Research on Low Carbon Bridge Evaluation System Based on CRITIC-Grey Clustering Method

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Abstract. As a core component of construction engineering, the carbon emission assessment of Bridges is crucial to achieve a green and low-carbon transition in the construction sector. In order to promote the further development of the field of bridge carbon emission assessment, this study established a low-carbon assessment system for bridge engineering in the whole life cycle by combining qualitative and quantitative analysis. The system calculates the comprehensive weight of low-carbon evaluation indicators through the subjective and objective combination of AHP-CRITIC, and then constructs a gray whitening weight function to judge the evaluation grade of low-carbon Bridges. In order to make up for the unicity of qualitative evaluation, the carbon footprint of Bridges is refined based on carbon emission factor method, and the improvement measures for low-carbon bridge construction are put forward in a targeted way, which is an important direction for the green low-carbon transformation of Bridges.

Keywords: Bridge engineering, Low carbon evaluation, Comprehensive weight, Grey clustering method, Carbon footprint

1 Introduction

In the context of global sustainable development, China has actively responded and put forward the ambitious goal of achieving "carbon peak" and "carbon neutrality", while promoting a series of measures aimed at slowing carbon emissions 1. Bridge engineering is the core component of sustainable development projects in the field of construction, and its current low-carbon impact assessment system research is still in the initial stage. Therefore, this study established the subjective and objective comprehensive low-carbon impact assessment index system for Bridges, and calculated the carbon footprint of bridge engineering throughout its life cycle, so as to take targeted measures to reduce the sustainable emission of Bridges.

By dividing the whole life cycle of a bridge into five stages, Liu Muyu and other scholars can be used as a basic means to quantify the cost of the environmental impact of the bridge life cycle, and can be applied to the comprehensive assessment of the environmental impact of bridge engineering .Based on the LCA theory, Zhang Tianchen evaluated the bridge emission reduction rate and membership degree, and put forward the relevant factors affecting the bridge carbon emission [2].Li Xiaojiao

W. Nie et al. (eds.), *Proceedings of the 2024 6th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2024)*, Atlantis Highlights in Engineering 37,
https://doi.org/10.2991/978-94-6463-726-7_47

established a carbon footprint measurement model for four stages of the bridge's life cycle. Visualize the control effect and precisely specify the next carbon emission control target[3].In order to quantify the carbon emission index of railway bridge construction to achieve green and low-carbon optimization and upgrading, Li Sihui et al. conducted an in-depth study. A set of carbon emission calculation framework for railway bridge construction period is established. The carbon emissions of segwise prefabricated continuous rigid frame bridge and full-hole prefabricated simple supported beam bridge are compared, and the feasible suggestions to reduce the carbon emissions of railway bridge during construction are put forward [4].Zhang Zhenhao and his team carefully calculated the carbon emissions of T-beam bridge during construction and built a carbon emission model of bridge during physical and chemical phase. The error of carbon emission calculation model of T-beam bridge is effectively reduced [5], In view of the problems in the complex application scenarios in the construction stage, Zhang Shengli proposed that the carbon emission monitoring system based on the construction site clearly presents the carbon emission distribution of each branch and item of the construction site is of great significance to achieve the "double carbon" goal in the construction field[6].

Based on this, this paper takes the whole life cycle stage of the bridge as the research object. In view of the complexity and opacity of its evaluation indicators, a comprehensive calculation method of subjective and objective weight based on AHP-Critic is proposed, and the Analytic Hierarchy Process (AHP) and CRITIC methods are comprehensively applied to calculate the weight in a more objective and scientific way. On this basis, a grey fuzzy clustering model is constructed to achieve the fine grade evaluation of Bridges. Taking Changxing Bridge as an example, the feasibility of this method in practical engineering application is verified. The aim is to provide feasible insights, suggestions and references for low-carbon construction in the future under the dual-carbon background.

