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ARTICLE

Research on Post Evaluation of Mechanized Construction in Power Transmission and Transformation Projects with Game Theory and Fuzzy Grey Projection

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ABSTRACT: Currently, the international economic situation is becoming increasingly complex, and there is significant downward pressure on the global economy. In recent years, China's infrastructure sector has experienced rapid growth, with the structure of its power engineering business gradually shifting from traditional infrastructure construction to more diversified areas such as production and operation, as well as emergency repairs. As a result, the transformation of mechanized construction in power transmission and transformation projects has become increasingly urgent. This article proposes a post-evaluation model based on game theory to improve comprehensive weighting and fuzzy grey relational projection sorting, which can be used to evaluate the optimal mechanized construction scheme for power transmission and transformation projects. The model begins by considering the entire lifecycle of power transmission and transformation projects. It constructs a post-evaluation index system that covers the planning and design stage, on-site construction stage, operation and maintenance stage, and the decommissioning and disposal stage, with corresponding calculation methods for each index. The fuzzy grey correlation projection sorting method is then employed to evaluate and rank the construction schemes. To validate the model's effectiveness, a case study of a power transmission and transformation project in a specific region of China is used. The comprehensive benefits of three proposed mechanized construction schemes are evaluated and compared. According to the evaluation results, Scheme 1 is ranked the highest, with a membership degree of 0.870945, excelling in sustainability. These results suggest that the proposed model can effectively evaluate and make decisions regarding the optimal mechanized construction plan for power transmission and transformation projects.

KEYWORDS: Mechanized construction; power transmission and transformation projects; game theory; fuzzy grey relational projection sorting

1 Introduction

Currently, the international economic landscape is becoming increasingly complex, and there is significant downward pressure on the global economy. In recent years, China's infrastructure sector has experienced rapid growth, and the structure of its power engineering business has gradually evolved from traditional infrastructure construction to a more diversified range of services, including production, operation, maintenance, and emergency repairs [1]. The central challenge now is how to shorten the construction timeline of power transmission and transformation projects under the dual carbon target, while ensuring environmental protection, on-site construction safety, and the economic benefits of the project. This issue has become an urgent topic that needs thorough investigation and resolution within the current power grid context. Consequently, the transformation of mechanized construction in power transmission and transformation projects is increasingly critical [2,3].

Compared to traditional manual construction, mechanized construction offers more diverse forms and is essential for achieving the long-term goals of mechanization replacement, automation reduction, and intelligent, unmanned construction in power transmission and transformation engineering [4,5]. On 7 February, 2023, the State Grid Corporation of China issued the "Implementation Opinions on Fully Promoting Mechanized Construction in Power Transmission and Transformation Engineering" (State Grid Infrastructure [2023] No. 6), emphasizing that mechanized construction represents a profound shift in the power grid construction method and is the only viable path to building an internationally competitive power grid [6]. This highlights the growing importance of mechanized construction in the industry.

However, current evaluations of mechanized construction's economic benefits often rely solely on individual indicators such as project cycle time or cost savings. These evaluations fail to account for the impact of other factors like construction quality, safety, environmental effects, and subsequent maintenance on economic performance [7–9]. To explore the full economic and social benefits and provide theoretical guidance for the full life cycle of power transmission and transformation projects, a comprehensive and effective multi-index evaluation method is essential for the development of power grid engineering [10–12]. Thus, assessing comprehensive benefits and sustainability within the power system has become a key area of research [13,14].

In recent years, scholars have developed multi-index evaluation systems for mechanized construction in power transmission and transformation projects, considering factors such as economy, energy consumption, and environmental impact. Qin proposed a comprehensive evaluation model based on AHP and VPRS, determining the risk level of construction projects to conduct a thorough analysis of safety risks and providing guidance for safe project execution [15]. Li et al. created a TTP evaluation index system, considering technical, economic, and social benefits to assist in precise investment decisions for transmission construction projects [16]. Sun et al. recognized that investment in power transmission projects is both a profit-oriented and public service activity. They established a job evaluation index system and employed fuzzy hierarchical evaluation methods to develop a fuzzy comprehensive evaluation model for power transmission and transformation projects [17]. Yin and Hou analyzed ultra-high voltage transmission and transformation engineering, proposing a grey evaluation model for construction quality by combining subjective and objective weighting methods [18]. Zhou et al., aligning with China's "dual carbon" strategic goals and the planning of new energy systems, created a comprehensive evaluation system based on the SMART principle for energy storage as a regulatory resource [19]. Liu et al. developed a system to evaluate the efficiency of multi-business integration in power grid projects, focusing on operational time and functional types [20].

For the successful construction and high-quality development of power transmission and transformation projects, mechanized construction must be applied throughout their life cycle. Post-evaluation plays a crucial role in advancing this development. However, most studies focus on only a few indicators, often neglecting social benefits, safety, and stability. Additionally, existing evaluation methods often struggle to balance subjectivity and objectivity, leading to less scientific and reasonable results. Therefore, this paper introduces several innovative aspects:

(1) This paper develops a comprehensive post-evaluation index system that spans the full life cycle of mechanized construction in power transmission and transformation projects. It includes the engineering planning, design stage, on-site construction stage, operation and maintenance stage, and shutdown disposal stage, with specific calculation methods for each index.

(2) A case study of a power transmission and transformation project in a certain location in China is used. Various data preprocessing methods are applied, and the AHP and entropy weight methods are employed to determine the weights of the indicators. Game theory is then used to optimize the combination of the two weights, determining the final indicator weights.

(3) The Fuzzy Grey Relational Projection (FGRP) method is used to comprehensively evaluate mechanized construction schemes for power transmission and transformation projects. Scheme 1, with a membership degree of 0.870945, performs the best in terms of sustainability. These results indicate that the proposed framework can scientifically guide decisions on mechanized construction plans, offering valuable insights for the sustainable development of diversified businesses in the future of mechanized power transmission and transformation projects.

In this paper, Section 2 introduces the post evaluation index system for the full life cycle of mechanized construction in power transmission and transformation projects. Section 3 outlines the comprehensive evaluation method based on game theory and fuzzy grey projection. Section 4 presents empirical analysis using real data. Section 5 concludes the paper.

2 Design of Post Evaluation Index System for the Full Life Cycle of Mechanized Construction in Power Transmission and Transformation Projects

2.1 Application of Mechanized Construction

Currently, mechanized construction has been widely applied throughout the entire life cycle of transmission and transformation projects, covering various stages such as project planning and design, on-site construction, operation and maintenance, and decommissioning and disposal.

