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Article

Application and Exploration of Global Optimization Algorithm for Construction Projects in Project Cost Management

Weiwei Zhang *

School of Construction Management, Jiangsu Vocational Institute of Architectural Technology, Xuzhou, Jiangsu, 221000, China; zww198705@126.com

Abstract: Construction quality, project progress, and cost are the three key control indicators in construction projects, which are interdependent and mutually influential. This paper constructs a multi-objective optimization model for schedule-cost-quality based on multi-objective optimization theory. Using an improved genetic algorithm to solve the problem, a Pareto solution set is obtained. Based on this, the entropy-VIKOR model is applied to make decisions on the solution set, identifying the optimal solution from the alternative options. This paper takes the YC Expressway Project as the research object for multi-objective optimization calculations in project cost management. Python programming is used for solution, resulting in an optimal construction period of 113 days, a reduction of 27 days compared to the planned 140 days. Costs were reduced by 1.4486 million yuan, and quality levels were improved. The optimization results validate the scientific and practical applicability of the project management multi-objective optimization model and the entropy value-VIKOR decision-making method.

Keywords: multi-objective optimization; improved genetic algorithm; entropy value-VIKOR; project cost management

1. Introduction

In today's highly competitive and complex construction projects, cost management and optimization have become critical factors in ensuring project success [1-2]. Effective cost management is not merely a means of financial control but also a key pathway to enhancing project efficiency and ensuring sustainable development [3-4].

Cost management is a critical project management activity aimed at effectively planning, monitoring, and controlling a project's economic expenditures [5-6]. It encompasses the entire process from project planning to delivery, including budget formulation, expense tracking, and cost control [7-8]. The essence of cost management lies in ensuring that projects are completed efficiently within budget by rationally allocating resources and minimizing waste [9-10]. The importance of cost management lies in its direct impact on the financial health and ultimate success of a project [11]. Through precise cost estimation and real-time cost monitoring, project teams can anticipate and address potential economic risks, prevent cost overruns, and ensure timely project delivery [12-13]. Additionally, cost management helps optimize resource utilization, improve overall project efficiency, thereby enhancing the project's competitiveness and sustainability [14-15].

In construction projects, cost management is not merely a financial control tool but also a key factor in project success [16-17]. Through scientific and effective cost management, maximum benefits can be achieved within limited resources, laying a solid foundation for the sustainable development of construction projects [18-20]. Currently, with the development of artificial intelligence, intelligent optimization algorithms are increasingly being applied to cost management in construction projects, particularly global optimization algorithms. Ant colony algorithms, particle swarm algorithms, simulated annealing algorithms, and Monte Carlo methods are commonly used global optimization algorithms, and they all possess certain global search capabilities in construction project cost management, enabling them to find optimal solutions in complex search spaces [21-24].

Literature [25] emphasizes the importance of cost management for construction projects and examines the factors influencing cost management in construction projects. Based on the literature review, it points out that different countries and different projects have different factors, with the most important factors being design changes, poor on-site management, and fluctuations in material prices. Literature [26] points out that due to the adjustment and upgrading of the economy and industrial structure, the construction industry faces many opportunities and challenges. It introduces the current status of construction cost management in China, analyzes the issues faced, and proposes optimization strategies. Literature [27] discusses the role of cost management and rework in construction projects, identifies the fundamental themes of cost management, and conducts a detailed analysis of the factors contributing to rework. It proposes methods for identifying and managing rework to reduce project costs. Literature [28] emphasizes that time and cost are the most critical factors in construction projects, explores the factors influencing project costs, and discusses various techniques and materials used for cost optimization, stressing the necessity of optimization. Literature [29] introduces the important role of construction cost management in the management system of construction enterprises and provides a combined system for calculating construction product costs within management accounting organizations to ensure that construction companies make effective management decisions. Literature [30] points out that the success of construction projects is measured by the achievement of project objectives, with primary objectives including adherence to project schedule duration and budget, and emphasizes the significant role of time and cost management of project activities in any project. Literature [31] aims to establish a model that provides a method for time-cost-quality optimization in construction projects using genetic algorithms. This model can perform and visualize advanced time, cost, and quality trade-off analyses, assisting construction general contractors in selecting the most suitable subcontractors.

This paper takes the construction plan in the construction process of a building project as the optimization object, with construction period, quality, and cost as the optimization objectives, and constructs a multi-objective optimization model for the construction plan of a building project. The construction plan is encoded using a binary coding method, and an improved genetic algorithm is designed by adopting an optimal retention strategy and introducing a penalty factor. This algorithm is then used to solve the multi-objective optimization model. To select the optimal solution from the solutions obtained, the entropy method is used to determine the weight values of the three indicators: project duration, cost, and quality. Next, using the standardized matrix formed by the solutions, the VIKOR method is applied to calculate the S, R, and Q values of each solution. Based on the Q, S, and R values, the solutions are ranked, and the optimal solution for the construction project is selected.

