

Article

Comprehensive Evaluation of Green Bridge Construction Based on a Game Theory–Radar Chart Combination

Qingfu Li, Mengyuan Wang , Hao Guo and Guanming Zhao

School of Water Conservancy and Civil Engineering, Zhengzhou University, Zhengzhou 450001, China; lqflch@zzu.edu.cn (Q.L.); ghfw@gs.zzu.edu.cn (H.G.); zgm@gs.zzu.edu.cn (G.Z.)

* Correspondence: wmyly@gs.zzu.edu.cn

Abstract: The construction of large bridges requires significant natural resource consumption and causes widespread environmental damage, violating the concept of sustainable development. Therefore, it is necessary to build a comprehensive evaluation system for green construction. This paper took a bridge as a research object to establish a green construction evaluation index system based on GB/T 50640-2010, the “Green Construction Evaluation Standard for Construction Projects”. A combined game theory–radar chart method was adopted to evaluate the level of green construction for five construction schemes. The results were Scheme II > Scheme IV > Scheme III > Scheme I > Scheme V, where Scheme II was the best. The evaluations in this paper were consistent with those obtained by the G1-TOPSIS method; however, a combined-assignment method was used to avoid the one-sidedness of single-assignment, and to make the evaluations more objective.

Keywords: G1 method; entropy weighting method; combinatorial assignment; radar chart method; bridge; green construction



Citation: Li, Q.; Wang, M.; Guo, H.; Zhao, G. Comprehensive Evaluation of Green Bridge Construction Based on a Game Theory–Radar Chart Combination. *Sustainability* **2023**, *15*, 11383. <https://doi.org/10.3390/su151411383>

Academic Editor: Antonio Caggiano

Received: 8 June 2023

Revised: 8 July 2023

Accepted: 10 July 2023

Published: 21 July 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In recent decades, China’s transportation infrastructure construction has made remarkable achievements, but often at the cost of the environment and consumption of natural resources, both of which violate the concept of sustainable development. As an example of transportation infrastructure, a bridge project is characterized by a long construction period and causes serious environment damage. In China, more attention is now being paid to protecting the natural environment, advocating green construction, and improving sustainable bridge construction. Evaluating the level of green construction is now the main problem of bridge engineering [1].

Many scholars have conducted research into evaluating green construction. Wu [2] established a high-speed railroad evaluation index system using 17 indicators of three aspects—soil erosion control, resource conservation, and environmental protection—and then used an uncertain hierarchical analysis and set-pair theory to obtain weight values. Finally, he combined this with a cloud model and fuzzy comprehensive judgment. Liu [3] developed a green construction evaluation index system for large hydropower projects based on environmental protection, resource conservation, and comprehensive management, then he used analytical hierarchy process–fuzzy comprehensive evaluation (AHP–FCE) to evaluate the green construction level. Tam [4] proposed a green construction assessment (GCA) system containing management performance indicators (MPIs) and operational performance indicators (OPIs). These used a multicriteria decision system to establish the weights of each criterion and subfactor to assess environmental performance during construction. Li [5] constructed a comprehensive effect evaluation index system of green construction material-saving measures for the Sichuan–Tibet Railway. Then, he determined the comprehensive weights by introducing subjective preference coefficients and using subjective and objective assignment weighting. Finally, he measured the applicability of the material-saving measures for construction by the size of the efficiency

index. Shi [6] established a green construction evaluation system for roads in seasonal permafrost areas, using hierarchical clustering to determine index weights and SPSS for cluster analysis to establish a gray clustering model. Finally, he determined the green construction evaluation level according to the principle of maximum affiliation. Shao [7] introduced fuzzy substance element theory into green construction evaluation and used the entropy weight to calculate index weights. He then established standard fuzzy substance elements and correlation degree values for each element to rank each scheme in order to select the optimal one. Li [8] established a comprehensive evaluation index system from six categories and then combined vector angle cosine with two-dimensional cloud theory to undertake a comprehensive evaluation of the green construction level of a wind volcano tunnel. Bao [9] established an index system of green construction levels for a railroad in the cold and arid region of northwest China, considering five aspects: four sections and one environmental protection. Then, she determined the final weights of each evaluation index based on hierarchical analysis and entropy weighting. Finally, she used a radar diagram analysis to determine the relative advantages and disadvantages of each evaluation index. Wang [10] proposed a mutation-level method to decompose the multilevel evaluation objectives of a green high-speed railroad construction scheme. She then used the normalization formula of different mutation models to obtain mutation-level values and optimal evaluation results. Liu [11] constructed a metro-green construction evaluation index system and then used a game-theoretic combination assignment model to combine subjective and objective weights. Finally, he combined gray cluster analysis with binary semantics to evaluate the level of metro-green construction. Li [12] introduced sub-modules and overall architecture into a green construction evaluation system based on the BIM cloud service, which can efficiently and accurately evaluate traditional green construction methods by converting and integrating computer protocol data storage methods. Liu [13] constructed a risk evaluation system for green residential buildings using an improved CRITIC method to calculate the weights of risk factors and grey system theory to evaluate residential risk. It was found that green construction research in the existing literature has been focused mainly on railroads, tunnels, and other buildings. There are relatively few studies and no perfect evaluation system for the green construction of bridges [14].

In this paper, the evaluation indexes for green construction and the characteristics of bridge construction were selected from five categories: land saving and land resource protection, material saving and comprehensive utilization of material resources, energy saving and comprehensive utilization of energy, water saving and comprehensive utilization of water resources, and environmental protection. The weights of each index were measured using the G1 and Entropy methods. The subjective and objective weights were based on game theory to determine the comprehensive weights. Radar-chart analysis was then used to analyze the relative advantages and disadvantages of each construction scheme, and to give a comprehensive evaluation of its green construction level. Finally, the G1-TOPSIS method was used to conduct a comparative study to verify the rationality of the method.

2. Theoretical Background

2.1. Review of the Evaluation of Green Construction

Current green construction evaluation mainly focuses on roads, tunnels, and other buildings, but there is relatively less research on bridges, and there is not yet a perfect green construction evaluation system for bridges. GB/T 50640-2010 “Green Construction Evaluation Standard for Construction Projects” [15] is the national standard that specifies the evaluation framework of green construction, principal evaluation indexes, evaluation methods, and evaluation procedures. Therefore, it was the main basis for constructing the green construction evaluation index system in this paper.

2.2. Construction of the Evaluation Index System

Bridge green construction evaluation is complex, so the establishment of a complete and scientific evaluation index system is key to achieving a scientific, reasonable, and

accurate evaluation. In this paper, according to the requirements of GB/T 50640-2010 “Green Construction Evaluation Standard for Construction Projects” [15] and “Regulations on Environmental Protection Management of Construction Projects” [16], we determined the five most important primary indexes for green construction requirements. We referred to the evaluation indexes related to green construction in the literature [9] and combined these with the characteristics of bridge construction, then the secondary evaluation indexes with strong representativeness were selected to ensure that the selected indexes could objectively and reasonably reflect the green construction status of bridges. The bridge green construction comprehensive evaluation index system was established as shown in Figure 1. The index system included 5 primary indexes: “land saving”, “energy saving”, “water saving”, “material saving”, and “environmental protection”, as well as 16 secondary indicators [17].