2 Qualitative Evaluation Model

2.1 Build a Low-Carbon Bridge Index System

According to the literature investigation and summary, this study takes the whole life cycle process of Bridges as the object. It is divided into four stages, namely, planning stage, construction stage, operation stage and abandonment stage, which are used as the carbon emission measurement boundary of low-carbon Bridges. The index was initially screened through expert letter consultation, and then the reliability and validity of the questionnaire was tested based on spss software. The results showed that the KMO value of each stage was greater than 0.5 and the Sig value was 0.000, which was lower than the significant level 0.05, indicating that the model was significant and factor analysis could be performed. According to the component matrix after rotation and the explanation rate of total variance greater than 80%, it is appropriate to modify the indicators of each life cycle stage. Finally, through factor analysis and expert opinions, the indicators are determined as 19 indicators of low-carbon bridge evaluation system as shown in Figure 1.

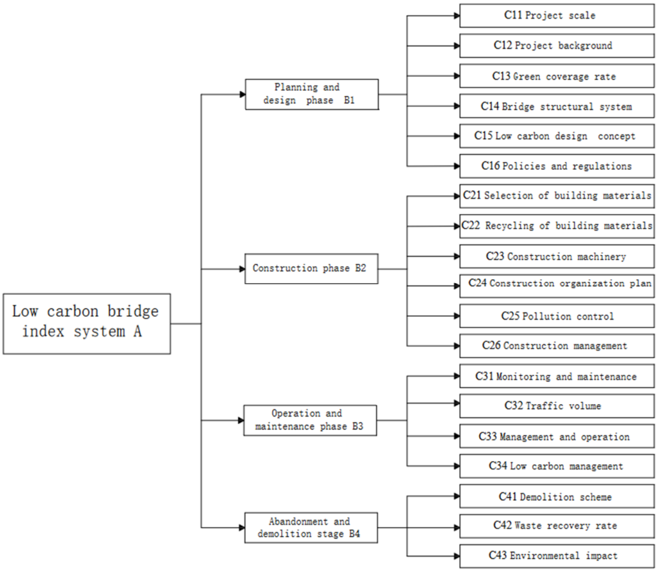

Fig. 1. Evaluation index system of low-carbon bridge

2.2 Objective Weight Calculation of CRITIC Method

The accurate calculation of index weight plays an important role in risk assessment. The results obtained by using subjective weight calculation or objective weight calculation method alone are not comprehensive. In order to fully take into account the subjective will of the evaluators and the objective importance of the indicators, this paper adopts the method of combining objective CRITIC and hierarchical analysis to determine the index weight of low-carbon Bridges.

Data Standardization Processing. There are k low carbon bridge evaluation indicators x1, x2,... xk. Invite relevant experts in the field of bridge engineering to evaluate the indicators. xij' is used to represent the score of the J-th expert for the I-th indicator, and the corresponding low-carbon evaluation matrix X' is formed, and the standardized matrix X is obtained.

Determine the Objective Weights of Indicators.

(1) Determine the indicator variability

In the CRITIC method, index variability is measured based on standard deviation. The difference of index values is positively correlated with standard deviation, and the fluctuation is more significant when standard deviation increases. The stronger the evaluation strength of the indicator itself, the more weight should be assigned to the indicator [7].

$$\begin{cases} \bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \\ S_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)}{n-1}} \end{cases} \tag{1}$$

S_j represents the standard deviation of the JTH index.