2.1.1 Engineering Planning and Design Stage

In the project planning and design stage, mechanized construction can assist engineers in the planning and design of transmission and transformation projects by using various software and simulation tools. For example, as shown in the Fig. 1 [20]:

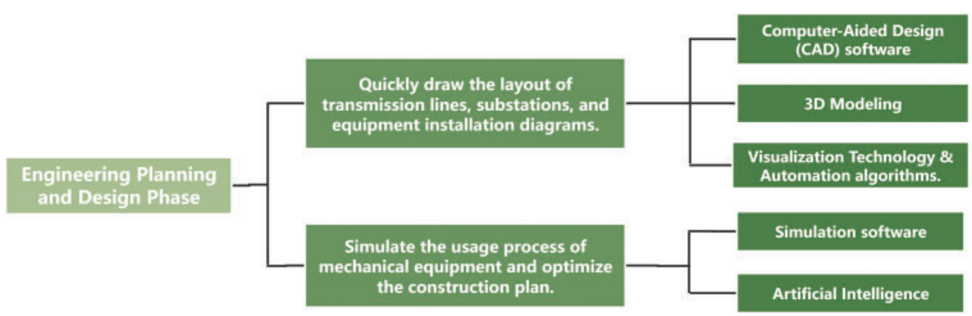

Figure 1: Example of mechanized construction application in the project planning and design stage

2.1.2 On-Site Construction Stage

In the on-site construction stage, mechanized construction is widely applied to various construction tasks, such as foundation construction, line installation, equipment installation, and more. Specifically, as shown in Fig. 2.

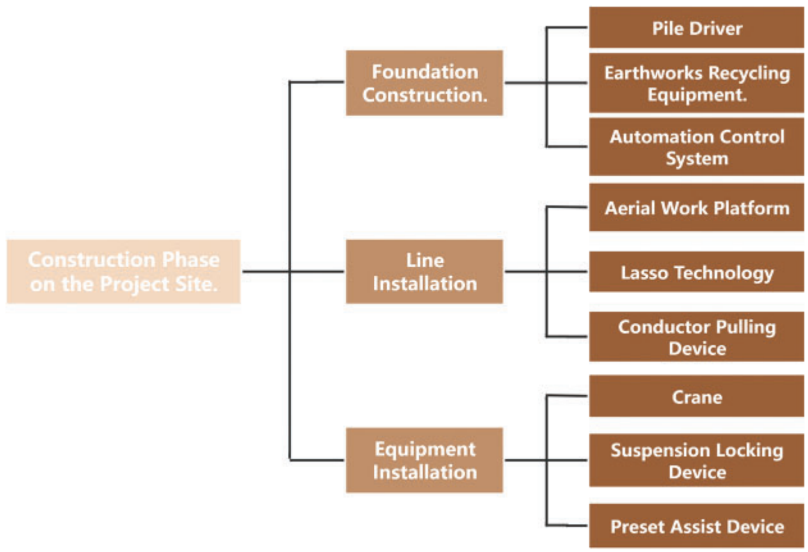

Figure 2: Example of mechanized construction application in the on-site construction stage

2.1.3 Operation and Maintenance Stage

In the operation and maintenance stage, mechanized construction for transmission and transformation projects is primarily applied to tasks such as inspections and patrols, equipment maintenance and repair, line inspections and maintenance, and more. Specifically, as shown in the Fig. 3.

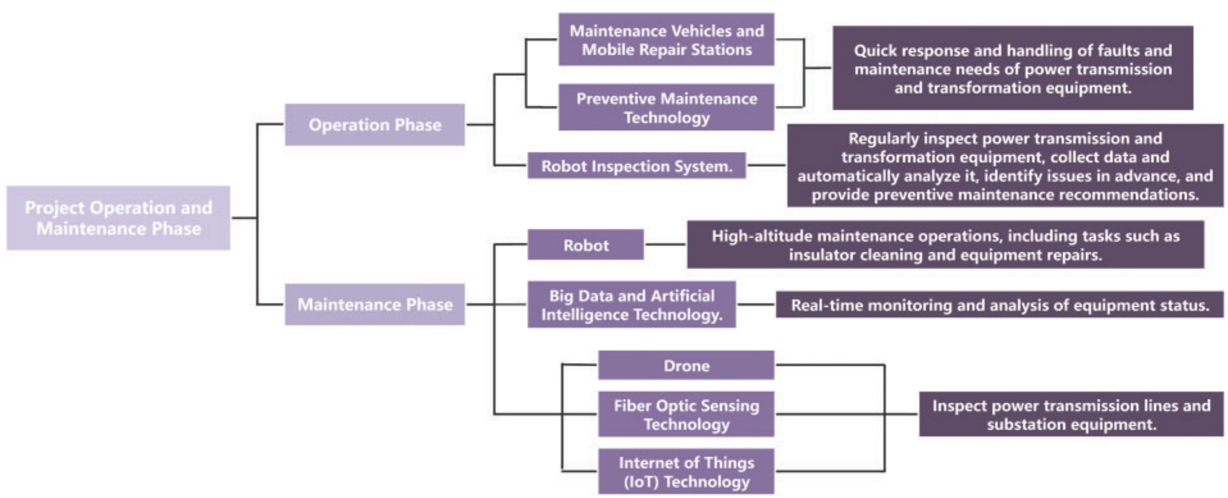

Figure 3: Example of mechanized construction application in the operation and maintenance stage

2.1.4 Decommissioning and Disposal Stage

In the decommissioning and disposal stage, mechanized construction for transmission and transformation projects is primarily applied to tasks such as equipment dismantling, facility cleaning, soil remediation, waste disposal, and more. Specifically, as shown in the Fig. 4.

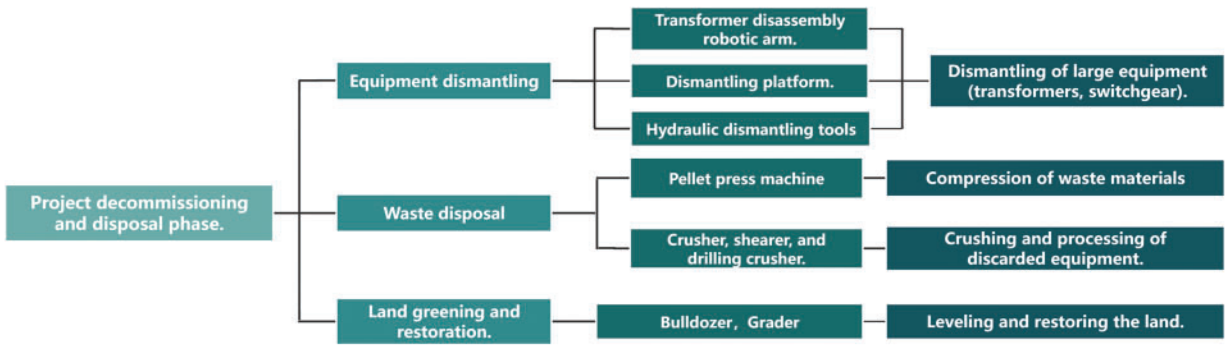

Figure 4: Example of mechanized construction application in the decommissioning and disposal stage

2.2 Establishing the Full Life Cycle Post-Evaluation Indicator System

This paper, centered around the full life cycle, breaks away from the traditional manual construction business model by making full use of mechanized construction. While ensuring effective operation and optimization of the project, it involves the planning, design, and analysis of each phase. With reference to the current post-evaluation indicator system for power transmission and transformation projects under the dual-carbon background, and considering the characteristics of mechanized construction, the paper outlines four stages: Engineering Planning and Design Stage, On-site Construction Stage, Operation and Maintenance Stage, and Decommissioning and Disposal Stage. It identifies the economic indicators (primarily reflecting the economic benefits of the project) and decision-making indicators (mainly reflecting the social, environmental, and technical benefits of the project) for each stage [21]. The mechanized construction post-evaluation indicator system for power transmission and transformation projects over the full life cycle is then constructed. The quantitative standards for economic indicators are based on engineering practices, with major valuation criteria such as labor costs, material costs (including fuel), and machinery costs (including operators). The quantitative standards for decision-making indicators are primarily determined through anonymous reviews by industry experts, and the final indicator system is shown in Table 1. The meanings of variables in Table 1 can be found in Table 2.