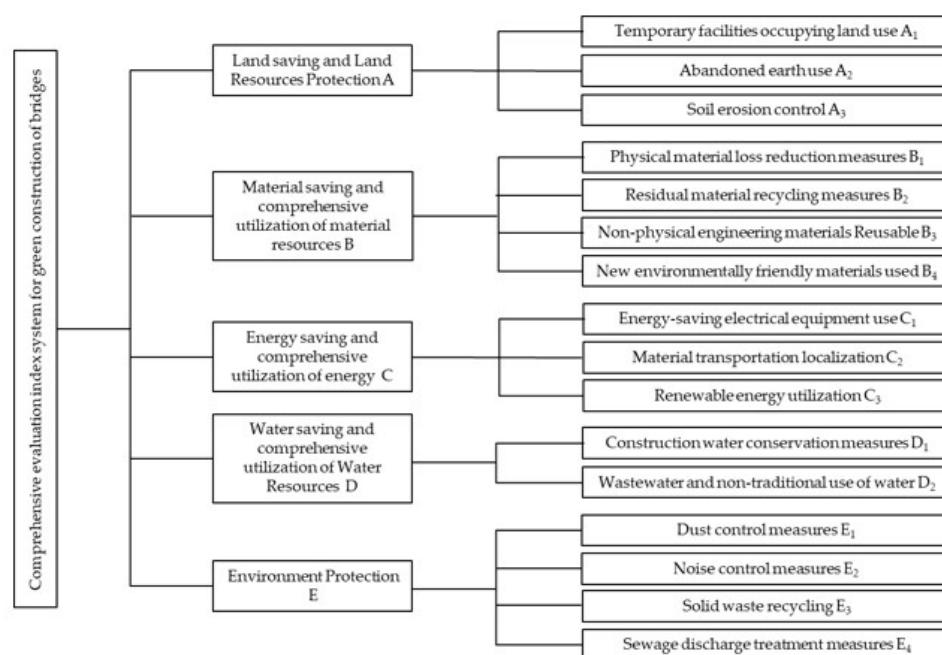


Figure 1. Bridge green construction comprehensive evaluation index system.

2.3. Determination of Index Grading Criteria

For the grading standards of the indexes, we integrated the division of grading standards of domestic and foreign evaluation systems, and we considered the relevant requirements of green construction and the level of green construction technology in China, as well as the maximum distinguishable ability of human beings. Then, based on current standards such as GB/T50378-2014 “Green Building Evaluation Standards” [18], GB/T50640-2010 “Green Construction Evaluation Standards for Construction Projects” [15], GB16297 “Comprehensive Emission Standards for Air Pollutants” [19], GB12523-2011 “Environmental Noise Emission Standards for Construction Sites” [20], etc., and referring to the relevant provisions in codes and standards such as GB/T50905 “Code for Green Construction of Construction Projects” [21] and the agreed standards of similar evaluation projects, the grading standards of each index were determined. We divided the indexes at all levels into five grades of excellent (90–100), good (80–90), medium (65–80), qualified (50–65), and unqualified (0–50), according to the degree the corresponding evaluation standards were met.

3. Evaluation Method

Determining the evaluation index weights was the core premise of comprehensive evaluation. Since each evaluation index in Figure 1 had independent properties and

“green” itself is a more subjective concept, the subjective weights of each evaluation index were first determined by the G1 method on the basis of expert opinion. In order to eliminate the disadvantage of the subjective arbitrariness of subjective weights, the entropy weighting method was introduced in this paper to determine the objective weights of each evaluation index. Then, the subjective weights and the objective weights of the evaluation indexes were combined based on game theory as the weights of bridge green construction level evaluation indexes [22]. Finally, the radar chart method was used to undertake a comprehensive evaluation of the degree of green construction of each evaluation object. The framework diagram of the assessment methodology is shown in Figure 2.

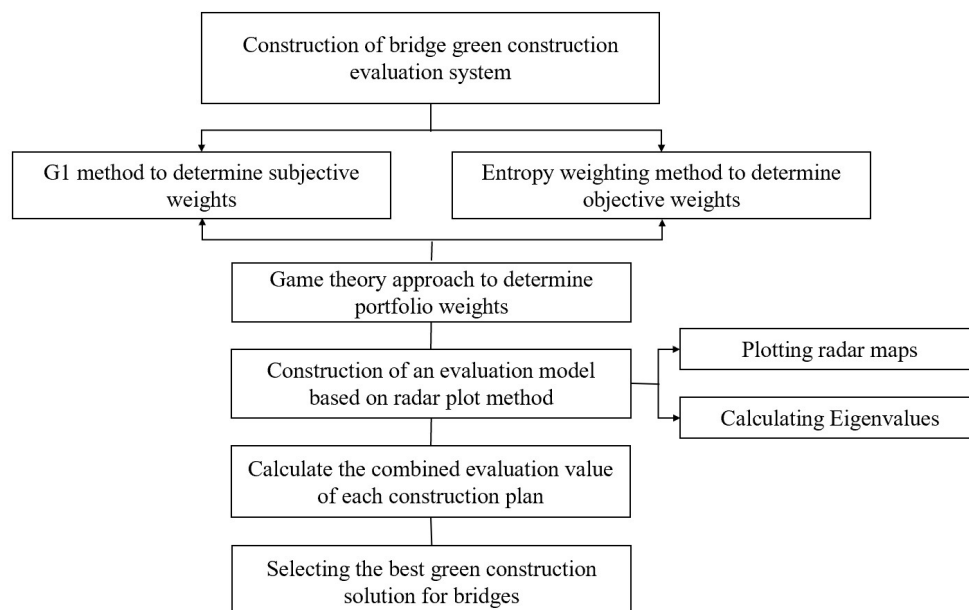


Figure 2. Framework diagram of assessment methods.

3.1. G1 Method to Determine the Subjective Weights of Indexes

To simplify the complexity of the subjective assignment, the G1 method was used, which is a subjective assignment method that first qualitatively ranks the influencing factors and then quantitatively assigns them (i.e., comparing judgments among adjacent indicators in turn). This process does not require the construction of judgment matrices and the calculation of consistency tests, and is simple and intuitive [23]. The specific steps are as follows in Sections 3.1.1–3.1.3.

3.1.1. Determine the Sequential Relationship

Let there be a total of n evaluation indexes. If the evaluation indexes T_i and T_j of each link of bridge green construction are such that $T_i > T_j, i, j = 1, 2 \dots n$, relative to the relevant evaluation criteria (or objectives), this means that T_i is more (or not less) important than T_j . For the set of evaluation indexes $\{T_1, T_2 \dots T_n\}$, the most important one among the n indexes is selected from them and marked as T'_1 ; the most important one among the remaining $n - 1$ indexes is selected and marked as T'_2 ; and so on, until the last evaluation index left after $n - 1$ screenings is labeled as T'_n . In this way, a unique sequential relationship is determined [24], denoted as

$$T'_1 > T'_2 > \dots > T'_{k-1} > T'_k > T'_{k+1} > \dots > T'_n \quad (1)$$

3.1.2. Judging the Relative Importance between T'_k and T'_{k-1}

Given the set $\{T'_1, T'_2, \dots, T'_{k-1}, T'_k, \dots, T'_n\}$, in which the weight of the k th index T'_k is w'_k , and defining the ratio of the importance of adjacent evaluation indexes T'_{k-1} , T'_k as r_k , the rational judgment criterion for r_k is

$$r_k = \frac{w'_{k-1}}{w'_k}, k = n, n-1, \dots, 3, 2 \quad (2)$$

where the values of r_k are given in Table 1 [25].

Table 1. r_k reference table of assignment values.

r_k	r_k Assignment Description
1.0	T'_{k-1} is equally important as T'_k
1.2	T'_{k-1} is slightly more important than T'_k
1.4	T'_{k-1} is obviously more important than T'_k
1.6	T'_{k-1} is strongly more important than T'_k
1.8	T'_{k-1} is extremely more important than T'_k
1.1, 1.3, 1.5, 1.7	The median of the above two adjacent judgments

To ensure that the weights are normalized, the weights of all indexes were made to sum to 1, i.e., they satisfied the following relational equation: $\sum_{k=1}^n w'_k = 1$

3.1.3. Calculation of Weighting Coefficients

First, the product is performed according to the definition of r_k , i.e., $\prod_{j=k}^n r_j = \frac{w'_{k-1}}{w'_n}$. Then, summing over k from 2 to n gives $\sum_{k=2}^n \left(\prod_{j=k}^n r_j \right) = \sum_{k=2}^n \frac{w'_{k-1}}{w'_n} = \frac{1}{w'_n} (\sum_{k=1}^n w'_k - w'_n)$. Because $\sum_{k=1}^n w'_k = 1$, we have $\sum_{k=2}^n \left(\prod_{j=k}^n r_j \right) = \frac{1}{w'_n} (1 - w'_n) = \frac{1}{w'_n} - 1$, and the weight of the n th index can be obtained as

$$w'_n = \left[1 + \sum_{k=2}^n \left(\prod_{j=k}^n r_j \right) \right]^{-1} \quad (3)$$