2. Establishment of a multi-objective optimization model

2.1. Multi-Objective Optimization Methods

2.1.1. Multi-Objective Model

A multi-objective optimization problem is an optimization problem with two or more objective functions, and its mathematical model is as follows.

Objective function:

$$\min f_i = (x_1, x_2, \cdots, x_n) \quad i = 1, 2, \cdots, s \tag{1}$$

Constraints:

$$g_i(x_1, x_2, \cdots, x_n) \geq 0 \quad i = 1, 2, \cdots, m \tag{2}$$

2.1.2. Multi-Objective Problem Solution

The complexity of solutions to multi-objective problems is determined by the multiplicity of objective functions and the complexity of the interdependent relationships between them. Generally speaking, multi-objective optimization problems rarely have optimal solutions, so it is often sufficient to find solutions that satisfy certain conditions as one of the optimal solutions [32]. To obtain solutions that meet our required conditions, certain conditions must be set to determine the scope of the solutions. Therefore, the method of setting new conditions becomes the fundamental approach to solving multi-objective optimization problems. Depending on the conditions set, these methods can be categorized into three types: hierarchical sequence method, constraint method, and functional coefficient method.

2.1.3. Stratified Sequential Method

The multi-level sequence method combines the characteristics of actual problems and converts the original multi-objective optimization problem into multiple single-objective optimization problems [33]. Assuming that the levels can be sequenced according to importance, in order of $f_1, f_2, \cdots, f_k$, the steps are as follows.

First-level optimization:

$$\begin{cases} \min f_1 = (x_1, x_2, \cdots, x_n) \\ g_i(x_1, x_2, \cdots, x_n) \geq 0 \end{cases} \quad \text{T} \qquad \text{t} \qquad D_1 \tag{3}$$

The solution set is D_1.

Second-level optimization:

$$\begin{cases} \min f_2 = (x_1, x_2, \cdots, x_n) \\ (x_1, x_2, \cdots, x_n) \in D_1 \end{cases} \quad \text{The solution set obtained is } D_2 \tag{4}$$

Similarly, perform k levels of optimization.

k th layer optimization:

$$\begin{cases} \min f_k = (x_1, x_2, \cdots, x_n) \\ (x_1, x_2, \cdots, x_n) \in D_{k-1} \end{cases} \tag{5}$$

The solution set is D_k, which is the optimal solution set for the multiple optimization problem.

2.1.4. Constraint Method

The basic idea of the constraint method is to select a sub-objective from multiple objective functions as the objective function, and then convert the other sub-objectives into constraint conditions:

$$\begin{cases} \min f_i = (x_1, x_2, \cdots, x_n) & i = 1, 2, \cdots, s \\ g_i(x_1, x_2, \cdots, x_n) \geq 0 & i = 1, 2, \cdots, m \end{cases} \tag{6}$$

Converted to:

$$f_j = \begin{cases} \min f_i = (x_1, x_2, \cdots, x_n) & \\ (x_1, x_2, \cdots, x_n) \geq f_0 & j = 1, 2, \cdots i-1, i+1, \cdots m \\ g_i(x_1, x_2, \cdots, x_n) \geq 0 & i = 1, 2, \cdots m \end{cases} \tag{7}$$

2.1.5. Functional Coefficient Method

The functional coefficient method is also known as the weight coefficient method: First, the sub-objectives that need to be optimized are aggregated into a single objective problem for solution calculation. Second, according to expert deliberation or the corresponding assignment method, each sub-objective is assigned a value based on its relative importance. Finally, the assigned single objectives are unified into a common objective, and the multi-objective optimization problem is solved.

Assuming there are p sub-objectives, the weight coefficient of the i th sub-objective is w_i, and the weight coefficients satisfy the following constraints:

$$\sum w_i = 1 \tag{8}$$

Since contractors undertake projects with the aim of making a profit, their goal is to optimize progress, cost, and quality. The company's objective is to minimize costs as much as possible while meeting the owner's requirements for progress and quality, thereby maximizing profit. Therefore, this paper adopts the constraint method, which constrains progress and quality according to the owner's requirements and seeks to minimize costs.

2.2. Construction of a multi-objective optimization model for cost, schedule, and quality

2.2.1. Basic Assumptions

In actual construction projects, a building can be divided into multiple construction processes from start to finish, each of which may have multiple construction plans. Different construction plans may require different costs, durations, and ultimately result in different quality levels. The goal is to achieve the expected quality level within the anticipated schedule while obtaining the lowest-cost plan. Based on these objectives, the following assumptions are proposed.

Assumption 1: Under limited project resources, achieve optimization of cost, schedule, and quality.

Assumption 2: Each construction plan must meet relevant quality standards, and the overall quality level of the project must meet the owner's quality requirements.