(2) Determine index correlation

If an indicator has a high correlation with other indicators, it indicates that it has less contradiction with other indicators, reflecting that they convey similar information to a greater extent. This means that there may be some duplicate information in the evaluation, thus weakening the evaluation impact of this indicator to some extent. Therefore, the weight assigned to this indicator should be moderately reduced to more accurately reflect its actual importance in the overall evaluation. The calculation formula is shown in equation (2)

$$R_j = \sum_{i=1}^{p}(1 - r_{ij}) \tag{2}$$

r_{ij} represents the correlation coefficient between evaluation indicators i and j

(3) Determine the indicator allocation weight

The amount of information is proportional to the importance of the evaluation index, and is also positively correlated with the assigned weight [8], Formula (3) is the calculation formula of index information.

$$C_j = S_j \sum_{i=1}^{p}(1 - r_{ij}) = S_j \times R_j \tag{3}$$

(4) The objective weight calculation formula is:

$$W_j = \frac{C_j}{\sum_{j=1}^{p} C_j} \tag{4}$$

2.3 AHP-CRITIC Comprehensive Empowerment

Firstly, the subjective weight wi is calculated by constructing a judgment matrix based on analytic hierarchy process [8], The weight of indicators is modified based on CRITIC method. The two are combined for index weighting. The indexes of the low-carbon bridge evaluation system have a total of k categories, and the subjective evaluation weights of various low-carbon indexes are obtained by using the analytic hierarchy process $w_i = (w_i^1, w_i^2, \ldots\ldots, w_i^k)$, $\sum_{i=1}^{k} w_i = 1$.The objective weight of indicators obtained based on CRITIC method is $w_j = (w_j^1, w_j^2, \ldots\ldots\ldots, w_j^k)$, $\sum_{i=1}^{k} w_j = 1$, Based on the subjective and objective weight calculation results of CRITIC and AHP, the comprehensive weight of indicators is calculated according to formula (5) based on the multiplier synthesis normalization method.

$$W = \frac{w_i w_j}{\sum_{i,j=1}^{n} w_i w_j} \tag{5}$$

2.4 The Grey Fuzzy Evaluation Model is Constructed

According to the incompleteness and uncertainty of the information required by the evaluation indicators, considering that the low-carbon evaluation of Bridges involves many influencing factors, it is a typical grey system. Based on this, this paper determines the grey class of the cluster object based on the improved triangular whitening weight function, and then carries out low-carbon evaluation on the whole life cycle process of the bridge. As shown in Table 1, according to the characteristics of bridge engineering, the evaluation gray is divided into five levels, with values of 1, 3, 5, 7 and 9 respectively. According to the green and low-carbon evaluation in the construction field, it is divided into five levels, including basic level, one star, two star, three star and five star [8].

Table 1. Low carbon classification of Bridges

Evaluation level	Qualitative declaration
Basic level	Carbon emissions are not up to standard, and low-carbon construction requirements are not met
One level	Basically reach the level of low-carbon construction, less consideration of carbon emission factors, and limited energy-saving and emission reduction effects
Second level	The low carbon construction level is medium, and the influencing factors of carbon emissions are considered, and certain energy-saving and emission reduction effects are achieved
Three-level	The low carbon construction level is good, and the influencing factors of carbon emissions are considered more, and good energy-saving and emission reduction effects are achieved
Band four	The low carbon construction level is very good, the influence factors of carbon emissions are considered comprehensively, and good energy-saving and emission reduction effects are achieved

(1) Index grey classification

According to the gray number s required by engineering evaluation, the value range of index j is divided into s cells

$$[a_1, a_2], \ldots . [a_{k-1}, a_k], \ldots . [a_{s-1}, a_s][a_s, a_{s+1}]$$

(2) The triangular whitening weight function is constructed

For $(a_k + a_{k+1})/2$ belonging to the k grey class $f_j^k(x_{ij}) = 1$, Join the point $((a_k + a_{k+1})/2$, 1) with the starting point of the *k*-1 interval a_{k-1} and the end point of the *k*+1 gray class a_{k+2}.The triangular whitening weight function of j index in k gray class is obtained $f_j^k(x_{ij})$.*j*=1,2,….*m*.*k*=1,2,….,*s*.For $f_j^1(x_{ij})$ and $f_j^s(x_{ij})$, The j index access field can be extended left a_0 and right a_{s+2} to sum respectively, Figure 2 shows the image of the triangular whitening weight function.