Next, the weights of the remaining $n-1$ evaluation indexes are calculated:

$$w'_{k-1} = r_k w'_k, k = n, n-1, \dots, 3, 2 \quad (4)$$

In summary, after calculating the ranking weights of all indexes $w'_k (k = 1, 2, \dots, n)$, the weights of each index $T_1 \sim T_n$ were reordered correspondingly according to the factor order relationship determined in step 2 above and formed into a vector set, noted as

$$w = (w_1, w_2, \dots, w_n)^T \quad (5)$$

3.2. Entropy Weighting Method to Determine Objective Weights

Entropy is the quantity that measures the uncertainty of a system in information theory. The greater the amount of information, the smaller the uncertainty and the smaller the entropy; conversely, the smaller the amount of information, the greater the uncertainty and the larger the entropy [26]. The entropy weighting method is an assignment method that uses a judgment matrix composed of the index values of the evaluated object to determine the weights [27], and the specific steps are as follows:

3.2.1. Define Attribute Matrix V

Let there be a total of m evaluation schemes and n evaluation indexes selected; the values of the evaluation indexes form an Attribute Matrix V .

$$V = (v_{ij})_{m \times n}, (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (6)$$

3.2.2. Define Normalized Decision Matrix M

The attribute matrix V is dimensionless according to Equations (8) and (9) [28], which gives the Normalized Decision Matrix, denoted as M .

$$M = (m_{ij})_{m \times n}, (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (7)$$

The bigger the better type:

$$m_{ij} = \frac{v_{ij} - \min_j(v_{ij})}{\max_j(v_{ij}) - \min_j(v_{ij})} \quad (8)$$

The smaller the better type:

$$m_{ij} = \frac{\max_j(v_{ij}) - v_{ij}}{\max_j(v_{ij}) - \min_j(v_{ij})} \quad (9)$$

Here, $\min_j(v_{ij})$ and $\max_j(v_{ij})$ are the minimum and maximum values of the same index in different schemes, respectively.

3.2.3. Calculate the entropy E_j

Based on the Normalized Decision Matrix M , the entropy E_j of each index is calculated according to Equation (10).

$$\begin{cases} E_j = -\frac{1}{\ln m} \sum_{i=1}^m f_{ij} \ln f_{ij} \\ f_{ij} = \frac{1+m_{ij}}{\sum_{i=1}^m (1+m_{ij})} \end{cases} \quad (10)$$

The greater the variability of an index in the evaluation system, the smaller E_j ; the smaller the variability, the larger E_j ; if $E_j = 1$, it means that index j has no influence on the evaluation system at this time [29].

3.2.4. Calculate the entropy weight w_j

Calculate the entropy weight w_j of each evaluation index according to Equation (11).

$$w_j = \frac{1 - E_j}{\sum_{j=1}^n (1 - E_j)} \quad (11)$$

Here, $0 \leq w_j \leq 1$, and the sum of the weights of each index is equal to 1.

3.3. Game Theory Portfolio Empowerment Method

Combination weighting based on game theory: the subjective weights and objective weights of bridge green construction evaluation indexes can be calculated by using the G1 method and the entropy weighting method, respectively, and the subjective and objective weights were fused according to the idea of game theory, so as to seek the optimal solution of the weights and obtain the combination weights of bridge green construction evaluation indexes [30]. The specific steps are as follows:

- (1) With s methods to assign weights to each evaluation index, the basic weight vector of evaluation indexes is constructed:

$$w_z = (w_{z1}, w_{z2}, \dots, w_{zn}) \quad (z = 1, 2, \dots, s) \quad (12)$$

where z is the number of methods and n is the total number of evaluation indexes.

Then, the linear combination of the s assignment methods is

$$w = \sum_{z=1}^s \alpha_z w_z^T \quad \left(\alpha_z > 0, \sum_{z=1}^s \alpha_z = 1 \right) \quad (13)$$

where w is one possible weight vector of the set of evaluation index weights, and α_z is the linear combination coefficient.

- (2) Solve the optimal weight coefficients α_z , for which a countermeasure model is introduced to minimize the deviation of w from each w_z [31], i.e.,

$$\min \left\| \sum_{z=1}^s \alpha_z w_z^T - w_z \right\|_2 \quad (14)$$

- (3) The optimal first-order derivative condition of the above equation is derived from the properties of differentiation.

$$\sum_{z=1}^s \alpha_z w_z w_z^T = w_z w_z^T \quad (15)$$

- (4) According to Equation (15), we can calculate $(\alpha_1, \alpha_2, \dots, \alpha_s)$, and then this is normalized to obtain the weighting coefficients [32].

$$\alpha'_z = \frac{\alpha_z}{\sum_{z=1}^s \alpha_z} \quad (16)$$

- (5) Then, the portfolio weights based on game theory are

$$w' = \sum_{z=1}^s \alpha'_z w_z^T \quad (17)$$

3.4. Reasonableness Analysis of Portfolio Empowerment

In this paper, a combination of the G1 method and entropy weighting method was used for the combined assignment, but it was unknown whether its use for calculating the weights was reasonable, so it was necessary to analyze the reasonableness of this combined assignment method. The specific steps [33] are as follows:

3.4.1. Summary of Weights

The results of calculating the weights of each index using the G1 method and the entropy weighting method are shown in Table 2, where β_j is the weight value of the j th evaluation index determined by the G1 method, and γ_j is the weight value of the j th evaluation index determined by the entropy weighting method.

Table 2. Weighting results of the evaluation indexes.

Method	Index 1	Index 2	...	Index n
G1 method	β_1	β_2	...	β_n
Entropy weighting method	γ_1	γ_2	...	γ_n

3.4.2. Weighting Order

The results obtained from the calculation of evaluation index weights by the two methods are ranked in Table 3, where β'_j is the ranked value of subjective weight

value β_j and γ_j' is the ranked value of objective weight value γ_j , and the ranked values are expressed by $1 \sim n$ (n is a positive integer). When the ranked value is 1, it means that the weight value of evaluation index is the largest, and when the ranking value is n , it means that the weight value of evaluation index is the smallest.

Table 3. Ranking results of the evaluation index weights.

Method	Index 1	Index 2	...	Index n
G1 method	β_1'	β_2'	...	β_n'
Entropy weighting method	γ_1'	γ_2'	...	γ_n'

3.4.3. Spearman Consistency Coefficient

The Spearman consistency coefficient [34] reflects the correlation between two sets of variables and is expressed by ρ . It was used in this paper to reflect the consistency between the weights obtained from the G1 method and the entropy weighting method, and was calculated as follows:

$$\rho = 1 - \frac{6}{n(n^2 - 1)} \sum_{j=1}^n (\beta_j' - \gamma_j')^2 \quad (18)$$

where β_j' is the ranking value of subjective weight value β_j , γ_j' is the ranking value of objective weight value γ_j , and the value range of ρ is $[-1, 1]$. When $\rho \in [-1, 0)$, it indicates that there is no consistency between the weights calculated by the two methods; when $\rho = 0$, the correlation between the weights calculated by the two methods is 0; when $\rho \in (0, 1]$, it indicates that there is consistency between the weights calculated by the two methods, and a combined assignment can be made.