Assumption 3: This paper downplays the relationship between cost, quality, and schedule. Instead, it uses standard rates to calculate the required cost and schedule for different schemes and construction methods, and evaluates their quality levels through a relevant quality evaluation system. This establishes a triplet $M_i^m(t_i^m, c_i^m, q_i^m)$ for each construction method, where M_i^m denotes the i th construction scheme for the m th construction process, and t_i^m, c_i^m, q_i^m represent the required duration, cost, and final quality standards for the i th construction scheme.

2.2.2. Establishment of a Construction Schedule Model

In a network diagram, each construction process has only one construction plan. Starting from the initial node of the network diagram and proceeding to the terminal node along the arrow direction, there are multiple routes. Among these routes, the one with the longest total duration is the critical path, and this total duration represents the project schedule. After introducing multiple construction plans, each construction process can only adopt one construction plan, and other construction plans are not considered in the project duration. A 0-1 distribution is adopted, where 1 indicates that the plan is adopted and 0 indicates that it is not adopted. The multi-objective project duration calculation model constructed is as follows:

$$T = \max \sum_{i=1}^{n} \sum_{M_i^m} \sum x_i^m \cdot t_i^m \tag{9}$$

2.2.3. Cost Model Establishment

In the formula: x_i^m represents whether the m th construction plan of construction process i is executed, with 1 indicating execution and 0 indicating non-execution. t_i^m represents the duration of the m th construction plan of construction process i.

Based on the cost types of the construction project, costs can be categorized into direct costs, indirect costs, profit, and taxes, and analyzed and calculated using the comprehensive unit price method. The comprehensive unit price is the total cost, including the unit prices of sub-projects and sub-items. The specific model is expressed as follows:

$$C = \sum_{i=1}^{n} \sum_{M_i^m} \sum x_i^m \cdot c_i^m \tag{10}$$

2.2.4. Establishment of a quality model

In the formula: x_i^m represents whether the m th construction plan of construction process i is executed, with 1 indicating execution and 0 indicating non-execution. c_i^m represents the cost required for the m th construction plan of construction process i.

The project quality studied in this paper is composed of the quality of various project activities. Project quality is not simply the sum of the quality of each construction process, as different construction processes have varying degrees of impact on the project. In this paper, the expert scoring method is used to determine the process importance coefficient ω_i, and the project quality is calculated as follows:

$$Q=\sum_{i=1}^{n}\sum_{M_i^m}\sum x_i^m\cdot q_i^m\cdot\omega_i \tag{11}$$

In the formula: x_i^m represents whether the m th construction plan of construction process i is executed, with 1 indicating execution and 0 indicating non-execution. q_i^m represents the quality of the m th construction plan of construction process i.

2.2.5. Optimization Model Establishment

When considering a project from the perspective of the contractor, the main focus is on minimizing costs while ensuring that the project is completed on schedule and meets quality standards. The ultimate goal is: $\min C, T\le T_p$ and $Q\ge Q_p$.

That is:

$$\begin{cases}\min C=\sum_{i=1}^{n}\sum_{M_i^m}\sum_{i}x_i^m\cdot c_i^m\\ T=\max\sum_{i=1}^{n}\sum_{M_i^m}\sum_{i}x_i^m\cdot t_i^m\le T_p\\ s.t.\quad Q=\sum_{i=1}^{n}\sum_{M_i^m}\sum x_i^m\cdot q_i^m\cdot\omega_i\ge Q_p\\ \sum_{M_i^m}x_i^m=1\\ x_i^m\in N\end{cases} \tag{12}$$

3. Multi-Objective Optimization Problem Solving Algorithms

This paper uses genetic algorithms [34] to solve multi-objective optimization models. To improve the optimization accuracy and convergence speed of genetic algorithms in the multi-objective optimization process of construction plans, the basic genetic algorithm is improved by adopting an optimal preservation strategy. A penalty factor is introduced to constrain individuals that do not meet the constraint conditions. The fitness function and decision variable encoding mapping are designed separately for the optimization objectives and optimization objects.

3.1. Fitness Function Design

For the optimization objective (construction period), the optimization objective of the improved genetic algorithm is to search for the minimum value of the construction period while satisfying the constraints. When an individual satisfies the constraints, the fitness function F_T of the optimization objective (construction period) is:

$$F_T=\frac{10^6}{\min(T)} \tag{13}$$

When an individual does not meet the constraints, the fitness function F_T of the optimization objective (construction period) is:

$$F_T=\frac{10^6}{\min(T)}\times P \tag{14}$$

In the formula: P is the penalty factor, $P<1$, which serves to restrict individuals that do not meet the constraint conditions during the selection operation.

Similarly, for the optimization objective (cost) and optimization objective (quality), the optimization objectives of the improved genetic algorithm are also to satisfy the constraint conditions, respectively. Search for the minimum cost and maximum quality, respectively.