Table 1: Post-evaluation indicator system for the full life cycle stages

Stage	Indicator classification	Indicator elements	Quantitative indicator model	Specific calculation formula for the model
Project planning and Design stage	Economic indicators	Equipment investment cost	$C_{EI} = C_{PUR} + C_{TRAN} + C_{INS} + C_{DEB} + C_{OTHER}$	$C_{PUR} = \sum_{i=1}^{n} P_i \times Q_i$ $C_{TRAN} = \sum_{i=1}^{n} T_i \times D_i$ $C_{INS} = \sum_{i=1}^{n} I_i \times H_i$ $C_{DEB} = \sum_{i=1}^{n} ED_i \times HW_i$ $C_{OTHER} = C_{insurance} + C_{tax} + C_{measure}$
	Decision-making indicators	Construction process management	This indicator is based on the quantification of expert ratings and multi model methods, with a rating range of 1–10 points (1 point: very dissatisfied, 10 points: very satisfied). $S_{QM} = 40\%S_{FSPP} + 30\%S_{S\&D} + 30\%S_{CP}$	

(Continued)

Table 1 (continued)

Stage	Indicator classification	Indicator elements	Quantitative indicator model	Specific calculation formula for the model
On-site construction stage	Economic indicators	Safety management cost	$C_{SM} = C_{SI} + C_{SP} + C_{ST} + C_{EM} + C_{AC} + C_I$	$C_{SI} = \sum_{i=1}^{n} C_{equipment}^{i} + C_{PPE}^{i}$ $C_P = \sum_{j=1}^{m} (SA_{manager}^{j} + SA_{supervisor}^{j})$ $C_{ST} = T_{course} \times N_{workers} + T_{drill} \times N_{workers}$ $C_{EM} = P_{plan} + P_{material} + P_{response}$ $C_{AC} = \sum_{k=1}^{l} P_{accident}^{k}$ $C_I = \sum_{p=1}^{q} (P_{injury}^{p} + P_{project}^{p})$
	Decision-Making indicators	Construction quality control	This indicator is based on the quantification of expert ratings and multi model methods, with a rating range of 1–6 points (1 point: very dissatisfied, 6 points: very satisfied). $S_{CQC} = 30\%S_{CPQ} + 20\%S_{MQC} + 20\%S_{SM\&OE} + 15\%S_{PCC} + 15\%S_{CAQ}$	
Operation and Maintenance stage (O&M Stage)	Economic indicators	Environmental protection cost	$C_{ENV} = C_{Fencing} + C_{Cover} + C_{washing} + C_{Hardening} + C_{wo} + C_{SealedTransport}$	$C_{Fencing} = (L_{Fen} \times P_{materialcost}) + C_{Ins} + C_{Main} + C_{Rem}$ $C_{Cover} = (A_{area} \times P_{Covermaterial}) + C_{Cl}$ $C_{washing} = C_{Ww} + C_{Wl} + C_{Drainage}$ $C_{Hardening} = (A_{area} \times P_{Hm}) + C_c$ $C_{wo} = C_{Ow} + C_{Ol} + C_{Om}$ $C_{ST}=C_{So} + C_{Sl} + C_{Sm}$
	Decision-Making indicators	Quality control of construction	This indicator is based on the quantification of expert ratings and multi model methods, with a rating range of 1–100 points (1 point: very dissatisfied, 100 points: very satisfied). $S_{QCC} = 25\%S_{SEO} + 20\%S_{MUE} + 20\%S_{OE} + 5\%S_{ERF} + 15\%S_{SMRC} + 15\%S_{EB}$	
Decommissioning and Disposal stage (D&D Stage)	Economic indicators	Equipment scrapping disposal cost	$C_{ESD} = C_{D\&T} + C_{W\&E} - R_{rv}$	$C_{D\&T} = C_{lmm} + C_{fuel}$ $C_{W\&E} = C_{recycling} + C_{disposal} + C_{ec}$ $R_{rv} = V_{material} \times RecoveryRate$
	Decision-making indicators	Environmental remediation assessment	This indicator is based on the quantification of expert ratings and multi model methods, with a rating range of 1–10 points (1 point: very dissatisfied, 10 points: very satisfied). $S_{ERA} = 40\%S_{ERE} + 25\%S_{CBR} + 35\%S_{DCP}$	

Table 2: The meanings of variables in Table 1

Variable	Meaning	Variable	Meaning
C_{EI}	Equipment investment cost	C_{PUR}	Equipment procurement cost
C_{TRAN}	Equipment transportation cost	C_{INS}	Equipment installation cost
C_{DEB}	Equipment debugging cost	C_{OTHER}	Other equipment expenses
P_i	Unit price of the i-th device	Q_i	The quantity of the i-th device
T_i	The transportation unit price of the i-th type of equipment (The unit is the transportation cost per ton or per piece)	D_i	The transportation distance of the i-th device
I_i	Unit price of installation labor for the i-th type of equipment	H_i	Installation hours for the i-th device
ED_i	The duration of the i-th device debugging	HW_i	Debugging personnel's hourly wage
S_{QM}	Scoring of management quality in the early stage	S_{FSPP}	Scoring of the quality of feasibility study project approval work
$S_{S\&D}$	Scoring of on-site survey and design work quality	S_{CP}	Scoring of construction planning work quality
n	Number of related equipment	C_{SM}	Safety Management Cost
C_{SI}	Safety investment cost	C_{SP}	Cost of security personnel
C_{ST}	Cost of safety training	C_{EM}	Emergency management costs
C_{AC}	Accident compensation cost	C_I	cost of insurance
$C^i_{equipment}$	The procurement and maintenance costs of the i-th safety equipment	C^i_{PPE}	Item i: Procurement and replacement costs of personal protective equipment
$SA^j_{manager}$	Annual salary of the jth security management personnel	$SA^j_{supervisor}$	Annual salary of the j-th safety supervisor
m	The number of safety management personnel and supervisory personnel	T_{course}	The cost of a single training course
$N_{workers}$	The cost of a single training course	T_{drill}	Cost of safety drills
P_{plan}	Cost for developing emergency plans	$P_{material}$	Emergency material reserve cost
$P_{response}$	Labor and equipment costs for accident response	$P^k_{accident}$	Compensation costs for the kth accident
l	The number of historical accidents	P^p_{injury}	Accidental injury insurance premium for each employee
$P^p_{project}$	Engineering insurance cost for the project	q	Total number of insured employees
S_{CQC}	Scoring of onstruction qualitycontrol	S_{CPQ}	Scoring of construction process quality
S_{MQC}	Scoring of material quality control	$S_{SM\&OE}$	Scoring of Safety management and on-site environment