3.5. Construction of an Evaluation Model Based on the Radar Chart Method

3.5.1. Draw the Radar Map

The radar chart method is a multivariate graphical analysis method, named for its resemblance to navigation radar screen graphics. It is mainly applied to the comprehensive evaluation of multi-index systems [35]. The radar chart method connects the values of each evaluation index in a closed graphical area by means of a fold line, and the quantitative evaluation results are derived from the area and perimeter of the closed graphical area [36]. The operational procedure [37] is as follows:

- (1) Make a unit circle and draw a ray from the center O of the unit circle to intersect the unit circle at point A.
- (2) With OA as the starting line, the second ray is made to intersect with the unit circle at the point B according to the circular angle $\theta_1 = 360w_1^\circ$ (where w_1 is the comprehensive weight accounted for by the first indicator). Make the 2nd ray and intersect the unit circle at the point B. According to this principle, the n th line segment, equal to the number of evaluation indexes, is made in turn.
- (3) The values of the indexes are dimensionless, so that the values are distributed in the range of $[0, 1]$, and the indexes are dimensionless in the following way:

$$x'_{ij} = \begin{cases} \frac{x_{ij}}{\max x_{ij}} & \text{Positive index processing} \\ 1 - \frac{x_{ij}}{\max x_{ij}} & \text{Reverse index processing} \end{cases} \quad (19)$$

- (4) With the center of the unit circle as the origin, the normalized data of n evaluation index values ($x'_1, x'_2 \dots x'_n$) of the proposed evaluation scheme X are marked on the axes of each index one by one. By connecting $x'_1, x'_2 \dots x'_n$ points in the order of dash lines to form a closed graphical region, i.e., a radar map is formed.

3.5.2. Calculation of Eigenvalues

- (1) Calculate the radar map area S_X and perimeter L_X of the proposed evaluation scheme X .

$$S_X = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \frac{1}{2} x'_i x'_j \sin \theta_{ij} \quad (20)$$

$$L_X = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \sqrt{x_i'^2 + x_j'^2 - 2x_i'x_j' \cos \theta_{ij}} \quad (21)$$

here, n is the number of indexes; x'_i is the normalized value of the i th index, i.e., the side length of the i th index axis; and θ_{ij} is the angle of the adjacent i, j index axis.

- (2) The evaluation vector is constructed. To facilitate comparison of the merits of each evaluation object, the evaluation vector V_X , $V_X = (V_{X1}, V_{X2})$ is obtained by extracting the feature vector and normalizing it.

$$V_{X1} = \frac{S_X}{S_{Xmax}} \quad V_{X2} = \frac{4\pi S_X}{L_X^2} \quad (22)$$

here, S_{Xmax} is the maximum value of the radar map area drawn by each construction scenario.

- (3) Calculation of the final integrated appraisal value f_X :

$$f_X = \sqrt{V_{X1} \times V_{X2}} \quad (23)$$

Note: The larger the value of f_X , the higher the level of green construction.

4. Evaluation Cases

4.1. Project Examples

Consider a south-to-north water transfer bridge 551 m long. The project construction process requires compliance with the requirements of green construction and evaluation standards. In order to protect the surface environment and prevent soil erosion and loss, the bare soil caused by the construction should be covered or planted with raw grass species in a timely manner to reduce soil erosion; in the case of soil loss due to surface runoff caused by the construction, measures should be taken to reduce soil loss by setting up surface drainage systems, as well as stabilizing side slopes and vegetation cover.

There are five construction schemes [23] to choose from, namely, I, II, III, IV, and V. We used the evaluation system constructed in this paper to evaluate the greenness of these five schemes in the construction process. We explained how the evaluation model preferred the best green construction scheme. Six companies with experience in green bridge construction and systematic understanding of green building systems were invited to send five experts to each company to form the evaluation team. To ensure the reliability of the evaluation results, each expert had an associate senior title or above, and had been engaged in green construction or research for more than eight years, with experience in green bridge construction and familiarity with bridge construction technology. The evaluation team evaluated and scored the green construction level of each construction plan, considering the evaluation standards of green construction at home and abroad and the relevant regulations and requirements of green construction in China. We took the average of all the experts' scores as the final score. The final score of each index is shown in Table 4.

Table 4. Score of each evaluation index.

Schemes	Indexes															
	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	E1	E2	E3	E4
I	85	75	78	69	91	83	57	70	77	69	72	78	69	68	85	72
II	87	88	87	96	89	76	87	84	85	78	85	88	90	86	85	86
III	61	77	62	81	73	91	73	71	91	69	73	91	84	73	71	65
IV	67	84	87	80	83	85	85	87	80	87	94	74	87	92	89	67
V	81	63	84	73	82	62	79	67	63	75	77	73	75	51	74	60

4.2. Determination of the Comprehensive Weight of the Evaluation Index

By referring to the regulations for the importance of green construction evaluation indexes in the book “Green Construction Organization and Management of Large Bridges” [36], and the evaluation of relevant experts, the relative importance of the first-level indexes A, B, C, D, and E was obtained. Therefore, the subjective weight of the criterion layer could be calculated according to the G1 method. Similarly, the subjective weight values of the 16 evaluation indexes of the index layer could be obtained, and then the objective weight of each index was determined by the entropy weighting method. Finally, the use of game theory led to the final weight value. The details are as follows.

4.2.1. The G1 Method Was Applied to Calculate the Subjective Weights of Each Evaluation Index

Through effective investigation, statistics, and sorting of the abovementioned evaluation indexes, we concluded that the orderly relationship between the first-level evaluation indexes was $E > D > B > C > A$, recorded as $T'_1 > T'_2 > T'_3 > T'_4 > T'_5$. At the same time, combined with the regulations in “Large Bridge Green Construction Organization and Management” [38], we have approximate values of $r_5 = 1.1, r_4 = 1.2, r_3 = 1.1, r_2 = 1.6$; therefore, $r_2 r_3 r_4 r_5 = 2.3232, r_3 r_4 r_5 = 1.452, r_4 r_5 = 1.32, r_2 r_3 r_4 r_5 + r_3 r_4 r_5 + r_4 r_5 + r_5 = 6.1952$. From Equation (3), it could be concluded that $w'_5 = (1 + r_2 r_3 r_4 r_5 + r_3 r_4 r_5 + r_4 r_5 + r_5)^{-1} = 0.1390$. From Equation (4), we obtained, in turn, $w'_4 = r_5 w'_5 = 0.1529, w'_3 = r_4 w'_4 = 0.1835, w'_2 = r_3 w'_3 = 0.2018, w'_1 = r_2 w'_2 = 0.3228$. Therefore, it can be concluded that the weights of the first-level indexes A, B, C, D, and E are $w = [0.1390, 0.1839, 0.1529, 0.2014, 0.3228]^T$.

Similarly, the subjective weights of the 16 evaluation indexes could be obtained from Equations (1)–(5), as shown in Table 5.

Table 5. Subjective weights of each index obtained by the G1 method.

	Guideline Layer Weights					Index Layer Weights
	A 0.139	B 0.184	C 0.153	D 0.201	E 0.323	
A1	0.284					0.040
A2	0.375					0.052
A3	0.341					0.047
B1		0.345				0.063
B2		0.169				0.031
B3		0.221				0.041
B4		0.265				0.049
C1			0.302			0.046
C2			0.423			0.065
C3			0.275			0.042
D1				0.583		0.118
D2				0.417		0.084
E1					0.276	0.089
E2					0.163	0.053
E3					0.231	0.074
E4					0.330	0.106

4.2.2. Determination of Objective Weights by the Entropy Weighting Method

According to Equations (6)–(9), the entropy-based normative decision matrix M based on the entropy weighting method was obtained from the final scores of the index level factors (Table 4):

$$M = \begin{pmatrix} 0.923 & 0.480 & 0.640 & 0.000 & 1.000 & 0.724 & 0.000 & 0.150 & 0.500 & 0.000 & 0.000 & 0.278 & 0.000 & 0.415 & 0.778 & 0.462 \\ 1.000 & 1.000 & 1.000 & 1.000 & 0.889 & 0.483 & 1.000 & 0.850 & 0.786 & 0.500 & 0.591 & 0.833 & 1.000 & 0.854 & 0.778 & 1.000 \\ 0.000 & 0.560 & 0.000 & 0.444 & 0.000 & 1.000 & 0.533 & 0.200 & 1.000 & 0.000 & 0.045 & 1.000 & 0.714 & 0.537 & 0.000 & 0.192 \\ 0.231 & 0.840 & 1.000 & 0.407 & 0.556 & 0.793 & 0.933 & 1.000 & 0.607 & 1.000 & 1.000 & 0.056 & 0.857 & 1.000 & 1.000 & 0.269 \\ 0.769 & 0.000 & 0.880 & 0.148 & 0.500 & 0.000 & 0.733 & 0.000 & 0.000 & 0.333 & 0.227 & 0.000 & 0.286 & 0.000 & 0.167 & 0.000 \end{pmatrix}$$

Then, the entropy value E_j and the corresponding entropy weight w_j of the index layer could be calculated from Equations (10) and (11). The results are shown in Table 6.