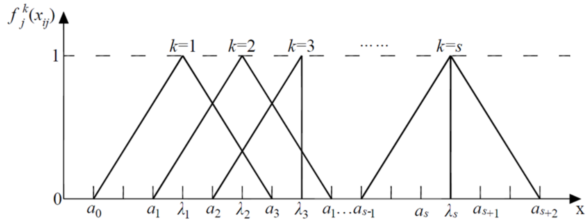

Fig. 2. Image of triangle whitening weight function

(3)

$$f_j^k(x_{ij}) = \begin{cases} 0 & x \notin (a_{k-1}, a_{k+2}) \\ \dfrac{x - a_{k-1}}{\lambda_k - a_{k-1}} & x \in (a_{k-1}, \lambda_k) \\ \dfrac{a_{k+2} - x}{a_{k+2} - \lambda_k} & x \in (\lambda_k, a_{k+2}) \end{cases} \tag{6}$$

Expression of whitening weight function for the observed value x

(4) The comprehensive clustering coefficient is calculated

$$\sigma_i^k = \sum\nolimits_{j=1}^{m} f_j^k(x_{ij}) \cdot \eta_j \tag{7}$$

Clustering coefficient vector of object *i*:

$$\sigma_i = (\sigma_i^1, \sigma_i^2, \ldots \sigma_i^s) = (\sum\nolimits_{j=1}^{m} f_j^1(x_{ij}) \cdot \eta_j, \ldots\ldots \sum\nolimits_{j=1}^{m} f_j^s(x_{ij}) \cdot \eta_j) \tag{8}$$

Where, $f_j^k(x_{ij})$ is the membership degree of object i belonging to grey class k under index j, and s is the number of grey classes and η_j is the comprehensive weight of the index.

(5) The clustering coefficient matrix is obtained

$$\sum = (\sigma_i^k) = \begin{bmatrix} \sigma_1^1 & \cdots & \sigma_1^s \\ \vdots & \ddots & \vdots \\ \sigma_n^1 & \cdots & \sigma_n^s \end{bmatrix} \tag{9}$$

Set $\max\limits_{1 \le k \le s} \left\{ \sigma_i^k \right\} = \sigma_i^{k*}$,Object i belongs to grey class k^*

3 Quantitative Measurement Model

In this study, the bridge carbon emission was calculated by carbon emission factor method. Due to the small carbon emissions in the design stage, which have little impact on the results, and the clear and fixed sources of carbon emissions, carbon emissions in the design stage usually account for 10% of the carbon emissions in the whole life cycle[9].Therefore, only the carbon emissions in the construction phase, operation phase and demolition phase are calculated and analyzed.

Carbon emission factor method is used for quantitative calculation. Carbon emission calculation in construction stage mainly includes carbon emission of material production and transportation, and energy emission of mechanical construction. The carbon emission calculation of bridge material production stage is standardized [10]:

$$C_j = \sum\nolimits_i Q_i \times a_{Qi} \tag{10}$$

Where, Q_i denotes the usage of each building material and a_{Qi} denotes the carbon emission factor of each building material.

The carbon emission in construction is mainly the carbon emission generated by the fossil energy used in the mechanical operation, Carbon emissions from the transport of building materials and the use of machinery are combined as:

$$C_s = \sum\nolimits_i D_i \times a_{Qi} + \sum\nolimits_i M_i \times a_{Mi} \tag{11}$$

In the formula, D_i is the distance of the Class i means of transport and a_i is the carbon emission factor of the Class i means of transport. M_i is the number of Class i construction machinery and equipment, and is the carbon emission factor of Class i construction machinery and equipment.