(Continued)

Table 2 (continued)

Variable	Meaning	Variable	Meaning
S_{PCC}	Scoring of Progress control and coordination	S_{CAQ}	Scoring of completion acceptance quality
$C_{Fencing}$	Construction site perimeter fence cost	C_{cover}	Material stacking and covering costs
$C_{washing}$	Vehicle washing fees for entry and exit	$C_{Hardening}$	Construction site ground hardening cost
C_{wo}	Wet operation at construction site	C_{ST}	Sealed transportation of waste soil vehicles
L_{Fen}	Total length of fence	P_{MC}	Material cost per meter
C_{Ins}	Installation cost of fence	C_{Main}	Maintenance costs during construction period
C_{Rem}	The cost of dismantling fences	A_{area}	Construction budget preparation level to project year time interval
$P_{Covermaterial}$	Cost of covering materials per square meter	C_{Cl}	Labor cost for material coverage installation
C_{Ww}	Water fee required for cleaning work	C_{Wl}	The labor cost of cleaning work
$C_{Drainage}$	The cost of drainage system	P_{Hm}	Cost per square meter of hardened material
C_c	Construction labor and equipment costs for ground hardening work	C_{Ow}	Water fee required for wet process operation
C_{Ol}	The labor cost of wet process operation	C_{Om}	Mechanical cost of wet process operation
C_{So}	Vehicle transportation fuel cost	C_{Sl}	The labor cost of vehicle transportation
C_{Sm}	Mechanical cost of vehicle transportation	S_{QCC}	Scoring of quality control of construction in the operation and maintenance stage
S_{SEO}	Scoring of stability of equipment operation	S_{MUE}	Scoring of Maintenance and upkeep efficiency
S_{OE}	Scoring of operating efficiency	S_{ERF}	Scoring of emergency response and fault handling
S_{SMRC}	Scoring of security management and risk prevention and control	S_{EB}	Scoring of economic benefits
C_{ESD}	Equipment scrapping disposal cost	$C_{D\&T}$	Dismantling and transportation costs of old equipment
$C_{W\&E}$	Cost of environmental protection treatment for demolition materials	R_{rv}	Residual value
C_{lmm}	The cost of using personnel and machinery involved in the demolition work	C_{fuel}	Oil costs involved in dismantling transportation work

(Continued)

Table 2 (continued)

Variable	Meaning	Variable	Meaning
$C_{recycling}$	Recycling cost	$C_{disposal}$	Final disposal cost of waste
C_{ec}	Carbon emission control cost	$V_{material}$	The original market value of the demolished object
S_{ERE}	Scoring of environmental restoration effect	S_{CBR}	Scoring of cost-benefit ratio
S_{DCP}	Scoring of response level (social benefits) of the "dual carbon policy"	S_{ERA}	Scoring of environmental remediation assessment

3 Comprehensive Evaluation Method

3.1 Standardization of Evaluation Indicators

Due to the differences in the evaluation effectiveness of different evaluation indicators on the overall goal, the obtained data is normalized and evaluated. Before standardization, a 5-level classification method was used to define the comment set for qualitative indicators, and the corresponding scores for each level are shown in Table 3.

Table 3: Expert scoring and assignment

Grade	Excellent (V_1)	Very good (V_2)	Good (V_3)	Weak (V_4)	Fail (V_5)
Points	1.0	0.8	0.6	0.4	0.2

When conducting a feasibility assessment of mechanized construction in power transmission and transformation projects, the number of evaluation objects i is m, and there are n evaluation indicators j in each object. The j-th indicator of the i-th evaluation object is denoted as $X_{ij}(i = 1, 2, 3, \ldots, m; j = 1, 2, 3, \ldots, n)$, forming the original matrix of the evaluation object. Eq. (1) is used to unify the original matrix of the evaluation object according to Eq. (2), and then normalized according to Eq. (3) to obtain the standardized data matrix $B_1 = \left(b_{ij}^*\right)_{m\times n}, b_{ij}^* \in [0, 1]$:

$$X = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nn} \end{bmatrix} \quad (1)$$

$$b_{ij} = \frac{X_{ij} - min(X_j)}{max(X_j) - min(X_j)} \quad (2)$$

In the formula, X_{ij} is a decision-making indicator.

$$X = \frac{\max(X_j) - Y_{ij}}{max(X_j) - min(X_j)} \quad (3)$$

In the formula, Y_{ij} is a cost indicator.

$$b_{ij}^{*} = \frac{b_{ij}^{*}}{\sqrt{\sum_{i=1}^{m} b_{ij}}}$$

3.2 *Improving the Comprehensive Weighting Method Based on Game Theory*

The subjective weighting method is greatly influenced by human factors and has a strong subjectivity, while the objective weighting method relies entirely on the inherent characteristics of the data and easily ignores the characteristics of the indicators. To solve the problems of subjective and objective weight calculation methods, the AHP+entropy weight method game theory weight determination method includes three parts. Firstly, the AHP method and entropy weight method are used to determine the indicator weights, and then the game theory idea is adopted to combine and optimize the subjective and objective weights to obtain the combined weight.

3.2.1 Analytic Hierarchy Process (AHP) Determines Subjective Weights

The Analytic Hierarchy Process (AHP) is a decision analysis method that combines qualitative and quantitative methods. It belongs to the subjective weight calculation method and can effectively solve multi criteria and multi-objective problems, achieving comprehensive treatment of qualitative and quantitative influencing factors. The method is simple and scientific, and is widely used in power generation technology optimization selection, project evaluation, plant site selection, power planning, load forecasting, and other aspects [22]. Subjective weighting of indicators through Analytic Hierarchy Process, combined with mathematical processing, increases credibility and makes them more logical [23].

1) Construct a judgment matrix. Using the 1-9 scale method to determine quantification, establish a corresponding positive and negative judgment matrix $C = \left(c_{ij}\right)_{r\times r}$ for the post evaluation index system of the entire life cycle of mechanized construction in power transmission and transformation projects, and describe the importance of each index corresponding to the upper level index in the evaluation system.

2) Hierarchical single sorting and its consistency check. By solving the eigenvalues $CW = \lambda_{max} W$ of matrix C, the eigenvector W is obtained, and after normalization, the weights of the indicators for the corresponding upper level indicators are obtained. The formula for calculating consistency index C_1 is

$$C_I = \frac{\lambda_{max} - r}{r - 1} \tag{4}$$

In the formula, λ_{max} is the maximum eigenvalue of the judgment matrix; r is the number of indicators.