Table 6. Entropy values E_j of the indicator layer and the corresponding entropy weights w_j .

	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	E1	E2	E3	E4
E_j	0.979	0.984	0.983	0.982	0.984	0.985	0.984	0.976	0.985	0.978	0.978	0.975	0.982	0.984	0.979	0.982
W_j	0.068	0.052	0.056	0.060	0.053	0.051	0.054	0.080	0.050	0.074	0.075	0.083	0.061	0.054	0.069	0.060

4.2.3. Game-Theory-Based Portfolio Empowerment and Rationality Analysis

Based on the index weights calculated by the G1 method and the entropy weighting method mentioned above, the results of the ranking of the weight values were formed as shown in Table 7.

Table 7. Evaluation index weight value ranking results.

	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	E1	E2	E3	E4
G1 method	15	9	11	7	16	14	10	12	6	13	1	4	3	8	5	2
Entropy weighting method	6	14	10	8	13	15	11	2	16	4	3	1	7	12	5	9

The consistency coefficient $\rho = 0.2251 \in (0, 1)$ can be calculated from Equation (18). The calculations showed that there was consistency between the weights calculated by the G1 method and the entropy weighting method, which could be combined to assign weights.

In this study, there were two different assignment methods, so $s = 2$. According to Equations (13)–(16), the comprehensive weight coefficient vector α_1 (subjective weight coefficient) and α_2 (objective weight coefficient) of each evaluation index could be determined as 0.609 and 0.391, respectively, so the final results of each index weight were obtained and are given in Table 8.

Table 8. Combination weights of evaluation indexes.

	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	E1	E2	E3	E4
Weight	0.051	0.052	0.051	0.062	0.039	0.045	0.984	0.059	0.059	0.055	0.101	0.084	0.078	0.053	0.072	0.088

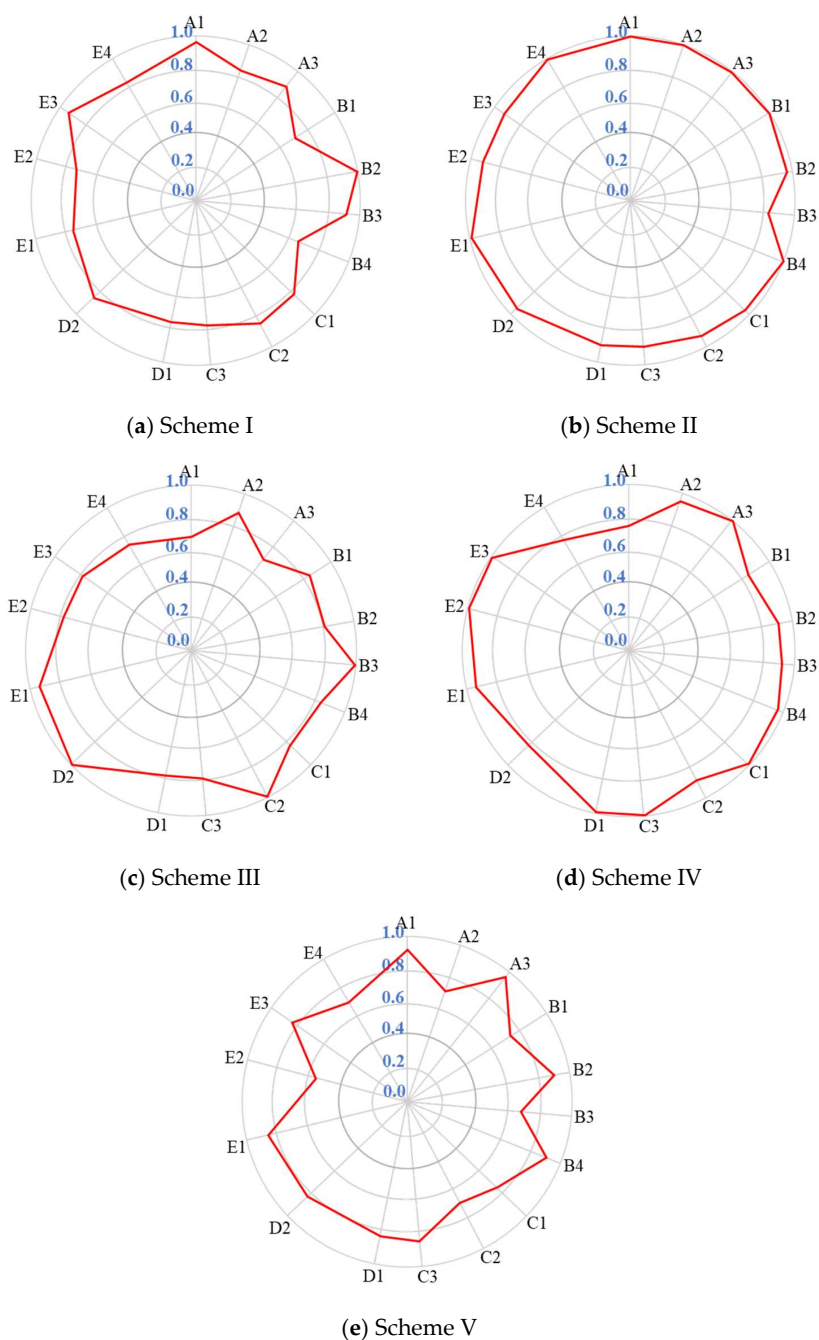
4.3. Drawing Radar Maps

First, the values of each index were dimensionless according to Equation (19), and the results are shown in Table 9.

Table 9. Evaluation indexes dimensionless processing results.

	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	E1	E2	E3	E4
I	0.977	0.852	0.897	0.719	1.000	0.912	0.655	0.805	0.846	0.793	0.766	0.857	0.767	0.739	0.955	0.837
II	1.000	1.000	1.000	1.000	0.978	0.835	1.000	0.966	0.934	0.897	0.904	0.967	1.000	0.935	0.955	1.000
III	0.701	0.875	0.713	0.844	0.802	1.000	0.839	0.816	1.000	0.793	0.777	1.000	0.933	0.793	0.798	0.756
IV	0.770	0.955	1.000	0.833	0.912	0.934	0.977	1.000	0.879	1.000	1.000	0.813	0.967	1.000	1.000	0.779
V	0.931	0.716	0.966	0.760	0.901	0.681	0.908	0.770	0.692	0.862	0.819	0.802	0.833	0.554	0.831	0.698

The radar maps were drawn according to the previous method, and the integrated radar maps for each construction scheme are shown in Figure 3.

**Figure 3.** Integrated evaluation radar charts of all schemes.

The relative advantages and disadvantages of each evaluation index in the five schemes can be seen from Figure 3. For example, in Scheme II, the values of 10 indexes were close to the ideal value, which means that the green construction measures of these 10 items were effective, and the normalized values of all index scores were above 0.8, so the overall green construction effect was good.

4.4. Calculate the Characteristic Quantity of the Radar Map

According to Equations (20)–(23), the surface area, circumference, area evaluation vector, circumference evaluation vector, and final evaluation value of the radar maps drawn by these five schemes can be calculated, as shown in Table 10.

Table 10. Calculation results of each scheme.

	Surface Area S_X	Circumference L_X	V_{X1}	V_{X2}	Final Evaluation Value f_X	Sorting
I	2.1155	5.6910	1.0010	0.8208	0.9065	4
II	2.8210	6.1061	1.3349	0.9508	1.1266	1
III	2.1520	5.6702	1.0183	0.8411	0.9255	3
IV	2.5750	5.9921	1.2185	0.9012	1.0479	2
V	1.9000	5.7963	0.8991	0.7107	0.7993	5

From Table 10, the individual characteristic values of the five construction schemes can be seen. Their final evaluation values were 0.9065, 1.1266, 0.9255, 1.0479, and 0.7993. Therefore, it can be concluded that the ranking of these five construction schemes regarding the green construction level was $II > IV > III > I > V$, so Scheme II was the best. Comparing the construction process of the five construction schemes, the cantilever construction method of the main bridge adopted by Scheme II, the reuse of construction wastewater, ecological vegetation restoration, prevention of pollutants entering the channel, and a series of green construction measures ensured a green construction effect. To maximize green construction, Scheme II is undoubtedly the best choice.