When an individual satisfies the constraint conditions, the fitness function F_C of the optimization objective (cost) is:

$$F_C = \frac{10^6}{\min(C)} \tag{15}$$

When an individual does not meet the constraints, the fitness function F_C of the optimization objective (cost) is:

$$F_C = \frac{10^6}{\min(C)} \times P \tag{16}$$

When an individual satisfies the constraints, the fitness function F_Q of the optimization objective (quality) is:

$$F_Q = \max(Q) \tag{17}$$

When an individual does not meet the constraints, the fitness function F_Q of the optimization objective (quality) is:

$$F_Q = \max(Q) \times P \tag{18}$$

3.2. Decision Variable Coding Mapping Design

During the construction process, the construction plans adopted for different processes are used as decision variables. The decision variables are encoded using a binary coding method. The construction process consists of a total of 15 processes, each of which is represented by a 10-digit binary number, i.e., a chromosome. The 15 chromosomes are linked together to form a gene.

In a gene, the mapping relationship between a chromosome and the construction plan number in the corresponding construction process is as follows:

$$j = round(n_i \frac{\sum_{k=1}^{10} A(k)^{(10-k)}}{2^{10}-1}) \tag{19}$$

In the formula: A is the set of binary strings corresponding to the construction plan for the i th construction process during construction, and $A(k)$ is the k th binary number in the set A .

4. Decision-Making for Multi-Objective Comprehensive Optimization Solutions

The preceding section improved the genetic algorithm to solve the multi-objective comprehensive optimization model for engineering project management, resulting in a Pareto solution set. The key difference between multi-objective optimization and single-objective optimization lies in the fact that single-objective optimization yields an optimal solution (which is the final solution), whereas multi-objective optimization cannot directly produce an optimal solution; instead, the most satisfactory solution must be selected from the Pareto solution set. During the decision-making process, each decision-maker may have subjective preferences or concerns, which could lead to biases in the decision outcomes. To avoid external factors influencing the decision outcomes, this paper employs a decision-making method based on the entropy-VIKOR model to identify the optimal solution within the Pareto solution set.

4.1. Entropy Method

When assigning weights to the indicators in this paper's scheme, commonly used methods include the AHP method, which has a subjective nature; the entropy method, which has an objective nature; and the combined objective-subjective weighting method. To ensure the objectivity of the indicator weights, this paper adopts the entropy method, which is inherently an objective weighting method, to assign weights to the indicators.

The core idea of the entropy method is to determine indicator weights based on indicator entropy, i.e., the larger the entropy value of an indicator, the greater its weight. Conversely, the smaller the entropy value of an indicator, the smaller its weight [35]. The specific steps for determining indicator weights using the entropy method are as follows.

(1) Determine the initial matrix of indicators: Construct an initial matrix of size $m \times n$ based on the optimized solutions, where m refers to the number of optimized solutions and n refers to the number of evaluation indicators. The initial matrix is as follows:

$$X = \begin{pmatrix} x_{11} & \cdots & \cdots & \cdots & x_{1n} \\ \vdots & \ddots & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ x_{m1} & \cdots & \cdots & \cdots & x_{mn} \end{pmatrix} \quad (20)$$

(2) Standardization of initial matrix data: The initial matrix data includes data such as construction period and cost, which vary in nature and cannot be directly used to calculate indicator entropy. Therefore, dimensionless processing is required. The range standardization method is used to divide the indicators into positive and negative indicators. The processing steps are as follows:

Processing of positive indicators:

$$y_{ij} = \frac{x_{ij} - x_{ij\min}}{x_{ij\max} - x_{ij\min}} \quad (21)$$

Handling negative indicators:

$$y_{ij} = \frac{x_{ij\max} - x_{ij}}{x_{ij\max} - x_{ij\min}} \quad (22)$$

In the formula:

$x_{ij\max}$ —The maximum value of the data under a certain indicator.

$x_{ij\min}$ —The minimum value of the data under a certain indicator.

y_{ij} —The standard value obtained after standardization under a certain indicator.

(3) Calculate the percentage value:

$$R_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}} \quad (23)$$

(4) Calculation of indicator entropy values:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} R_{ij} \ln R_{ij} \quad (24)$$

(5) Calculation of the coefficient of variation:

$$g_j = 1 - e_j \quad (25)$$

(6) Determine indicator weights:

$$w_j = \frac{g_j}{\sum_{j=1}^{n} g_j} \quad (26)$$

4.2. VIKOR Decision-Making Method

VIKOR is a compromise-based multi-criteria decision-making method based on ideal solutions. Its core idea is to first determine the positive ideal solution and the negative ideal solution, and then rank the alternative options based on how close their evaluation scores are to the positive ideal solution [36].

Compared with other decision-making ranking methods, VIKOR takes into account the interactions between indicators, avoiding the negative impact of individual indicators being offset by other indicators, resulting in a more objective and realistic ranking of decision-making options.

The specific steps of the VIKOR decision-making method are as follows.