In summary, the carbon emission in the bridge construction stage is,

$$C_1 = C_j + C_s \tag{12}$$

The main carbon emission in the operation and maintenance stage mainly comes from the traffic flow during the operation period. Since the Changxing Great Bridge is under construction, the traffic volume during the operation period of the bridge is calculated based on the data of Zhejiang Changxing Statistical Yearbook. Standardize the amount of traffic during operations to calculate carbon emissions from their energy consumption.

The carbon emission in operation and maintenance stage is:

$$C_2 = \sum_i N_i \times a_{Ni} \tag{13}$$

Where N_i is the operating mileage of Class i vehicles and a_{ni} is the carbon emission factor of Class i vehicles.

The carbon emission of the abandoned and dismantled stage consists of two parts, namely, the use of construction tools and the waste gas recovery of building materials. Since the cable-stayed bridge is in the operation period, the carbon emission of the abandoned and dismantled stage is quantified in the form of prediction. The utilization of recyclables is considered in the construction stage according to the recovery coefficient of building raw materials. In formula (2), the carbon emission during transportation is not affected by the recovery coefficient 11.For the treatment of non-recyclable materials, the formula summarized by Liu Yan [12]was adopted to standardize the carbon emission in the demolition stage with 8.95% of the mechanical carbon emission in the construction process.

4 Project Overview

The Cable-stayed bridge under construction is located in Changxing County, Huzhou City, mainly across the North Huancheng Road and Yangjiapu Channel. As shown in Figure 3, The main bridge adopts (50.7+94+240+94+50.7) m double-tower concrete cable-stayed bridge with a total length of 529.4m. The full length of the main beam adopts prestressed concrete box girder with a single box and single chamber section. The bridge floor width is 14.4m, the full width of the box girder is 16.2m, and the beam height at the center is 3.8m.

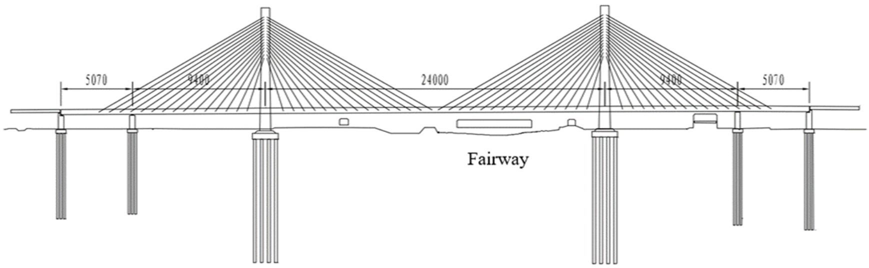

Fig. 3. Cable-stayed bridge type diagram of Changxing Large Bridge

The quantity of main building materials and machinery used in the construction phase of this project is shown in Table 2 and 3 below

Table 2. Quantity table of main building materials

Type	Unit	Quantity
Hot rolled round steel bar HPB300	t	113.90
Hot rolled round steel bar	t	729.53
Hot rolled ribbed bar HRB400	t	8090.83
Gravel	t	126.70
Ordinary Portland cement PO 42.5	t	616.17
Steel strand	t	480.50
Ordinary Portland cement PO 42.5	t	1079.62
Section steel	t	123.73
Hot rolled ribbed bar HRB500	t	138.11

Table 3. Main machinery quantity table

Type of machinery	Unit	Quantity
Ac arc welding machine 32kV·A	Stage crew	9175.76
Mud tanker 5000L	Stage crew	5277.02
Crawler electric crane 5t	Stage crew	7701.35
Mud pump 100mm	Stage crew	2259.00
Woodworking circular saw machine 500mm	Stage crew	14762.4
Rotary disk drilling machine 1500mm	Stage crew	1826.47
Crawler crane 15t	Stage crew	1853.01
Rotary disk drilling machine 2000mm	Stage crew	888.91
Prestressed reinforcement drawing machine 3000kN	Stage crew	2047.52
Electric winch - single cylinder slow speed 50kN	Stage crew	2766.14
Dump truck 15t	Stage crew	389.29
Truck 4t	Stage crew	633.16