In summary, the game theory combined empowerment–radar graph method was well tested in this comprehensive evaluation study of bridge green construction. The accuracy and applicability of the method were confirmed, providing a new method for the green construction evaluation of bridges.

4.5. Control Study

4.5.1. Basic Theory of G1-TOPSIS Method

To illustrate the rationality and scientific validity of the above method, a comparative study was carried out in this paper using the G1-TOPSIS method. The use of the GI method to calculate subjective weights was explained in detail in the previous section, and the TOPSIS method is highlighted here.

The TOPSIS method was proposed by Mallika, C.H, to rank a finite number of solutions according to their proximity to the idealized solution, making it one of the multi-attribute decision methods [39]. It mainly ranks the evaluation objects with the help of positive and negative ideal solutions of the multi-attribute problem, where the positive ideal solution is a virtual optimal solution whose values of each indicator reach the optimal value among the evaluation objects, and the negative ideal solution is a virtual worst solution whose values of each indicator reach the worst value among the evaluation objects [40].

The basic principle of the TOPSIS method [41] is to calculate the positive and negative ideal solutions of the multi-attribute decision problem, and then rank each solution according to the distance between the positive and negative ideal solutions. If the solution to be chosen is closest to the positive ideal solution and at the same time furthest from the negative ideal solution, it is the optimal solution. Conversely, if the solution to be chosen is closest to the negative ideal solution and at the same time furthest from the positive ideal solution, it is the worst solution [42].

The comprehensive evaluation process of the TOPSIS method is shown in Figure 4 [43].

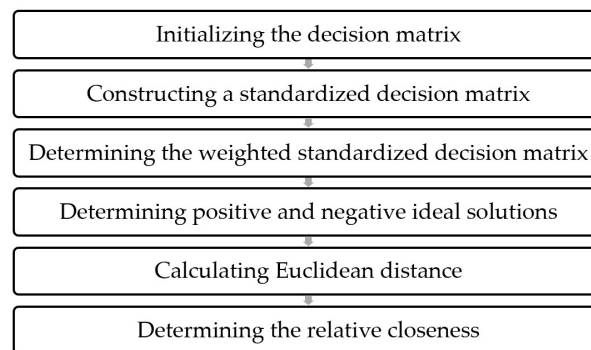


Figure 4. Combined weighting—TOPSIS method comprehensive evaluation process.

(1) Initial decision matrix

Consider a set of scenarios $F = (F_1, F_2, \dots, F_m)$ and a set of evaluation indexes for each scenario $D = (D_1, D_2, \dots, D_m)$; the evaluation index e_{ij} denotes the index value of scenario F_i under index D_j , where $i = 1, 2, \dots, m; j = 1, 2, \dots, n$. The initial decision matrix formed by the evaluation index values is

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

(2) Standardized decision matrix

The evaluation indexes are divided into benefit indexes and cost indexes, and for benefit indexes, the larger the value the better; for cost indexes, the smaller the value the better. Since the evaluation indexes have different scales and scale units, they are not comparable. In order to eliminate the incommensurability of the indexes, it is necessary to dimensionlessly process the evaluation indexes and obtain the standardized decision matrix $C = (c_{ij})_{m \times n}$.

For benefit-based indexes, the expression is calculated as

$$c_{ij} = \frac{e_{ij} - \min_j(e_{ij})}{\max_j(e_{ij}) - \min_j(e_{ij})} \quad (25)$$

For cost-based indexes, the expression is calculated as

$$c_{ij} = \frac{\max_j(e_{ij}) - e_{ij}}{\max_j(e_{ij}) - \min_j(e_{ij})} \quad (26)$$

where $\max_j(e_{ij})$ is the maximum value of column j in the initial decision matrix E , and $\min_j(e_{ij})$ is the minimum value of column j in the initial decision matrix E .

(3) Weighted standardized decision matrix

Using the weight values w_j derived from the above G1 method assignment, the data in the standardized decision matrix were multiplied by the weights of the corresponding indexes to obtain the weighted standardized decision matrix $Z = (z_{ij})_{m \times n}$.

$$Z = (z_{ij})_{m \times n} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix} = \begin{bmatrix} w_1 e_{11} & \cdots & w_n e_{1n} \\ \vdots & \ddots & \vdots \\ w_1 e_{m1} & \cdots & w_n e_{mn} \end{bmatrix} \quad (27)$$

- (4) Determine the positive ideal solution and negative ideal solution

The positive ideal solution Z^+ consists of the maximum value in each column of Z , i.e.,

$$Z^+ = (Z_1^+, Z_2^+, \dots, Z_n^+) = (\max Z_{i1}, \max Z_{i2}, \dots, \max Z_{in}) \quad (28)$$

The negative ideal solution Z^- consists of the smallest value in each column of Z , i.e.,

$$Z^- = (Z_1^-, Z_2^-, \dots, Z_n^-) = (\min Z_{i1}, \min Z_{i2}, \dots, \min Z_{in}) \quad (29)$$

- (5) Calculate Euclidean distance

The expression for the distance S_i^+ of each object to be evaluated from the positive ideal solution is

$$S_i^+ = \sqrt{\sum_{j=1}^n (z_{ij} - z_j^+)^2} \quad (30)$$

The expression for the distance S_i^- of each object to be evaluated from the negative ideal solution is

$$S_i^- = \sqrt{\sum_{j=1}^n (z_{ij} - z_j^-)^2} \quad (31)$$

where $i = 1, 2, \dots, m; j = 1, 2, \dots, n$

- (6) The relative closeness of each evaluation object to the positive ideal solution is

$$G_i = \frac{S_i^-}{S_i^- + S_i^+}, \quad i = 1, 2, \dots, m \quad (32)$$

- (7) The relative closeness of each solution is compared, and the larger the relative closeness, the better the solution.

4.5.2. Instance Validation

- (1) Build the initial decision matrix

In this case, the set of solutions $F = (F_1, F_2, \dots, F_5)$, the set of evaluation indexes for each program $D = (D_1, D_2, \dots, D_{16})$, and the initial decision matrix consisting of the evaluation index values was obtained from Table 4 as

$$E = (e_{ij})_{m \times n} = \begin{pmatrix} 85 & 75 & 78 & 69 & 91 & 83 & 57 & 70 & 77 & 69 & 72 & 78 & 69 & 68 & 85 & 72 \\ 87 & 88 & 87 & 96 & 89 & 76 & 87 & 84 & 85 & 78 & 85 & 88 & 90 & 86 & 85 & 86 \\ 61 & 77 & 62 & 81 & 73 & 91 & 73 & 71 & 91 & 69 & 73 & 91 & 84 & 73 & 71 & 65 \\ 67 & 84 & 87 & 80 & 83 & 85 & 85 & 87 & 80 & 87 & 94 & 74 & 87 & 92 & 89 & 67 \\ 81 & 63 & 84 & 73 & 82 & 62 & 79 & 67 & 63 & 75 & 77 & 73 & 75 & 51 & 74 & 60 \end{pmatrix}$$

- (2) Using Equations (25) and (26) to dimensionlessly size the values of each evaluation index, the standard decision matrix was obtained as

$$C = \begin{pmatrix} 0.923 & 0.480 & 0.640 & 0.000 & 1.000 & 0.724 & 0.000 & 0.150 & 0.500 & 0.000 & 0.000 & 0.278 & 0.000 & 0.415 & 0.778 & 0.462 \\ 1.000 & 1.000 & 1.000 & 1.000 & 0.889 & 0.483 & 1.000 & 0.850 & 0.786 & 0.500 & 0.591 & 0.833 & 1.000 & 0.854 & 0.778 & 1.000 \\ 0.000 & 0.560 & 0.000 & 0.444 & 0.000 & 1.000 & 0.533 & 0.200 & 1.000 & 0.000 & 0.045 & 1.000 & 0.714 & 0.537 & 0.000 & 0.192 \\ 0.231 & 0.840 & 1.000 & 0.407 & 0.556 & 0.793 & 0.933 & 1.000 & 0.607 & 1.000 & 1.000 & 0.056 & 0.857 & 1.000 & 1.000 & 0.269 \\ 0.769 & 0.000 & 0.880 & 0.148 & 0.500 & 0.000 & 0.733 & 0.000 & 0.000 & 0.333 & 0.227 & 0.000 & 0.286 & 0.000 & 0.167 & 0.000 \end{pmatrix}$$