Calculate the value of the random consistency ratio $C_R = \frac{C_I}{R_I}$, where R_I is the average random consistency index of the judgment matrix. When $C_R \le 0.1$, it is considered that the consistency of the judgment matrix is good, otherwise the relative importance values of the judgment matrix need to be adjusted.

3) Hierarchical sorting. By calculating layer by layer from left to right, the target layer weight $W_1 = \left[v_1, v_2, \ldots, v_n\right]^T$ of the evaluation system can be obtained.

3.2.2 Entropy Weight Method Determines Objective Weights

Entropy weighting method is an objective weighting method that calculates weights based on the discreteness of each evaluation index data itself. For evaluation indicators, the degree of dispersion can be determined by the entropy value. Therefore, information entropy can be used to calculate the weights of each indicator, providing a basis for comprehensive evaluation of multiple indicators. The specific steps of using entropy weight method for objective weighting are as follows:

1) Standardize the judgment matrix to eliminate the dimensionality of the original values of various indicators.

2) Calculate the entropy j of evaluation indicator E_j as

$$E_j = -\frac{1}{lnm}\sum_{i=1}^{m} P_{ij} lnP_{ij} \tag{5}$$

In the formula, $P_{ij} = V_{ij}^{*}/\sum_{j=1}^{n} V_{ij}^{*}$; m is the number of evaluation objects.

3) According to entropy calculation, the weight w_j of the j-th evaluation index is

$$w_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \tag{6}$$

3.2.3 Combination Weight Based on Game Theory

Game theory is an important part of operations research, which assumes that each solution is the result of rational decision-making by decision-makers to safeguard their own interests [24]. This article applies the idea of game theory to calculate the final combination weight by combining the subjective and objective weights. The specific steps are as follows:

1) Let the basic weight set be: $u = \{u_{i1}, u_{k2}, \ldots, u_{in}\}$, $i = 1, 2, 3\ldots, l$. l is the number of weight determination methods, and in this article, any linear combination of vectors with a value of 2 is

$$u = \sum_{i=1}^{l} a_i u_i^T > 0,\ i = 1, 2, 3, \ldots, l, \tag{7}$$

In the formula, u is the comprehensive weight vector of l weight sets; a_i is the weight coefficient.

2) According to game theory, ultimately minimizing the difference between u and u_i, optimizing l weight vectors a_i, that is

$$min\|\sum_{i=1}^{l} a_i u_i^T - u_i\|_2 \ i = 1, 2, 3, \ldots, l. \tag{8}$$

3) The linear differential equation system with the optimal first-order derivative condition of Eq. (8) is

$$\begin{bmatrix} u_1 \cdot u_1^T & u_1 \cdot u_2^T & \cdots & u_1 \cdot u_l^T \\ u_2 \cdot u_1^T & u_2 \cdot u_2^T & \cdots & u_2 \cdot u_l^T \\ \vdots & \vdots & \cdots & \vdots \\ u_l \cdot u_1^T & u_l \cdot u_2^T & \cdots & u_l \cdot u_l^T \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_l \end{bmatrix} = \begin{bmatrix} u_1 \cdot u_1^T \\ u_2 \cdot u_2^T \\ \vdots \\ u_l \cdot u_l^T \end{bmatrix} \tag{9}$$

By using Matlab to calculate $(a_1, a_2, \ldots, a_l)$ and then normalizing it, we can obtain

$$a_i^{*} = a_i/\sum_{i=1}^{l} a_{1i} \tag{10}$$

The comprehensive weight for obtaining the combination weighting in game theory is

$$u^* = \sum_{i=1}^{l} a_i^* u_i^T \tag{11}$$

3.3 Fuzzy Grey Relational Projection Sorting Method

1) Determine ideal and inferior mechanized construction plans. Let the ideal optimal solution be $G_0 = \{1, 1, \ldots, 1\}$; based on the smallest attribute value of each indicator processed by nondimensionalization, which is 0, the ideal inferior solution is obtained as $G_0^- = \{0, 0, \ldots, 0\}$.

2) Positive and negative weighted grey relational decision matrix. By calculation, the degree of correlation between each plan and the ideal plan can be obtained:

The grey correlation coefficient between scheme G_i and $G_0^+ = \{1, 1, \ldots, 1\}$ is

$$r_{ij}^+ = \frac{min_n min_m |b_{0j}^+ - b_{ij}| + \alpha max_n max_m |b_{0j}^+ - b_{ij}|}{|b_{0j}^+ - b_{ij}| + \alpha max_n max_m |b_{0j}^+ - b_{ij}|} \tag{12}$$

The grey correlation coefficient between Scheme G_i and Scheme $G_0^- = \{0, 0, \ldots, 0\}$ is

$$r_{ij}^- = \frac{min_n min_m |b_{0j}^- - b_{ij}| + max_n max_m |b_{0j}^- - b_{ij}|}{|b_{0j}^- - b_{ij}| + \alpha max_n max_m |b_{0j}^- - b_{ij}|} \tag{13}$$

Among them, α is the resolution coefficient used to adjust the size of the comparison environment, usually $\alpha = 0.5$; b_{0j}^+ is the index value of the ideal optimal solution, $b_{0j}^+ = 1, (j = 1, 2, \ldots, n)$; b_{0j}^- is the index value of the ideal worst solution, $b_{0j}^- = 0, (j = 1, 2, \ldots, n)$. Obviously, $\gamma_{01}^+ = \gamma_{02}^+ = \ldots = \gamma_{0n}^+ = 1$, $\gamma_{01}^- = \gamma_{02}^- = \ldots = \gamma_{0n}^- = 0$.

Due to the varying importance of each evaluation indicator in the indicator system, the grey relational decision matrix is weighted. The weight w_i of each indicator should meet the following requirements:

$$0 \le w_i \le 1, \sum_{j=1}^{n} w_j = 1, \ j = 1, 2, \ldots, n \tag{14}$$

Obtain positive and negative weighted grey relational decision matrix γ_w:

$$\gamma_w^+ = \gamma_w w = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \\ w_1\gamma_{11}^+ & w_2\gamma_{12}^+ & \cdots & w_n\gamma_{n2}^+ \\ \vdots & \vdots & \cdots & \vdots \\ w_1\gamma_{n1}^+ & w_2\gamma_{n1}^+ & \cdots & w_n\gamma_{nm}^+ \end{bmatrix}, \tag{15}$$

$$\gamma_w^- = \gamma^- w = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \\ w_1\gamma_{11}^- & w_2\gamma_{12}^- & \cdots & w_n\gamma_{n2}^- \\ \vdots & \vdots & \cdots & \vdots \\ w_1\gamma_{n1}^- & w_2\gamma_{n1}^- & \cdots & w_n\gamma_{nm}^- \end{bmatrix}, \tag{16}$$

In the formula, the i-th row vector of γ_w^+, γ_w^- represents the weighted grey correlation between decision scheme G_i and positive and negative ideal plans at each point.

