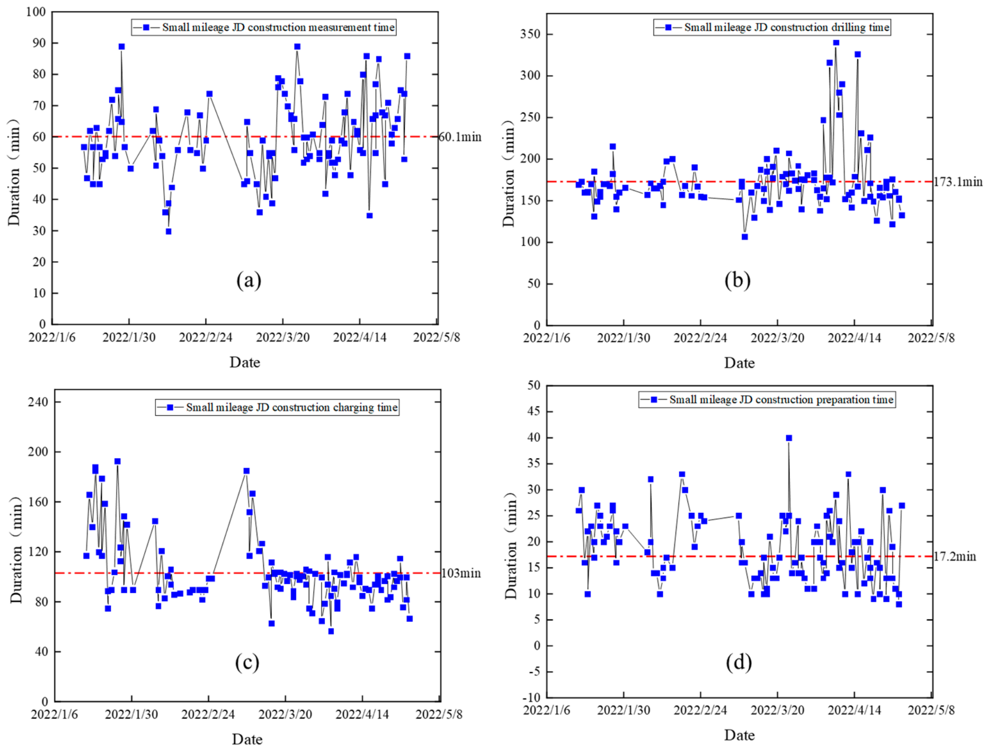

Figure 7. Duration statistics of excavation by JD at large mileage: (**a**) the measurement time of small–mileage JD construction; (**b**) the drilling time of small–mileage JD construction; (**c**) the charging time of small–mileage JD construction; and (**d**) the preparation time of small–mileage JD construction.