(1) Determine the initial decision matrix:

$$X = \begin{pmatrix} x_{11} & \cdots & \cdots & \cdots & x_{1n} \\ \vdots & \ddots & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ x_{m1} & \cdots & \cdots & \cdots & x_{mn} \end{pmatrix} \tag{27}$$

(2) Standardization of the initial decision matrix: The initial decision matrix is standardized using the range standard method. The processing steps are shown in Equations (21) and (22). After processing, a standardized decision matrix is obtained, which is shown in the following table:

$$F = \begin{pmatrix} f_{11} & \cdots & \cdots & \cdots & f_{1n} \\ \vdots & \ddots & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ f_{m1} & \cdots & \cdots & \cdots & f_{mn} \end{pmatrix} \tag{28}$$

(3) In the standardized matrix Y, calculate the positive ideal solution values and negative ideal solution values of the five indicators (the positive ideal solution is f_j^* and the negative ideal solution is f_j^-). The calculations are shown in Equations (29) and (30):

$$f_j^* = \begin{cases} \max\limits_i f_{ij}, j \in I_1 \\ \min\limits_i f_{ij}, j \in I_2 \end{cases} \tag{29}$$

$$f_j^* = \begin{cases} \min_i f_{ij}, j \in I_1 \\ \max_i f_{ij}, j \in I_2 \end{cases} \tag{30}$$

In the formula: I_1 belongs to the benefit-type indicators. I_2 belongs to the cost-type indicators.

(4) Calculate the group benefit value S_i and individual regret value R_i of the decision-making scheme. The calculations are shown in Equations (31) and (32):

$$S_i = \sum_{j=1}^{n} w_j (f_j^* - f_{ij}) / (f_j^* - f_j^-) \tag{31}$$

$$R_i = \max(w_j (f_j^* - f_{ij}) / (f_j^* - f_j^-)) \tag{32}$$

In the formula: w_j is the indicator weight.

(5) Calculate the benefit ratio value Q_i of the decision-making plan:

$$\begin{aligned} Q_i &= v(S_i - \min_i S_i) / (\max_i s_i - \min_i S_i) \\ &+ (1-v)(R_i - \min_i R_i) / (\max_i R_i - \min_i R_i) \end{aligned} \tag{33}$$

In the formula: v is the decision-making mechanism coefficient, $v = 0.5$.

(6) Rank the alternative options: Rank the alternative options based on the values of Q_i, S_i and R_i. When the following two conditions are satisfied, use the value of Q_i as the ranking criterion; the smaller the value of Q_i, the higher the ranking of the i th alternative.

Condition 1: $Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1)$.

Condition 2: $A^{(1)}$ is the top-ranked alternative in either S or R.

$A^{(1)}$ is the optimal alternative in the Q ranking, $A^{(2)}$ is the second-best alternative in the Q ranking, and m is the number of alternatives.

5. Empirical analysis of construction projects

5.1. Project Overview

(1) Project Description

The YC Expressway (Y City Section) project crosses a major river to the west, passes through a cluster of rice fields on the south side of the road, crosses over the subway line and G107, then turns southward, running parallel to the high-speed rail line and sharing a corridor to cross two clusters. After crossing over the city road along the route, it continues to run parallel to the high-speed rail line, then crosses over the city ring expressway. After the route separates from the high-speed rail line, continues southward to the city boundary, connecting with the design starting point of the YC Expressway (HB Section). The project adopts a dual-lane eight-lane expressway construction standard throughout. The design speed from the starting point to the mainline toll station is 110 km/h, and from the mainline toll station to the city boundary is 130 km/h. The standard roadbed width is 42 meters. The project includes 1 extra-large bridge, 4 elevated bridges, five interchange overpasses. The total length of mainline bridges is 25 km, the total length of ramp bridges is 15 km, the total area of mainline bridges is 1.3 million square meters, the total area of interchange ramps is 190,000 square meters, and the total area of bridges is 1.5 million square meters.

One of the sub-projects of the cross-ring highway was selected for the empirical analysis of multi-objective optimization. The starting and ending stations of the whole section of the upper span ring expressway are K13 328.67~K16 820.42, the length of the main line bridge is 3500m, and there are 7 ramps L1~L7. There are a total of 40 production sections of the whole bridge, and the steel beams are arranged in a straight line. All steel plates of steel beams are made of Q345qD steel.

(2) Project Objectives

The YC Expressway is the primary transportation artery connecting the two cities. The construction of this expressway has established a one-hour transportation circle between the two regions, which is conducive to promoting the economic development of City Z and holds significant importance for fostering integrated and coordinated development between the two regions and their surrounding areas. The YC Expressway (Y City section) starts from the southern part of Y City's urban area and extends to the Z City section. The construction environment within Y City is complex, as the project not only involves typical urban road construction but also crosses rivers, subways, railways, and the ring expressway, resulting in high construction difficulty and stringent quality requirements. The project has established objectives for schedule, quality, and cost in accordance with requirements, as detailed below:

1) Schedule Objectives

The contract schedule for this project is 140 days. Construction deployment will be reasonably arranged based on priority, ensuring smooth coordination of critical processes, and coordinating construction sequence and progress to guarantee the project schedule is met. This is a key focus of the project.