5 Model Application and Analysis

5.1 Grey Fuzzy Qualitative Evaluation Analysis Based on CRITIC Method

Index Weight Calculation. Fifteen experts from different units in the bridge field were invited to evaluate and score the importance of low-carbon bridge indicators. With 1, 3, 5, 7, 9 as the five grades of the score, respectively, indicating not important, more important, slightly important, important, very important. 2, 4, 6, 8 as the middle scores. The score results are used as the basic data for the weight calculation of critic method. The AHP method is used to calculate the weight based on the expert survey, the relative importance is scored based on the 1-9 scale method to form the judgment matrix, and the comprehensive weight is calculated based on the multiplier normalization method. The critic method of formula (1)-(4) is used to calculate the objective weight of indicators, and the subjective weight of indicators is calculated based on AHP. Formula (5) is used to calculate the comprehensive weight. The subjective and objective weights and the comprehensive calculation results are shown in Table 4 below.

Table 4. Itemized and comprehensive weight calculation results (Take floor B1 as an example)

Target layer	First-order index	First-order index weight	Second level index	Critic	AHP	Synthesis weight
A	B1	0.06	C11	0.080	0.0263	0.0421
			C12	0.056	0.0150	0.0170
			C13	0.074	0.0026	0.0038
			C14	0.054	0.0096	0.0104
			C15	0.061	0.0048	0.0059
			C16	0.065	0.0017	0.0022

Evaluation of Grey System Theory.

(1) Ten experts in the field of Bridges were invited to score 0-9 low-carbon evaluation impact indicators for the bridge, and the low-carbon evaluation matrix was formed, as shown in D:

$$D=\begin{bmatrix}
7&7&7&6&7&4&4&4&5&8&7&8&7&7&8&3&3&7&8\\
7&8&6&7&8&6&4&3&5&8&8&8&7&7&8&5&1&7&7\\
7&9&6&8&8&7&3&5&7&9&6&8&5&6&9&5&1&8&7\\
7&9&7&5&6&7&3&3&7&7&7&7&6&5&9&5&2&7&9\\
8&7&8&6&6&7&5&5&8&7&8&7&5&6&8&4&2&7&9\\
8&6&7&6&5&8&5&4&8&8&8&7&5&6&8&5&3&7&7\\
7&7&7&7&4&6&3&4&6&8&8&7&6&6&9&3&1&8&7\\
8&8&7&7&4&7&5&2&7&8&7&8&6&7&9&3&3&9&8\\
5&8&6&6&5&6&3&2&8&7&7&8&6&6&9&3&2&7&8\\
8&7&8&6&5&6&5&3&7&7&6&8&5&7&8&5&3&8&8
\end{bmatrix}$$

(2) Based on formula (6) and the above matrix data, the whitening weight function value of the project instance is calculated and determined, as shown in table 5. Taking criterion layer B1 as an example, the index evaluation weight of Changxing Superbridge cable-stayed bridge in the planning and design stage is obtained as shown in the table.

Table 5. Whiteness weight function of low carbon index evaluation for cable-stayed bridge of Changxing Large Bridge (Take floors B1-C11 to C12 as an example)

Criterion layer	K=9	K=7	K=5	K=3	K=1
C11	0.084	0.854	0.059	0.003	0.000
C12	0.382	0.401	0.217	0.000	0.000

(3) According to formula (7)-(9), the clustering coefficients of criterion layer B1-B4 and target layer A are calculated to obtain the construction grade of Changxing Great Bridge, and the results are shown in Table 6.