- (3) Then, we used Equation (27) to multiply the data in the standardized decision matrix by the weights corresponding to each index ω_j to obtain the weighted decision matrix as

$$Z = \begin{pmatrix} 0.037 & 0.025 & 0.030 & 0.000 & 0.031 & 0.030 & 0.000 & 0.007 & 0.033 & 0.000 & 0.000 & 0.023 & 0.000 & 0.022 & 0.058 & 0.049 \\ 0.040 & 0.052 & 0.047 & 0.063 & 0.028 & 0.020 & 0.049 & 0.039 & 0.051 & 0.021 & 0.070 & 0.070 & 0.089 & 0.045 & 0.058 & 0.106 \\ 0.000 & 0.029 & 0.000 & 0.028 & 0.000 & 0.041 & 0.026 & 0.009 & 0.065 & 0.000 & 0.005 & 0.084 & 0.064 & 0.028 & 0.000 & 0.020 \\ 0.009 & 0.044 & 0.047 & 0.026 & 0.017 & 0.033 & 0.046 & 0.046 & 0.039 & 0.042 & 0.118 & 0.005 & 0.076 & 0.053 & 0.074 & 0.029 \\ 0.031 & 0.000 & 0.041 & 0.009 & 0.016 & 0.000 & 0.036 & 0.000 & 0.000 & 0.014 & 0.027 & 0.000 & 0.025 & 0.000 & 0.012 & 0.000 \end{pmatrix}$$

- (4) Then, the positive ideal solution Z^+ and the negative ideal solution Z^- of the weighted decisionalized matrix Z could be obtained using Equations (28) and (29). $Z^+ = (0.040, 0.052, 0.047, 0.063, 0.031, 0.041, 0.049, 0.046, 0.065, 0.042, 0.118, 0.084, 0.089, 0.053, 0.074, 0.106)$, $Z^- = (0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)$. The distance S_i^+, S_i^- between each object to be evaluated and the positive and negative ideal solutions could be calculated from Equations (30) and (31). Finally, the relative closeness G_i of each construction solution to the positive ideal solution was obtained from Equation (32), and the evaluation results of the five green construction solutions are listed in Table 11.

Table 11. Green construction program evaluation results.

Scheme Number	S_i^+	S_i^-	G_i	Sorting
I	0.2047	0.1121	0.3539	4
II	0.0633	0.2300	0.7843	1
III	0.1921	0.1437	0.4280	3
IV	0.1257	0.2064	0.6216	2
V	0.2284	0.0774	0.2531	5

As can be seen from Table 11, the relative closeness of these five schemes was 0.3539, 0.7843, 0.4280, 0.6216, 0.2531. Their green construction levels were ranked as $II > IV > III > I > V$, with scheme II being the best and scheme V being the worst.

Throughout the paper, the comparison revealed that the evaluation of the five green construction options to be selected for the bridge using two different methods was consistent, which was also consistent with the actual construction option selected for the bridge. In the controlled study, the G1 method was used to calculate the weights, and it was difficult to ensure scientific and accurate weights due to the varying levels of the experts. This paper adopted the G1 method and the entropy method to assign subjective and objective weights to each evaluation index, while weighting the subjective and objective weights based on game theory. It is good to avoid the one-sidedness of a single assignment method and take into account the subjective intention of decision makers and the objective attributes of the data itself. Therefore, using the radar chart method to determine the green construction level was clear and unambiguous. The obtained evaluation results were consistent with the results determined by G1-TOPSIS. The comparative study highlighted the rationality of the proposed method in this paper.

5. Conclusions

- (1) By referring to the standard GB/T 50640-2010[44], and the meaning of green construction, this paper identified five primary evaluation indexes: “land saving”, “material saving”, “energy saving”, “water saving”, and “environmental protection”. Further, we subdivided the important influencing factors of these five aspects, and we established a comprehensive evaluation index system for the green construction of bridges. The weight of the indexes was determined by the combination of the G1 method and entropy weighting method, based on game theory, which reduced the subjective arbitrariness in the evaluation and improved the accuracy of the bridge green construction project evaluation.
- (2) For the current small sample, the evaluation model was established based on the radar chart analysis method. This can not only realize the overall evaluation of the green construction effect of different schemes, but also makes a vertical and horizontal

comparison of the relative advantages and disadvantages of the evaluation indexes. It is a convenient method to determine the main problems of green construction measures in the research object, and it provides a theoretical basis for choosing the optimal solution.

- (3) The model was applied to a special bridge for validation, and a comparative study was carried out in combination with the G1-TOPSIS method. The evaluation results were consistent with the results obtained from the method used in this paper and matched the actual situation, thus verifying the feasibility and accuracy of applying the game-theoretic combined empowerment–radar graph method to the selection of green construction solutions for bridges. This could be used to guide the subsequent construction.
- (4) This paper evaluated the level of green construction of bridges. Since there are many factors affecting the green construction of bridges, this paper only selected the most common and influential 5 primary indexes and 16 secondary indexes, which are inadequate in many aspects. Therefore, it remains necessary to conduct more in-depth exploration and research into the comprehensive evaluation of green construction of bridges in future.

Author Contributions: Conceptualization, Q.L.; Methodology, H.G.; Software, H.G.; Validation, M.W.; Formal analysis, G.Z.; Data curation, Q.L.; Writing—original draft, M.W.; Writing—review & editing, M.W.; Supervision, G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are from our own research projects.

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

References

1. Wang, W.; Liu, W. Application of Green Construction Technology in Road and Bridge Engineering. *Eng. Technol. New Mater.* **2022**, *56*, 143–144. (In Chinese)
2. Wu, W.; Huang, P.; Zhong Mn Wan, X.; Pan, H. Green Construction Grade Evaluation of high-speed railway based on cloud Model: A case study of Southwest China. *J. Railw. Sci. Eng.* **2021**, *18*, 1418–1425. (In Chinese)
3. Liu, L.; Zhang, Y.; Zhao, L.; Zhan, C.; Liang, C. An Attempt to Evaluate the Green Construction of Large-Scale Hydropower Projects: Taking Wudongde Hydropower Station on the Jinsha River, China as an Example. *Sustainability* **2021**, *14*, 194. [[CrossRef](#)]
4. Tam, C.M.; Tam Vivian, W.Y.; Tsui, W.S. Green construction assessment for environmental management in the construction industry of Hong Kong. *Int. J. Proj. Manag.* **2004**, *22*, 563–571. [[CrossRef](#)]
5. Li, Y.; Bao, X. Comprehensive Effect evaluation of Green Construction Material Saving Measures for Sichuan-Tibet Railway. *J. Railw. Sci. Eng.* **2021**, *18*, 1613–1621. (In Chinese)
6. Shi, Z.; Li, Z.; Tan, X.; Hua, S. Study on Green Construction Evaluation of Highway in Seasonal Frozen Zone. *J. Inf. Technol. Res. (JITR)* **2021**, *14*, 17. [[CrossRef](#)]
7. Shao, B.L.; Yang, M.M.; Liu, B.Q. Study on Green Construction Evaluation Based on the Fuzzy Matter-Element. *Appl. Mech. Mater.* **2013**, *2746*, 1137–1143. [[CrossRef](#)]
8. Li, H.; Bao, X. Comprehensive evaluation of green construction level of Railway tunnel in Qinghai-Tibet Plateau. *J. Railw. Sci. Eng.* **2021**, *18*, 524–532. (In Chinese)
9. Bao, X.; Zhang, J.; Wang, Q. Study on Green Construction Grade Evaluation of railway in Cold and drought area in Northwest China. *J. China Railw. Soc.* **2019**, *41*, 33–39. (In Chinese)
10. Wang, M.; Zhang, Q.; Ling, F.; Ni, S. Construction evaluation of Green high-speed Railway based on catastrophe progression method. *J. Railw. Eng.* **2017**, *34*, 76–80. (In Chinese)
11. Liu, R. *Evaluation of Metro Green Construction Based on Game Theory and Grey Binary Semantics*; Shijiazhuang Tiedao University: Shijiazhuang, China, 2021.
12. Li, Y.; Gao, X.; Liu, X.; Zhang, R.; Wu, Y. Green Construction Evaluation System Based on BIM Distributed Cloud Service. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *760*, 012055. [[CrossRef](#)]