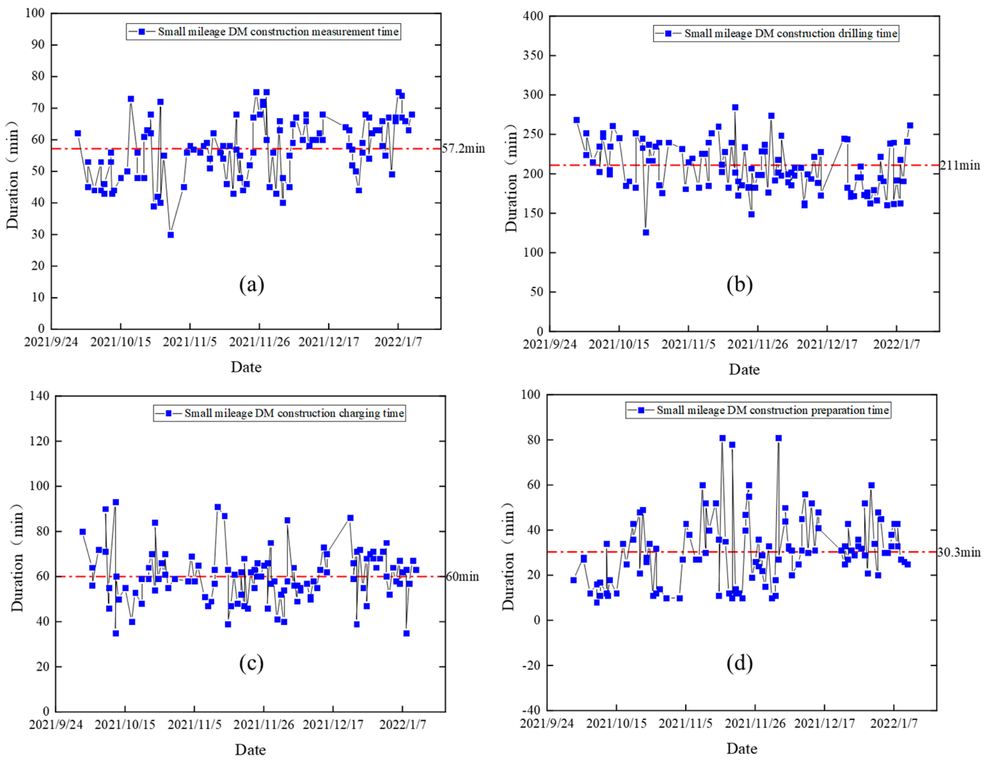

Figure 8. Duration statistics of excavation by DM at small mileage: (**a**) the measurement time of small–mileage DM construction; (**b**) the drilling time of small–mileage DM construction; (**c**) the charging time of small–mileage DM construction; and (**d**) the preparation time of small–mileage DM construction.

3. Synergistic impact factors include: construction quality, construction staffing, and comprehensive cost. The construction quality of tunnel drilling and blasting excavation is measured by the over-under excavation; the construction quality of JD excavation versus DM excavation is shown in Table 5. In the actual construction process, there will be a small transfer of personnel. Therefore, we take the average value of each construction section; the comparison of the construction staffing between JD excavation and DM excavation is shown in Table 6. The comparison of the comprehensive cost between JD excavation and DM excavation is shown in Table 7.

Table 5. Comparison of over-excavation between JD excavation and DM excavation.

Construction Objects	Excavation Method	Average Linear Over-Excavation (cm)
Large mileage	JD excavation	5
	DM excavation	8
Small mileage	JD excavation	5
	DM excavation	8

Table 6. Comparison of JD excavation and DM excavation personnel.

Construction Objects	Construction Method	Site Construction Personnel (People)				Lead Staff (Person)	Total (People)
		Operators	Auxiliary Workers	Handyman	Chargers		
Large mileage	JD excavation	6	1	2	12	0	21
	DM excavation	25	1	0	23	1	50
Small mileage	JD excavation	6	1	2	14	0	23
	DM excavation	22	1	0	21	1	45

Table 7. Combined cost analysis of JD excavation and DM excavation (Yuan/m).

Projects	Large Mileage		Small Mileage	
	JD Excavation	DM Excavation	JD Excavation	DM Excavation
Machinery depreciation	635.6	415.7	635.6	415.7
Labor cost	2274.1	4603.6	2591.7	4043.2
Electricity	612.7	1184.9	612.7	1000.9
Water bill	212.9	27.8	212.9	27.8
Firework supplies	2914.3	2612.2	3315.7	2709.7
Parts wear and tear charges	991.4	137.1	991.4	137.1
Machinery maintenance fee	106.4	74.8	106.4	74.8
Total	7747.4	9056.1	8466.4	8409.2

4. In summary, the drilling efficiency, construction process duration, and synergistic impact factors were obtained for each piece of data of the construction with JD and DM during the construction of large and small mileage. The nature of the raw data and evaluation index of the construction ergonomics index are shown in Table 8.

Table 8. Table of raw data and nature of evaluation indicators.