Table 6. Levels of each evaluation dimension

Evaluation dimension	K=9	K=7	K=5	K=3	K=1	Rating
B1	0.016	0.051	0.013	0.001	0.001	Three-level
B2	0.133	0.165	0.167	0.107	0.000	Second level
B3	0.066	0.078	0.022	0.010	0.000	Three-level
B4	0.024	0.026	0.018	0.014	0.008	Three-level
A	0.091	0.113	0.092	0.058	0.001	Three-level

According to the comprehensive clustering coefficient, the low carbon evaluation grade of the project is three stars. spssau software is used to check the fuzzy comprehensive operator, and the membership degree of the evaluation set is 0.011, 0.130, 0.220, 0.358 and 0.281, respectively. According to the principle of maximum membership, the low carbon grade of the Changxing Bridge construction project is three stars. It has a good effect of energy saving and emission reduction, and the impact of carbon emissions is considered more in the whole life cycle process.

5.2 Quantitative Measurement and Analysis of Carbon Footprint

Based on the established carbon footprint calculation model, the carbon emission of the cable-stayed bridge of Changxing Large Bridge was quantitatively analyzed. The total carbon emission was 8.02×104t. As shown in Figure 4, the carbon emission ratio of each stage of its life cycle was shown, among which the construction stage accounted for the largest carbon emission, reaching 44.9%. Operation and maintenance phase and construction phase accounted for 87.4%. Planning, design and abandonment account for only 10% and 2.6% respectively.

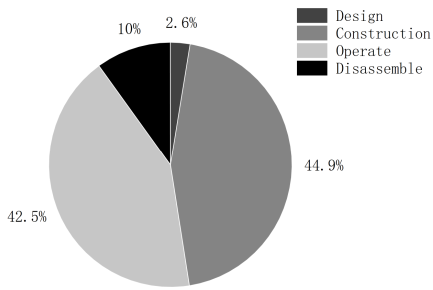

Fig. 4. Carbon emission ratio of each stage of the whole life cycle

Figure 5 shows the specific components of carbon emissions at each stage. It can be seen that the carbon emissions during operation and maintenance and construction are much higher than the other two stages. This section of carbon emissions recommends optimizing traffic management, encouraging the use of low-carbon modes of transport, and promoting green transport and urban planning to reduce the burden on the transport system. The construction phase and the demolition phase recommend the use of green recyclable building materials, the optimization of logistics, and the use of more efficient and environmentally friendly machinery to reduce the carbon footprint. The planning and design stage can improve efficiency by optimizing the bridge structure, considering integrated energy efficiency, and by using information modeling tools such as BIM, thus avoiding unnecessary modifications and additional carbon emissions.

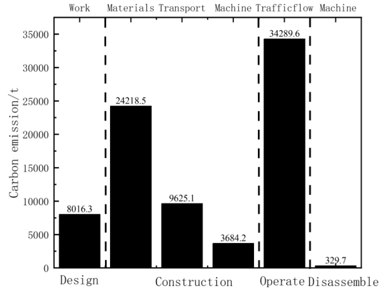

Fig. 5. Carbon emission composition at each stage

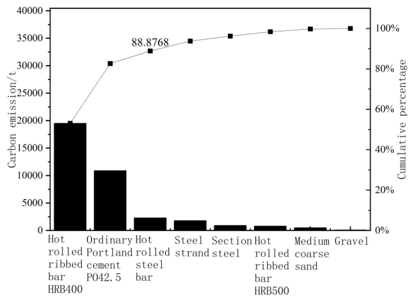

Fig. 6. Pareto diagram of material carbon emission during construction phase

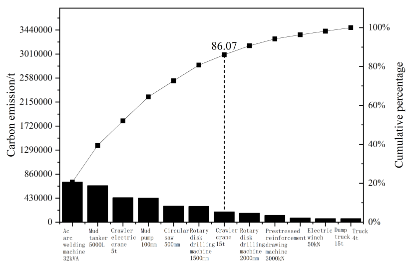

Fig. 7. Pareto diagram of mechanical carbon emission during construction

Figure 6 shows the carbon emissions of materials used in the bridge structure during the construction phase, in which the cumulative carbon emissions of hot-rolled ribbed rebar and ordinary Portland cement account for 88.87% of the total. Sustainable materials can be considered to replace traditional high-carbon emission materials. For example, some polymeric materials can be used to replace traditional cement-based materials, and recyclable steel can be used to reduce carbon emissions and improve material performance.