3) Grey correlation projection value. Consider each alternative solution as a row vector, and the gray correlation projection angle is the angle θ_i between each alternative solution A_i and the ideal solution A^* [25]. The cosine of the angle is

$$cos\theta_i = \frac{A_i A^*}{||A_i A^*||} = \frac{\sum_{j=1}^{n} f_{ij} w_j^2}{\sqrt{\sum_{j=1}^{n} w_j^2}\sqrt{\sum_{j=1}^{n} (w_j f_{ij})^2}} \tag{17}$$

In the formula, $i = 1, 2, \ldots, m$.

The projection D_i of scheme G_i on ideal scheme G_0 is

$$D_i = \left|\overline{G_i}\right| cos\theta_i = \frac{\overline{G_i G_0}}{\left|\overline{G_0}\right|} = \sum_{j=1}^{n} \gamma_{ij} \frac{w_j^2}{\sqrt{\sum_{j=1}^{n} w_j^2}} \tag{18}$$

In the formula, $i = 1, 2, \ldots, m$.

Normalize the weights to obtain the grey relational projection weights:

$$\mu_j = \frac{w_j^2}{\sum_{j=1}^{n} \left(w_j\right)^2}, \ j = 1, 2, \ldots, n \tag{19}$$

$$D_i = \sum_{j=1}^{n} \gamma_{ij}\mu_j, \ i = 1, 2, \ldots, m \tag{20}$$

D_i reflects the degree of correlation between scheme G_i and ideal scheme G_0. The larger scheme D_i, the closer it is to the ideal scheme. Specifically, the grey correlation projection values of the ideal optimal solution and the ideal inferior solution on themselves are

$$D_0^+ = \sum_{j=1}^{n} \gamma_{ij}\mu_j = \sum_{j=1}^{n} \mu_j, i = 1, 2, \ldots, m \tag{21}$$

$$D_0^- = \sum_{j=1}^{n} \gamma_{ij}\mu_j, i = 1, 2, \ldots, m \tag{22}$$

Obviously, $D_0^+ = D_0^-$. Let $D_0 = D_0^+ = D_0^-$ be, in essence, the modulus of the ideal solution after weighting.

4) Superior membership degree. If the degree of superiority of scheme G_i is u_i, then its degree of inferiority to the ideal inferior scheme is $1 - u$. The generalized weighted distance between scheme F and the ideal superior scheme is defined as

$$D_{gi}^+ = u_i\left(D_0 - D_0^+\right) \tag{23}$$

Similarly, the generalized weighted distance between Scheme G_i and the ideal inferior scheme is defined as

$$D_{gi}^- = \left(1 - u_i\right)\left(D_0 - D_0^+\right) \tag{24}$$

According to the minimum sum of squares criterion, the objective function is

$$min\left\{F\left(u_i\right) = \left(D_{gi}^+\right)^2 + \left(D_{gi}^-\right)^2\right\} \tag{25}$$

Obtained by $\frac{\partial F(u_i)}{\partial u_i} = 0$

$$u_i = \frac{1}{1 + \left(\frac{D_0 - D_i^+}{D_0 - D_i^-}\right)} \tag{26}$$

The larger u_i is, the greater the membership degree of scheme G_i to the ideal optimal scheme. By sorting each plan in descending order of u_i, the order of superiority and inferiority of each plan can be obtained.

3.4 Information Feedback Mechanism

In order to fully utilize the full life cycle post evaluation system, ensure close connection between various links of mechanized construction in power transmission and transformation projects, and achieve information sharing among various departments, it is necessary to establish a supporting information feedback mechanism for post evaluation management of mechanized construction in power transmission and transformation projects. Firstly, establish an evaluation index system, analyze and compare the mechanization construction plans of power transmission and transformation projects in the historical database, and make decisions on the optimal plan. Secondly, analyze the relevant construction plans of the project to be evaluated and compare them again with the optimal plan in the experience database. The final optimal plan will be used for on-site implementation and form a case study to be included in the experience database; The eliminated plan will be analyzed for improvement space and measures. If improvements can be made, optimize and re plan; If improvement is not possible, summarize the lessons of failure and synchronize them into the experience library. The specific process is shown in Fig. 5.

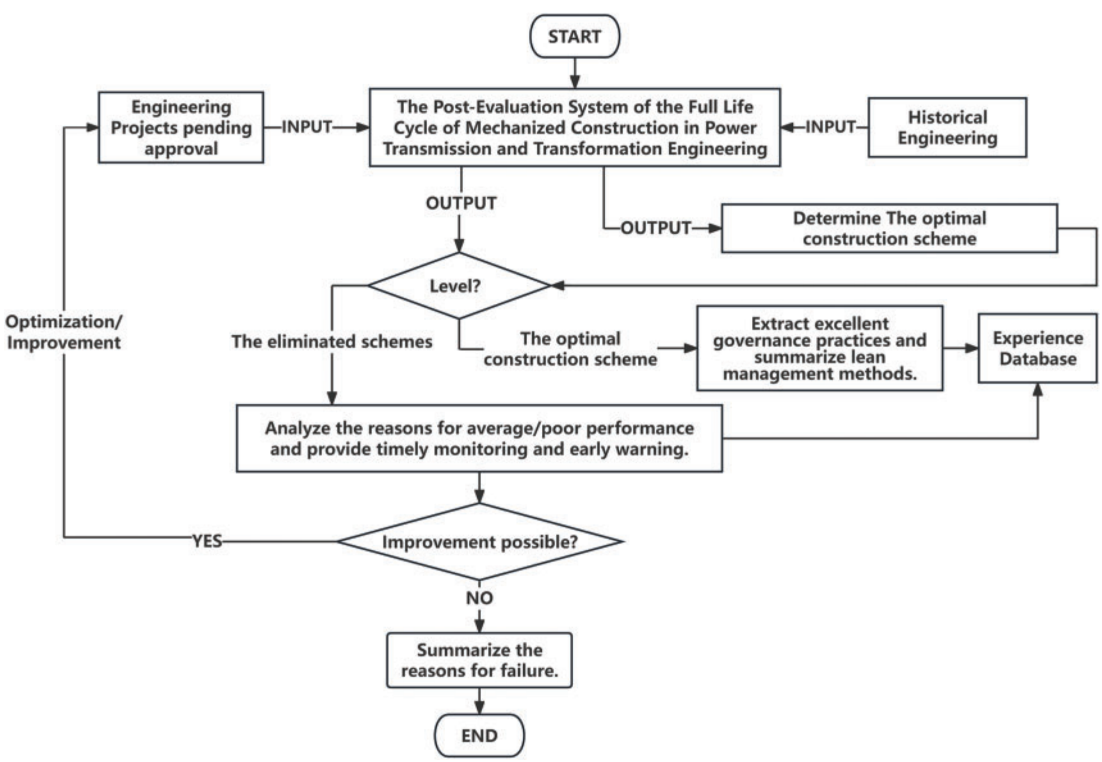

Figure 5: Process of the information feedback mechanism in the post-evaluation system for the full life cycle of mechanized construction in transmission and transformation projects

3.5 Post Evaluation of the Full Life Cycle of Mechanized Construction in Power Transmission and Transformation Projects

The post evaluation process for the full life cycle of mechanized construction in power transmission and transformation projects constructed in this article is shown in Fig. 6. Firstly, establish a post evaluation index system for the full life cycle of mechanized construction in power transmission and transformation projects. Use AHP and entropy weight method to determine the weights of the indicators, and optimize the subjective and objective weights using game theory to calculate the combined weights. Using the fuzzy grey relational projection sorting method to comprehensively evaluate the quality and efficiency of mechanized construction schemes for power transmission and transformation.