2) Quality Objectives

The project strictly adheres to relevant quality policies, standards, and design documents, rigorously follows construction standards, and ensures the full functionality of the project to guarantee quality. The project aims to achieve a quality reliability of no less than 0.9 and up to 1.0 at the time of handover acceptance.

3) Cost Objectives

The contract value of this project is 113,638,600 yuan, with an indirect cost rate of 65,000 yuan per day. The construction unit must strictly control costs while ensuring project schedule and quality, and maximize profits by enhancing management and technical capabilities.

This section of the project includes seven construction processes, with the specific work breakdown shown in Table 1.

Table 1. The main engineering quantity of the high speed segment of the YC highway.

Process number	Procedure name	Job content	Rework sequence
1	A	Construction preparation	B, F
2	B	Structure engineering (pile foundation, socket, pier column, cap beam, support installation)	C
3	C	Foundation treatment (gravel cushion layer)	D
4	D	Support system (support foundation concrete, steel bar and transport)	E
5	E	Mounting	G
6	F	Steel box beam transport (steel box girder processing, transportation)	G
7	G	Construction of steel box girder (pack, top push, fall beam, welding)	H
8	H	Scaffold removal	I
9	I	Bridge construction	J
10	J	Bridge dress	K, L
11	K	Crosswise engineering	-
12	L	Mechanical and electrical lighting engineering	-

To more clearly illustrate the logical relationships between processes, a double-numbered network schedule diagram was drawn based on the relationships between the processes in Table 1, as shown in Figure 1.

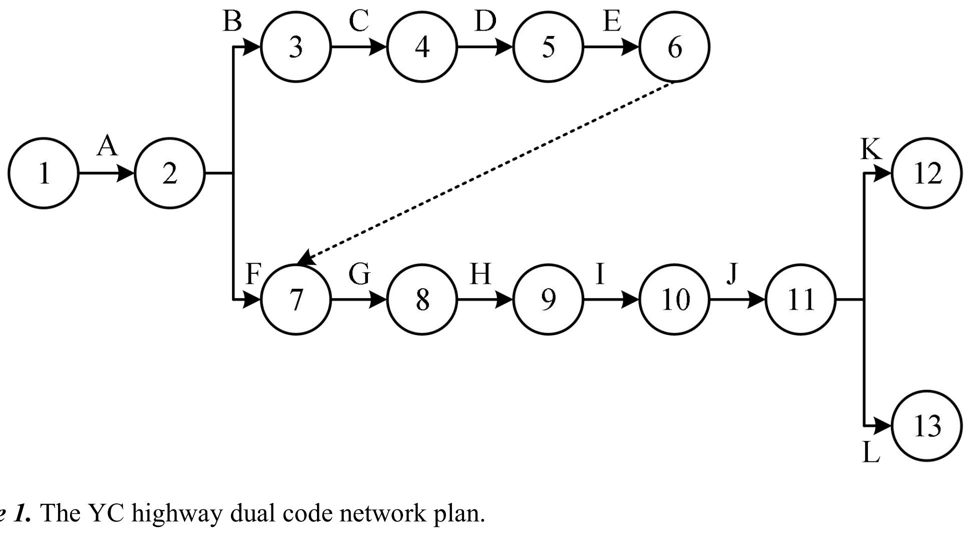

Figure 1. The YC highway dual code network plan.

The YC Expressway (overpass section of the ring expressway) involves key and challenging construction processes such as steel box girder top-pushing and splicing installation. The project command center and construction zones have set high expectations for schedule, quality, and cost. An expert panel composed of representatives from the command center, construction project managers, supervisors, and external experts was formed. By combining their own experience and referencing data from related projects, the panel comprehensively considered the impacts of human resources, materials, funding, and environmental factors. The parameters for each construction process are shown in Table 2.

The parameters include the minimum duration of the process ($t_{ij}^{\min}$), the duration of the process (t_{ij}), the maximum duration of the process ($t_{ij}^{\max}$), the minimum quality reliability of the duration ($P_{ij}^{\min}$), the maximum quality reliability of the duration ($P_{ij}^{\max}$), minimum duration direct cost ($c_{ij}^{\max}$), and maximum duration direct cost ($c_{ij}^{\min}$).

Table 2. The parameters of each process.