Indicators	Large Mileage		Small Mileage	
	JD Excavation	DM Excavation	JD Excavation	DM Excavation
A_{11}	2.7	15	2.7	15
A_{12}	3	15	3	15
A_{13}	2.7	17	2.7	17
A_{14}	2.7	15	2.7	15

Table 8. *Cont.*

Indicators	Large Mileage		Small Mileage	
	JD Excavation	DM Excavation	JD Excavation	DM Excavation
A_{21}	59.2	58.1	60.1	57.2
A_{22}	160.7	258.3	173.1	211
A_{23}	165.2	62.9	103	60
A_{24}	18.6	32.3	17.2	30.3
A_{31}	5	8	5	8
A_{32}	21	50	23	50
A_{33}	7445.3	9358.2	8466.4	8409.2

3.3. Evaluation Criteria

In order to make the evaluation results more intuitive and effective, this paper establishes a set of evaluation criteria for the excavation ergonomics of the drilling and blasting method. The indicators are subdivided into five levels according to the daily construction of the tunnel, which are excellent (I), good (II), average (III), rather poor (IV), and poor (V). For the quantifiable evaluation indicators, expert consultation and field research are used to determine the evaluation level, as shown in Table 9.

Table 9. Tunnel drilling and blasting method construction ergonomics evaluation index criteria.

Indicator Level	Excellent (I)	Good (II)	Average (III)	Rather Poor (IV)	Poor (V)
Perimeter eye drilling efficiency	$A_{11} < 4$	$4 \le A_{11} < 8$	$8 \le A_{11} < 12$	$12 \le A_{11} < 16$	$16 \le A_{11}$
Trenching eye drilling efficiency	$A_{12} < 4$	$4 \le A_{12} < 8$	$8 \le A_{12} < 12$	$12 \le A_{12} < 16$	$16 \le A_{12}$
Auxiliary eye drilling efficiency	$A_{13} < 4$	$4 \le A_{13} < 8$	$8 \le A_{13} < 12$	$12 \le A_{13} < 16$	$16 \le A_{13}$
Bottom plate eye drilling efficiency	$A_{14} < 4$	$4 \le A_{14} < 8$	$8 \le A_{14} < 12$	$12 \le A_{14} < 16$	$16 \le A_{14}$
Measurement time	$A_{21} < 55$	$55 \le A_{21} < 57$	$57 \le A_{21} < 59$	$59 \le A_{21} < 61$	$61 \le A_{21}$
Drilling time	$A_{22} < 165$	$165 \le A_{22} < 190$	$190 \le A_{22} < 215$	$215 \le A_{22} < 240$	$240 \le A_{22}$
Charging time	$A_{23} < 70$	$70 \le A_{23} < 95$	$95 \le A_{23} < 120$	$120 \le A_{23} < 145$	$145 \le A_{23}$
Preparation time	$A_{24} < 15$	$15 \le A_{24} < 20$	$20 \le A_{24} < 25$	$25 \le A_{24} < 30$	$30 \le A_{24}$
Construction quality	$A_{31} < 3$	$3 \le A_{31} < 6$	$6 \le A_{31} < 9$	$9 \le A_{31} < 12$	$12 \le A_{31}$
Construction staffing	$A_{32} < 30$	$30 \le A_{32} < 35$	$35 \le A_{32} < 40$	$40 \le A_{32} < 45$	$45 \le A_{31}$
Comprehensive cost	$A_{33} < 7500$	$7500 \le A_{33} < 8000$	$8000 \le A_{33} < 8500$	$8500 \le A_{33} < 9000$	$9000 \le A_{33}$

4. Results and Analysis

4.1. Calculation of Indicator Weights

According to the Equations (4)–(9) to calculate the evaluation index subjective weights (ε = 0) (See Tables A1–A4 for evaluation data); the Equations (10)–(17) to calculate the evaluation index objective weights (See Tables A5–A8 for evaluation data); and the Equations (19)–(23) to calculate the combined weight coefficients μ_1 and μ_2, we can obtain μ_1 = 0.3139 and μ_2 = 0.6861, and, furthermore, we can calculate the evaluation index combination weights. The subjective weights, objective weights, and combination weights of the evaluation indices are given in Figure 9, respectively.