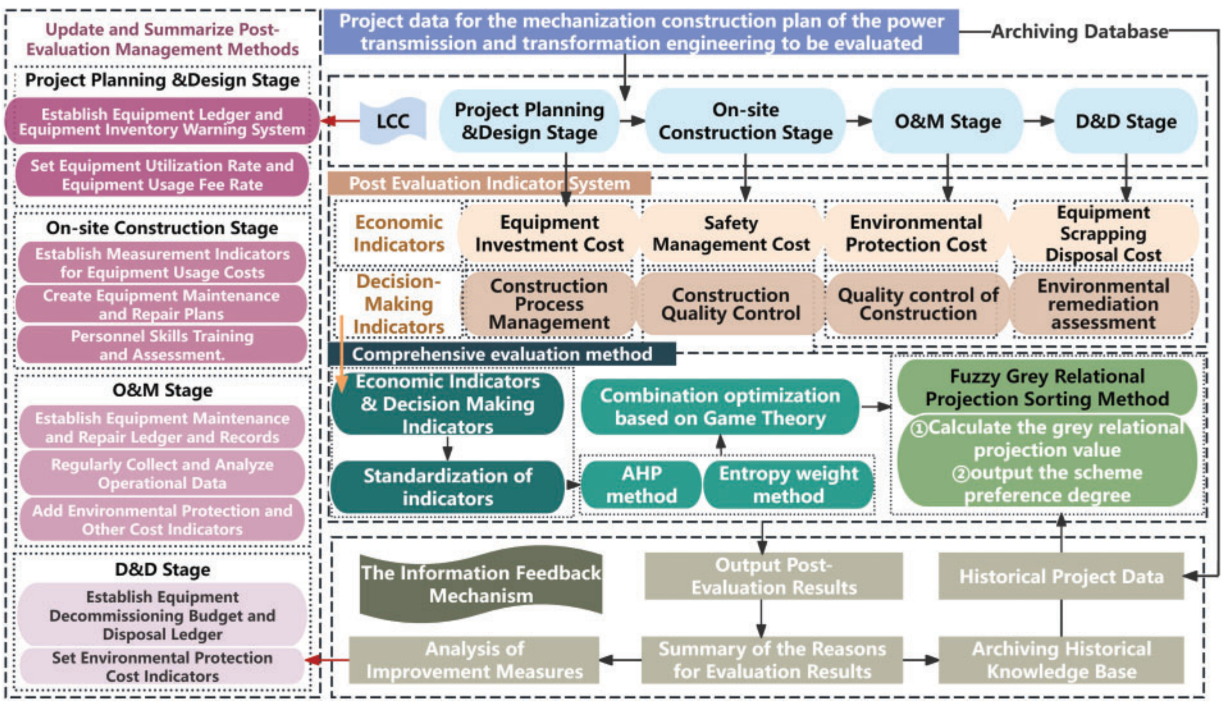

Figure 6: Post-evaluation system for the full life cycle of mechanized construction in power transmission and transformation projects

4 Example Analysis

4.1 Case Background

This article selects the 220 kV main transformer expansion project in Zhejiang Province to construct one main transformer with a capacity of 180 MVA; The main transformer is equipped with 3 × 8 Mvar and reactive power compensation capacitors; There are eight 10 kV outgoing lines. The project received initial design approval on 10 August 2024. The sustainability of three mechanized construction schemes for power transmission and transformation projects proposed by different contractors was evaluated using the method described in this article. The scheme data is detailed in Table 4.

Table 4: Initial data for various schemes indicators

Indicator elements	Scheme 1	Scheme 2	Scheme 3
Equipment investment cost/million yuan	0.67	0.78	0.82
Construction process management/points	8.71	6.92	6.07
Safety management cost/million yuan	0.0827	0.1029	0.1381
Construction quality control/points	5.27	4.71	3.73
Environmental protection cost/million yuan	0.02	0.01	0.01
Quality control of construction/points	78.32	66.32	76.86
Equipment scrapping disposal cost/million yuan	0.68	0.74	0.81
Environmental remediation assessment/points	5.4	6.3	8.1

4.2 Weight Determination

According to the indicator weight calculation method described in Section 3.2, combined with the importance of each indicator in the indicator system and the scoring of qualitative indicators by four relevant experts in the field, the subjective and objective weights of the sustainability evaluation indicators for the mechanized construction of the power transmission and transformation project are calculated through the AHP method and entropy weight method. The combination weight of the evaluation indicators is calculated using game theory. The subjective and objective weights and their combination weights of the secondary indicators are shown in Table 5, while the subjective and objective weights and their combination weights of the primary indicators are shown in Fig. 7. It can be seen that the weights of AHP indicators fluctuate greatly, and the reason for this is that they are easily influenced by the subjective opinions of various evaluation experts. The objective weights obtained by entropy weighting method, although relatively stable, cannot clearly reflect the differences between various indicators. In contrast, combination weights can simultaneously consider the will of decision-makers and the differences in indicator data, resulting in combination weights that fall between subjective and objective weights, making them more persuasive.

Table 5: Calculation results of evaluation index weights

Indicator classification	Indicator elements	Weight/%		
		AHP method	Entropy weight method	Combination optimization
Economic indicators	Equipment investment cost	6.39	11.52	6.64
Decision-Making indicators	Construction process management	11.04	15.00	11.23
Economic indicators	Safety management cost	10.05	11.88	10.14
Decision-Making indicators	Construction quality control	7.02	14.30	7.40
Economic indicators	Environmental protection cost	2.73	11.23	3.13
Decision-Making indicators	Quality control of construction	4.35	11.25	4.70

(Continued)

Table 5 (continued)

Indicator classification	Indicator elements	Weight/%		
		AHP method	Entropy weight method	Combination optimization
Economic indicators	Equipment scrapping disposal cost	16.32	13.10	16.15
Decision-Making indicators	Environmental remediation assessment	42.11	11.73	40.60