Figure 7 shows the Pareto diagram of carbon emission of various machinery in the construction stage, among which 32kV·A AC arc welding machine produces relatively high carbon emission. If feasible, it is recommended to use more environmentally friendly welding technology or equipment. Implement monitoring and data tracking mechanisms to continuously assess and improve the level of carbon emissions from equipment use to further reduce carbon emissions.

6 Conclusion

(1) Taking the whole life cycle construction process of bridge as the research object, an evaluation model suitable for low-carbon construction is constructed. The model uses the CRITIC method to correct the single subjective weight, which enhances the accuracy and rationality of the weight calculation results. The grey clustering method was used to evaluate the low-carbon grade of the bridge, and the maximum membership rule was used to verify the model.

(2) The carbon emission factor method was used to calculate the quantitative carbon footprint of the bridge, and the carbon emission during the whole life cycle process of the bridge was analyzed in detail.

(3) Although this study has made a relatively comprehensive assessment and analysis of the carbon emissions of the bridge during its whole life cycle, due to the complexity of the bridge-related data and the difficulty in collecting them.Further research is needed to build a more accurate model.

References

1. Zhang Weining, Yin Mingkai, Meng Zifan. Research on requirements and development of low-carbon buildings in the context of Low-carbon cities -- A case study of Nanjing [J]. Architecture in Anhui, 2024, 31(11):96-97+133.
2. Zhang Tianchen. Research on Evaluation system of Low-carbon Bridge based on Whole Life cycle [D]. China University of Mining and Technology, 2018.
3. Li Xiaojiao. Research on carbon emission calculation of Long span suspension Bridge in Mountain area [D]. Southwest Jiaotong University, 2020.
4. Li Sihui, Li Yidi, Huang Shiqing. Comparative analysis of carbon emission of different prefabrication schemes in railway bridge construction period [J/OL]. Railway standard Design:1-9 [2024-01-13].
5. Zhang Zhenhao, TAN Rongping, Fang Ming. Establishment and Analysis of carbon emission Model of T-Beam Bridge during Construction [J]. Journal of Changsha University of Science and Technology (Natural Science Edition), 2018, 15(03):71-78.

6. Zhang Shengli. Research on carbon emission monitoring System in Building construction stage [J/OL]. Railway Construction Technology, 1-4 [2024-10-18].
7. Chen Ruihan, LI Le, WU Jianpeng et al. Research on Performance Degradation Evaluation Method of Special Vehicle Integrated Transmission Hydraulic System [J]. Equipment Management and Maintenance, 2023, (19):47-53.
8. Wu Yuanjin, LIU Yongsheng, Yin Long et al. Research on low-carbon evaluation of Railway Tunnel construction Process based on grey clustering [J]. Journal of Xi 'an University of Technology, 2023, 39(03):353-359.
9. Ma Jiaxing, Jiang Jiannan, Xie Hanjun et al. Lifetime carbon emission calculation Model of Cable-stayed Bridge [J]. Journal of Tianjin University (Natural Science and Engineering), 2024, 57(01):31-41.
10. Zhou Lingyun, Wang Yuhang, Ma Jun, et al. Research on carbon emission estimation and emission reduction strategy of railway logistics base based on Whole Life Cycle evaluation [J]. Railway transportation and economy, 2024, 46(10):25-33.
11. Wei X. Carbon footprint assessment of mountain Bridges based on full life cycle [J]. Transportation energy saving and Environmental Protection., 2023, 19(03):117-122.
12. Liu Yan. Evaluation model of building carbon emission based on whole life cycle [D]. Dalian University of Technology,2015.