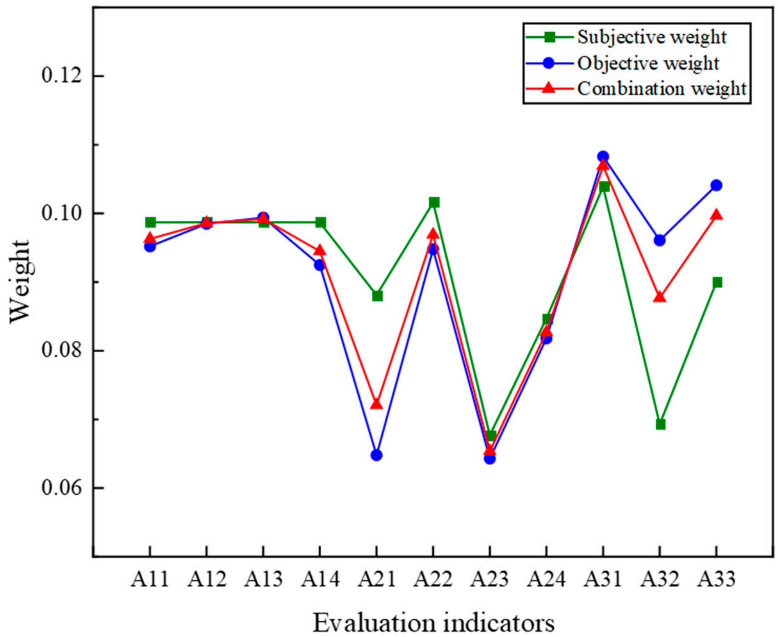

Figure 9. Comparison of evaluation index weights.

4.2. Tunnel Drilling and Blasting Method of Excavation Ergonomics and Evaluation Level Criteria Calculation

According to Table 9 in the tunnel drilling and blasting method of the excavation ergonomics evaluation index sub-polar values and the combination of weights in Figure 9 to build a weighted judgment matrix. We can obtain the grade criteria for the tunnel drilling and blasting method of excavation ergonomics. As the selected evaluation indicators are very small indicators, so the smaller the grade value (A), the higher the level of the tunnel drilling and blasting method of excavation ergonomics. In addition, according to Equations (24)–(35), we calculate the sub-polar value to the "positive ideal solution" and "negative ideal solution" of the Euclidean spatial distance and relative proximity; the closer the relative proximity to 1, the closer it is to the optimal evaluation level. In summary, the grade intervals are shown in Table 10.

Table 10. Indicator ergonomics and evaluation level standard table.

Grade	Grade Interval	
	Ergonomics Grade	**Evaluation Grade**
I	$A < 778.03$	$0.74 \leq C_i \leq 1$
II	$778.03 \leq A < 834.81$	$0.47 \leq C_i < 0.74$
III	$834.81 \leq A < 891.59$	$0.33 \leq C_i < 0.47$
IV	$891.59 \leq A < 948.37$	$0.25 \leq C_i < 0.33$
V	$948.37 \leq A$	$0.17 \leq C_i < 0.25$

4.3. Comprehensive Evaluation of Tunnel Drilling and Blasting Method Excavation Ergonomics

According to Table 9 and Figure 9, the grade values for the tunnel drilling and blasting method of excavation ergonomics are derived. As the indicators selected for evaluation are all extremely small, the smaller the grade (A), the higher the level of the tunnel excavation ergonomics. According to Equations (24)–(35), the Euclidean spatial distance and relative proximity of the "positive ideal solution" and the "negative ideal solution" are calculated. The closer the relative proximity is to 1, the closer it is to the optimal evaluation level. The results of the calculations are shown in Table 11.

Table 11. Drilling and blasting method of excavation ergonomics relative proximity calculation results.

Construction Objects	Construction Method	D_i^+	D_i^-	C_i	A	Evaluation Level	Excavation Ergonomics Grade
Large mileage	JD excavation	0.23	0.67	0.75	777.93	I	I
	DM excavation	0.68	0.22	0.24	980.28	V	V
Small mileage	JD excavation	0.27	0.63	0.70	877.00	II	III
	DM excavation	0.60	0.32	0.35	880.66	III	III

5. Discussion

Existing researchers [54–57] have explored the evaluation of tunnel mechanized excavation ergonomics using engineering practice and theoretical research methods, respectively. However, from an overall perspective, on the one hand, the construction of the tunnel drilling and blasting method in the mechanical excavation and manual excavation ergonomics comparison of the information construction level varies, and is in urgent need of a set of scientific and comprehensive standard system to guide it. On the other hand, due to the lack of a set of quantifiable tunnel drilling and blasting method excavation ergonomics evaluation index system and method, it is difficult to accurately assess the ergonomics of tunnel drilling and blasting method excavation, and cannot provide an effective assessment basis for its continuous improvement. This paper presents a set of evaluation methods for the ergonomics of tunnel drilling and blasting method excavation based on the game theory G2-EW-TOPSIS model. It can provide an important reference value for mechanized tunnel construction.