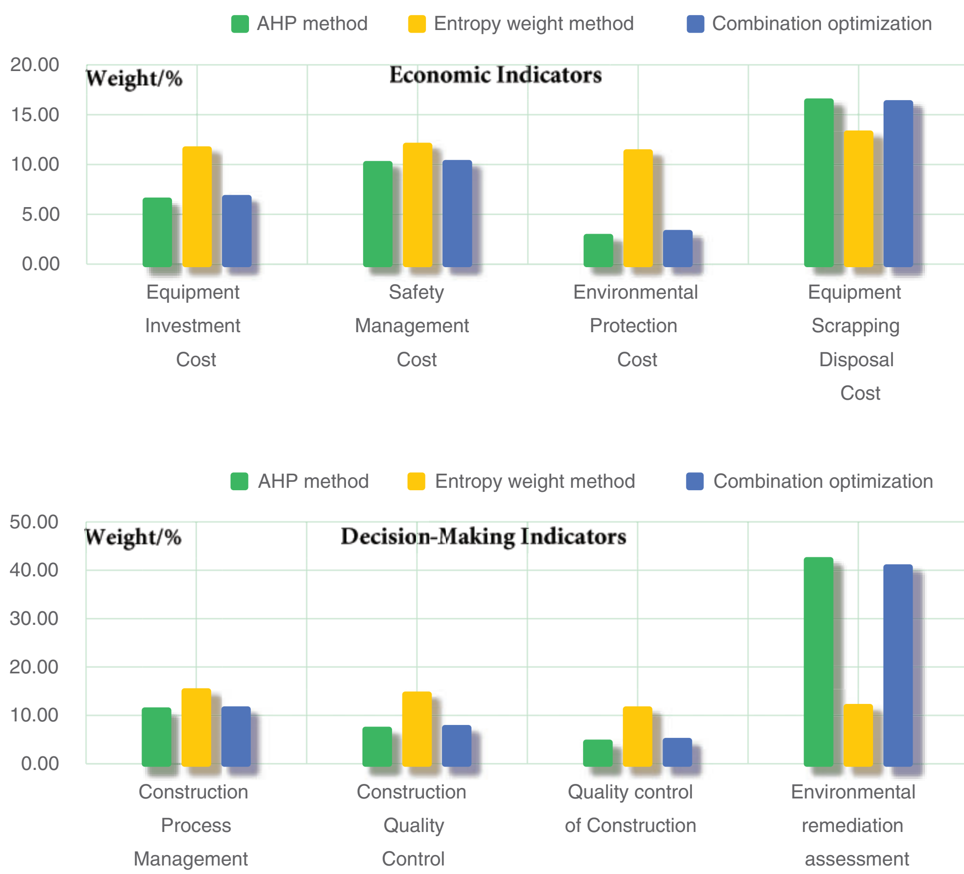

Figure 7: Post-evaluation system for the full life cycle of mechanized construction in power transmission and transformtion projects

4.3 Post-Evaluation Result Analysis

4.3.1 Engineering Quality Ranking

Based on the combined weight calculation results of the above indicators, the fuzzy grey correlation projection sorting method was used to analyze the three schemes, and the positive and negative grey correlation schemes values and membership degrees of each scheme were obtained, as shown in Table 6.

Table 6: Positive and negative gray correlation projection values and degree of superiority for each scheme

Scheme	D_i^+	D_i^-	u_i
1	0.747 820	0.344 883	0.870 945
2	0.667 846	0.465 214	0.721 625
3	0.600914	0.729 942	0.314 087

4.3.2 Post Evaluation Results of the Project

According to u_i's ranking of the three options, option $u_1 > u_2 > u_3$ is obtained, so option 1 is the best. According to the comprehensive evaluation results, Scheme 1 performs the best in terms of sustainability. This plan prioritizes the use of economically efficient mechanized construction techniques, reasonably controls equipment investment and maintenance costs, and optimizes the allocation of safety management resources, significantly reducing the overall cost of the entire period while ensuring construction quality (with the highest Construction Quality Control index value). Although Scheme 3 performs well in the application of environmental protection technologies (such as outstanding environmental remediation assessment indicators), excessive reliance on high cost equipment leads to an increase in disposal costs, and there are significant fluctuations in construction quality control, resulting in an imbalance between overall benefits and investment. Although Scheme 2 has advantages in some environmental indicators, its construction management capability is weak (with the lowest Construction Process Management indicator value), and the stability of quality control is insufficient, making it difficult to achieve sustainable improvement of the entire life cycle benefits. Therefore, Scheme 1 has more comprehensive advantages in the coordinated optimization of economic benefits, construction quality, and safety management.

4.3.3 Application of Information Feedback Mechanism

Based on project data, the following two processes can be used to analyze the post evaluation system for the entire life cycle of mechanized construction in power transmission and transformation projects:

Process 1: Start → Evaluation Index System for the Whole Life Cycle of Mechanized Construction in power transmission and transformation projects → Evaluation Model for the Whole Life Cycle of Mechanized Construction in power transmission and transformation projects Based on Game Theory and Fuzzy Grey Projection → Substitute Historical Project Data into the Model → Decide on the Optimal Plan from Historical Project Data.

Process 2: Start → Evaluation index system for the full life cycle of mechanized construction in power transmission and transformation projects → Evaluation model for the full life cycle of mechanized construction in power transmission and transformation projects based on game theory and fuzzy grey projection → Substitute the construction plan of the project to be evaluated into the model → Output the results and compare them with the optimal plan in Process 1 to determine the optimal construction plan.

Taking the result of Section 4.3.2 as an example, the contracting party analyzed that the Safety Management Cost of the optimal construction plan 1 was relatively low, but it could achieve the best Construction Quality Control index among the three plans, which is worth learning from. Finally, this index was input into the experience database. For the eliminated construction plans 2 and 3, analyze that the indicators such as equipment investment cost and construction quality control in this plan need to be improved, and make revisions and improvements. Among them, in order to ensure the stable operation of power transmission and transformation, designated equipment must be used in project implementation. Therefore, indicators such as Equipment Investment Cost cannot be adjusted or corrected, and will be synchronously input into the experience database. If there are devices with higher cost-effectiveness in the next stage, this indicator will be further optimized and decided upon.

5 Conclusion and Outlook

1) The framework for mechanized construction of power transmission and transformation projects employs game theory to optimize the combination of subjective and objective weights, aiming to maximize collective interests. It also considers the grey and incomplete factors that influence the construction process, as well as the grey correlation between decision-making and economic indicators.

2) The mechanized construction plan for power transmission and transformation projects is evaluated to identify the optimal decision-making solution. Compared to traditional single-weighting methods, this model demonstrates greater applicability and decision sensitivity, offering a more efficient way to optimize construction plans tailored to the specific project.

3) The proposed mechanized construction framework for power transmission and transformation projects provides data-driven support and guidance for future power engineering construction planning. It also serves as a valuable reference for assessing the economic and social benefits of mechanized construction in these projects.

4) The current research primarily focuses on the routine aspects of mechanized construction in power transmission and transformation projects. Future studies can expand upon this work by incorporating factors such as the impact of electricity markets [26] and extreme weather [27].

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Ethics Approval: This study was conducted in accordance with ethical standards. Informed consent was obtained from all participants (if applicable), and all data were collected and analyzed ethically and confidentially.

Conflicts of Interest: The author declares no conflicts of interest to report regarding the present study.

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