Procedure name	$t_{ij}^{\min}$	t_{ij}	$t_{ij}^{\max}$	$P_{ij}^{\min}$	$P_{ij}^{\max}$	$c_{ij}^{\max}$	$c_{ij}^{\min}$
A	1	2	2	0.9	1	1.23878	0.85392
B	27	26	36	0.9	1	1168.78986	1148.60947
C	6	7	10	0.88	1	151.65821	144.40621
D	9	9	16	0.84	1	134.16504	126.71156
E	2	0	3	0.9	1	0.18546	0.18211
F	22	27	26	0.86	1	6836.48893	6594.71526
G	18	23	25	0.91	1	1896.12462	1815.73046
H	11	8	10	0.95	1	4.22613	3.98649
I	9	11	10	0.86	1	175.01546	174.16732
J	3	4	5	0.92	1	89.37412	89.09936
K	7	8	9	0.91	1	20.79875	19.95164
L	10	12	12	0.89	1	6.73538	6.68473

5.2. Solving multi-objective optimization models

Substitute the designed parameters into the algorithm according to Table 2, and run it to obtain the optimal solution. The parameters are shown in Table 3. A total of eight optimal solution samples were selected in this study.

Table 3. The institute selects the optimal solution sample.

Serial number	Time/Day	Cost/10k Yuan	Quality/%
1	101	11355	98.89
2	105	11312	97.72
3	106	11296	97.53
4	113	11219	95.32
5	108	11255	92.06
6	110	11236	96.22
7	116	11206	94.96
8	119	11009	94.63

In order to clarify the relationship between project cost, schedule, and quality, the study used linear interpolation to fit all optimal solutions into a surface. The schedule-cost-quality equilibrium analysis is shown in Figure 2.

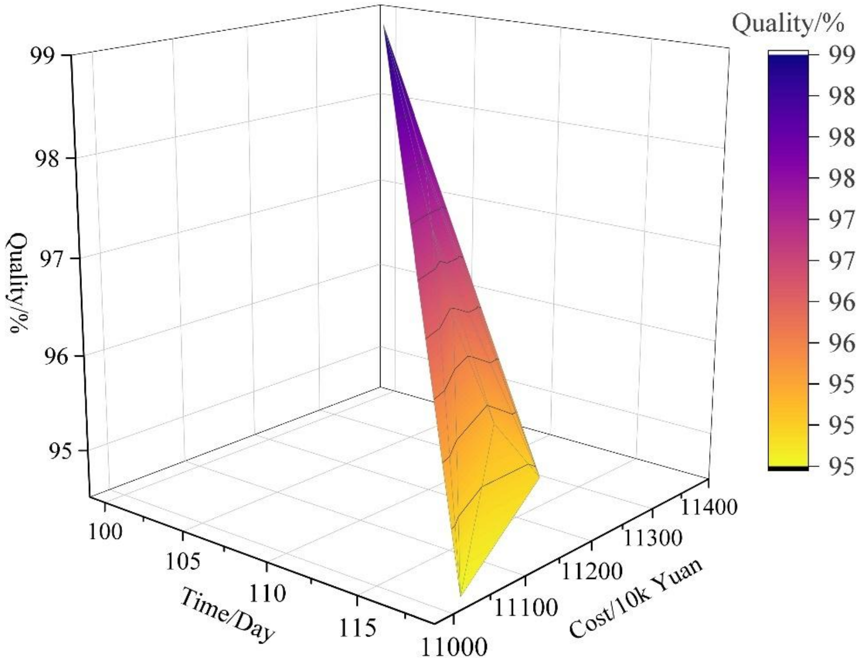

Figure 2. Period - Cost - Quality equilibrium analysis surface diagram.

Using the optimal sample solution from Table 3, the study fitted its numerical values into a two-way relationship diagram of construction period, cost, and quality to provide scientific basis for decision-making by construction project managers. The relationships between the three factors are shown in Figure 3, where (a) to (c) represent the relationship diagrams between construction cost and construction period, construction quality and construction period, and construction quality and construction cost, respectively. As shown in Figure (a), the shorter the construction schedule, the higher the cost. As the schedule increases, the cost decreases accordingly. In Figure (b), project quality decreases as the schedule lengthens, indicating an inverse relationship between project quality and schedule duration. Shorter schedules result in higher quality, while longer schedules lead to lower quality. From Figure (c), it can be seen that project quality increases as costs rise, indicating a direct relationship between project quality and costs. The more funds invested as project costs, the higher the quality of the completed project.