This paper uses the combined assignment method in GTM to calculate the index weights to eliminate the limitations of objective evaluation, and uses the relative posting progress in the TOPSIS method to calculate the drilling and blasting method excavation level. Ju, W. et al. used the same method for fire safety in metro stations, and established a combined assignment model based on the game theory and TOPSIS method for fire prevention and the implementation of feasible measures in advance [58]. It is shown that GTM can correct the resulting weights to further approach the real results. At the same time, the introduction of the TOPSIS method enables the evaluation results to be more clearly expressed. Although the evaluation model was established by the optimal combination of assigned weights, the model still has certain limitations. In addition to the above-mentioned indicators, there are also reference indicators such as vibration, safety, environmental issues, and contour profile quality during the construction of the tunnel drilling and blasting method [59,60]. In the next research, it is necessary to further refine and study them in depth.

6. Conclusions

In this paper, based on the actual construction process of the tunnel drilling and blasting method, the excavation ergonomics evaluation index system of the tunnel drilling and blasting method is built, a comprehensive evaluation model of the game theory G2-EW-TOPSIS is established, and two types of construction methods of two construction objects are selected for the calculation of the case analysis, and the following conclusions are obtained:

1. Game-theory-combined weighting overcomes the limitations of the subjective and objective evaluation methods. In Figure 9, we can see clearly that the curve of the game theory combination weighting method is in the middle of the other two curves. Whenever the G2 method or EWM has a minimum or maximum weight, the game theory combination weighting will correct it. The curve after linear weighting is closer to the real result, which effectively solves the limitations of the G2 method and EWM. Meanwhile, the concept of the relative closeness degree in thet TOPSIS method

is introduced to represent the evaluation level, so that the evaluation level can be quantified and expressed more clearly.

2. Regarding the weighting proportion of the evaluation index system, the top five factors were construction quality A31, comprehensive cost A33, auxiliary eye drilling efficiency A13, trenching eye drilling efficiency A12, and drilling time A22. Among them, the construction quality remains a concern throughout the entire project life cycle. During the actual construction of the tunnel, the construction quality affects the construction progress, and if the construction quality is too low, it is necessary to reconstruct or take remedial measures, which is not only time-consuming and laborious, but also causes a waste of resources. Therefore, construction quality is one of the core indicators of concern in the tunnel construction process, which is in line with the actual needs of current tunnel construction and further illustrates the effectiveness of the combined weighting model proposed in this paper.
3. According to Table 11, in both large- and small-mileage construction, the JD excavation is rated no less than the DM excavation in terms of evaluation level and the excavation ergonomics grade. In the large–mileage construction, the evaluation level and ergonomics grade of the JD excavation are higher than those of the DM excavation. Among them, the evaluation level of the JD excavation is Grade I, that is, excellent. The evaluation level of the DM excavation is Grade V, that is, poor. In addition, the excavation ergonomics level of the JD excavation is Grade I, that is, excellent. The excavation ergonomics grade of the DM excavation is Grade V, that is, poor. In the small-mileage construction, the evaluation level and ergonomics grade of the JD excavation are higher than those of the DM excavation. Among them, the evaluation level of the JD excavation is Grade II, that is, good. The evaluation level of the DM excavation is Grade III, that is, average. In addition, the excavation ergonomics grade of the JD excavation is Grade III, that is, average. The excavation ergonomics grade of the DM excavation is Grade III, that is, average.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Evaluation data of the first-level indicators of G2 method.

Evaluation Indicators	Drilling Efficiency A_1	Duration of Construction Process A_2	Synergy Impact Factor A_3
Upper limit	1.4	1.2	1
Lower limit	1.6	1.4	1
Median of the interval	1.5	1.3	1
Length of interval	0.2	0.2	0

Table A2. Evaluation data of drilling efficiency indicators by G2 method.