13. Liu, Q. *Research on Risk Evaluation of Green Residential Building Construction Stage Based on Grey System Theory and Improvement CRITIC Method*; Jiangxi University of Science and Technology: Nanchang, China, 2022. (In Chinese)
14. Lin, S.; Zhang, Y. The Establishment of Green Construction Evaluation of Building Projects Based on Cloud Model. In Proceedings of the 2015 International conference on Applied Science and Engineering Innovation, Jinan, China, 30–31 August 2015.
15. GB/T 50640-2010; Evaluation standard for green construction of building. National Standard of the People's Republic of China: Beijing, China, 2010.
16. Ministry of Commerce of the People's Republic of China. *Regulations on Environmental Protection of Construction Projects*; Ministry of Commerce of the People's Republic of China: Beijing, China, 2013. (In Chinese)
17. Zeng, H. Research on Green Construction Evaluation System Based on Improved Genetic Algorithm. *J. Jilin Univ. Archit. Archit.* **2021**, *81*, 17–19. (In Chinese)
18. GB/T50378-2014; Green Building Evaluation Standard. IEA: Paris, France, 2014.
19. GB16297; Integrated emission standard of air pollutants. National Standard of the People's Republic of China: Beijing, China, 1996.
20. GB12523-2011; Technical requirements for the assessment of green transportation facilities—Part 3: Green channel. National Standard of the People's Republic of China: Beijing, China, 2011.
21. GB/T50905; Green Construction Code for Construction Engineering. National Standard of the People's Republic of China: Beijing, China, 2014.
22. Geng, D.; Zhu, H.; Chen, S. Research on Performance Evaluation of Green Supply Chain of Agricultural Products Based on G1-Entropy Weight Method. *Agric. For. Econ. Manag.* **2022**, *5*, 19–24.
23. Chai, N.; Zhou, W.; Chen, Y. Green Construction Bid Evaluation Method of Railway Based on Combination weighting and improved PCA. *J. Civ. Eng. Manag.* **2020**, *37*, 100–107.
24. Yang, W.; Liu, Q.; Deng, M. Application of G_1 Method weight Constraint Superefficiency DEA model in comprehensive evaluation of urban emergency management capacity. *J. Shaanxi Univ. Sci. Technol.* **2022**, *40*, 204–210. (In Chinese)
25. Li, X.; Zhan, J.; Lv, T.; Wang, S.; Pan, F. Comprehensive evaluation model of the urban low-carbon passenger transportation structure based on DPSIR. *Ecol. Indic.* **2023**, *146*, 109849. [\[CrossRef\]](#)
26. Liu, Z.; Chang, J.; Li, H. High Robust Estimation Method of Atmospheric Boundary Layer Height based on K-means and entropy weight method. *Acta Opt. Sin.* **2022**, *96*, 1–20. (In Chinese)
27. Khan, A.; Gong, Z.; Shah, A.A.; Haq, M. A multi-criteria decision-making approach to vulnerability assessment of rural flooding in Khyber Pakhtunkhwa Province, Pakistan. *Environ. Sci. Pollut. Res.* **2023**, *30*, 56786–56801. [\[CrossRef\]](#)
28. Yang, H.; Jiang, F.; Wu, X.; Zhao, G.; Shi, X.; Liu, G.; Wang, M. Optimizing the cutting edge geometry of micro drill based on the entropy weight method. *Int. J. Adv. Manuf. Technol.* **2023**, *125*, 2673–2689. [\[CrossRef\]](#)
29. Qin, S.; Lin, J.; Zhang, Y. Integrated energy system planning for parks based on entropy power adaptive information gap decision. *Power Grid Technol.* **2023**, *15*, 1–13. (In Chinese)
30. Huang, W.; Zhang, S.; Wang, G.; Huang, J.; Lu, X.; Wu, S.; Wang, Z. Modeling Methodology for Site Selection Evaluation of Underground Coal Gasification Based on Combination Weighting Method with Game Theory. *ACS Omega* **2023**, *8*, 11544–11555. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Wu, R.; Sun, H.; Yan, D. Flood risk evaluation of China-Pakistan economic corridor based on grid data and game theory combination of empowerment. *J. Agric. Eng.* **2021**, *37*, 145–154.
32. Li, X.; Wang, J.; Sun, C. Safety Evaluation of Steel Temporary Beam Service Status Based on the Combination Weighting-Fuzzy Model of Game Theory. *Math. Probl. Eng.* **2023**, *202*, 105–109. [\[CrossRef\]](#)
33. Jiang, Y.; Zhang, Y.; Wang, J. Evaluation of water hazard in karst tunnels based on unconfirmed measure-SPA. *People's Change* **2021**, *52*, 78–85. (In Chinese)
34. Wang, K.; Huang, T. Spearman correlation method based on trend rank. *J. Fujian Norm. Univ. (Nat. Sci. Ed.)* **2010**, *26*, 38–41. (In Chinese)
35. Zhang, R.; Tian, Y.; Li, H. Application of improved radar chart in the health evaluation model of hydraulic gate. *Mech. Ind.* **2022**, *23*, 24.
36. Cheng, B.; Fang, Y.; Peng, W.; Du, Z. Comprehensive performance evaluation of swarm intelligence algorithms based on radar map method. *J. Beijing Univ. Aeronaut. Astronaut.* **2022**, *6*, 1–14.
37. Gao, J.; Li, S.; Wu, F.; Li, W. Thermal environment evaluation of mine based on combined weighted radar map. *J. Saf. Environ* **2022**, *9*, 1–9. (In Chinese)
38. Li, Q.; Geng, B.; Li, Q.; Li, Z.; Li, L. *Green Construction Organization and Management of Large Bridges*; Yellow River Water Conservancy Press: Zhengzhou, China, 2017. (In Chinese)
39. Mallika, C.H.; Sireesha, V. An Interval-Valued Trapezoidal Intuitionistic Fuzzy TOPSIS Approach for Decision-Making Problems. *SN Comput. Sci.* **2023**, *4*, 327. [\[CrossRef\]](#)
40. Tian, C.; Song, M.; Xue, R.; Tian, J. Evaluation of air warfare control capability based on eye-movement metrics and entropy-weighted-TOPSIS. *Syst. Eng. Electron. Technol.* **2023**, *6*, 1743–1754. (In Chinese)
41. Mandal, P.; Mukhopadhyay, A.; Mukherjee, S.; Mukhopadhyay, U.; Bhattacharya, S.; Paul, S. Assessing the suitability of a reservoir site in a water-stressed area in Purulia, India, using AHP-TOPSIS. *Sustain. Water Resour. Manag.* **2023**, *9*, 1–19. [\[CrossRef\]](#)

42. Hasanzadeh, R.; Mojaver, P.; Azdast, T.; Khalilarya, S.; Chitsaz, A.; Rosen, M.A. Decision analysis for plastic waste gasification considering energy, exergy, and environmental criteria using TOPSIS and grey relational analysis. *Process. Saf. Environ. Prot.* **2023**, *174*, 414–423. [[CrossRef](#)]
43. Bi, M. Research on the Evaluation and Control of BYD Group's Financial Risk Based on Entropy TOPSIS Method. Master's Thesis, Hebei University of Geosciences, Shijiazhuang, China, 2022. (In Chinese).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.