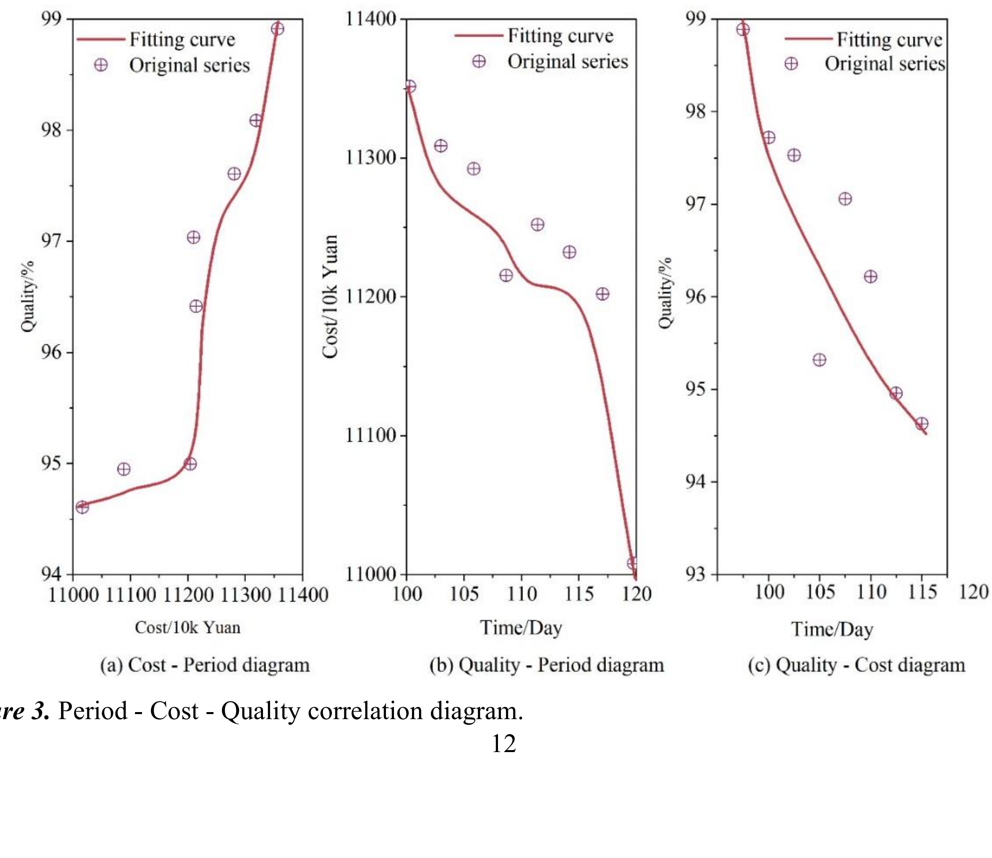

Figure 3. Period - Cost - Quality correlation diagram.

5.3. Analysis of Construction Plan Selection and Optimization Results

(1) Determining target weights using entropy values

Using the optimized plan obtained in the previous section, construct an initial $m \times n$ indicator matrix, with $m = 8$ for the alternative plans and $n = 3$ for the indicators. Standardize the data in the initial indicator matrix to obtain the standardized matrix shown in Table 4.

Table 4. Index standardization matrix.

Serial number	Period	Cost	Mass
1	0.42	0.63	0.75
2	0.87	0.2	0.14
3	0.5	0.81	0.59
4	0.63	0.43	0.57
5	0	1	1
6	0.21	0.98	0.9
7	0.42	0.63	0.75
8	0.87	0.2	0.14

The entropy values and weights of the indicators were determined according to formulas (23) to (26), and the results are shown in Table 5. Among them, quality has the largest weight, reaching 36.2%, indicating that the quality of this construction project needs to be guaranteed first and foremost.

Table 5. Index entropy and weight.

	Period	Cost	Mass
Index entropy value	0.9963	0.9952	0.9941
Index weights	0.342	0.296	0.362

(2) VIKOR Method for Ranking Construction Plans

The VIKOR method was used to rank the construction plans within the Pareto solution set, and the optimal plan was further selected. The ranking results of the VIKOR method are shown in Table 6. After sorting using the VIKOR method, Scheme 4 ranks first and is superior to other construction schemes. Therefore, it is concluded that among the Pareto solutions obtained by optimizing the various objectives of the YC construction project, decision-makers should select Scheme 4 as the current optimal scheme and subsequently manage and make decisions regarding the project's various objectives in a reasonable manner.

Table 6. The VIKOR method sort results.

Serial number	S	Q	R	Program sort
1	0.459	0.166	0.245	8
2	0.594	0.154	0.542	2
3	0.578	0.2	0.657	7
4	0.44	0.095	0.008	1
5	0.463	0.217	0.497	3
6	0.526	0.211	0.594	5
7	0.555	0.214	0.667	6
8	0.665	0.21	0.888	4

6. Conclusion

The study employs multi-objective global optimization theory to establish mathematical models from three dimensions: schedule, quality, and cost. Based on this, an improved genetic algorithm is employed to solve the model. Finally, the entropy-VIKOR decision-making model is used to determine the optimal solution for this study. Taking the YC Expressway project as an example, the project's schedule target is 140 days, the cost target is 113,638,600 yuan, and the quality reliability must be no less than 0.9. The study solves the constructed schedule-cost-quality multi-objective optimization model and ultimately obtains eight optimal solution samples. Using the entropy-VIKOR decision-making method, the optimal solution was determined to have a construction period of 113 days, an optimal cost of 112.19 million yuan, and a quality level of 95.32%. The construction plan obtained in this paper based on the multi-objective optimization model for project management and the entropy-VIKOR decision-making method can meet the project objectives.

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