Evaluation Indicators	Perimeter Eye Drilling Efficiency A_{11}	Trenching Eye Drilling Efficiency A_{12}	Auxiliary Eye Drilling Efficiency A_{13}	Bottom Plate Eye Drilling Efficiency A_{14}
Upper limit	1	1	1	1
Lower limit	1	1	1	1
Median of the interval	1	1	1	1
Length of interval	0	0	0	0

Table A3. Evaluation data of duration of construction process indicators by G2 method.

Evaluation Indicators	Measurement Time A_{21}	Drilling Time A_{22}	Charging Time A_{23}	Preparation Time A_{24}
Upper limit	1.2	1.4	1	1.1
Lower limit	1.4	1.6	1	1.4
Median of the interval	1.3	1.5	1	1.25
Length of interval	0.2	0.2	0	0.3

Table A4. Evaluation data of synergy impact factor indicators by G2 method.

Evaluation Indicators	Construction Quality A_{31}	Construction Staffing A_{32}	Comprehensive Cost A_{33}
Upper limit	1.4	1	1.2
Lower limit	1.6	1	1.4
Median of the interval	1.5	1	1.3
Length of interval	0.2	0	0.2

Table A5. Evaluation data of the first-level indicators of the EWM.

Evaluation Indicators	Drilling Efficiency A_1	Duration of Construction Process A_2	Synergy Impact Factor A_3
Expert 1	89	85	81
Expert 2	85	86	82
Expert 3	84	80	82
Expert 4	90	88	85
Expert 5	87	86	83
Expert 6	85	87	84
Expert 7	79	81	80
Expert 8	85	83	83
Expert 9	88	86	87
Expert 10	81	75	76

Table A6. Evaluation data of drilling efficiency indicators of the EWM.

Evaluation Indicators	Perimeter Eye Drilling Efficiency A_{11}	Trenching Eye Drilling Efficiency A_{12}	Auxiliary Eye Drilling Efficiency A_{13}	Bottom Plate Eye Drilling Efficiency A_{14}
Expert 1	82	85	81	79
Expert 2	85	86	82	78
Expert 3	84	80	82	78
Expert 4	85	88	85	81
Expert 5	87	86	83	81
Expert 6	85	87	84	80
Expert 7	79	81	80	76
Expert 8	85	83	83	80
Expert 9	83	86	87	82
Expert 10	75	75	76	72

Table A7. Evaluation data of duration of construction process indicators of the EWM.

Evaluation Indicators	Measurement Time A_{21}	Drilling Time A_{22}	Loading Time A_{23}	Preparation Time A_{24}
Expert 1	85	84	81	89
Expert 2	82	83	80	85
Expert 3	85	86	78	84
Expert 4	87	88	84	92
Expert 5	86	83	78	87
Expert 6	84	86	80	85
Expert 7	75	81	72	83
Expert 8	81	86	80	85
Expert 9	92	89	81	88
Expert 10	79	82	74	81

Table A8. Evaluation data of synergy impact factor indicators of the EWM.

Evaluation Indicators	Construction Quality A_{31}	Construction Staffing A_{32}	Comprehensive Cost A_{33}
Expert 1	80	81	85
Expert 2	85	80	82
Expert 3	84	87	85
Expert 4	86	84	81
Expert 5	82	78	86
Expert 6	79	80	84
Expert 7	83	85	81
Expert 8	85	80	81
Expert 9	85	90	84
Expert 10	81	74	79

Table A9. Abbreviations list.

Abbreviations	Full Name
G2 method	The improved sequential relationship analysis method
GTM	Game theory method
TOPSIS	The technique for order preference by similarity to an ideal solution
JD	Jumbo drills
DM	Drilling machines
AHP	Analytic hierarchy process
G1 method	Sequential relationship analysis method
EWM	Entropy weight method
CRITIC	Criteria importance though intercriteria correlation method
FAHP	Fuzzy analytic hierarchy process
G2-EW-TOPSIS	The improved sequential relationship analysis method, entropy weight method, and the technique for order preference by similarity to an ideal solution

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