WARSAW UNIVERSITY OF TECHNOLOGY | Index 351733 | DOI: 10.24425/ace.2024.150988
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
ARCHIVES OF CIVIL ENGINEERING
POLISH ACADEMY OF SCIENCES | ISSN 1230-2945 | Vol. LXX | ISSUE 3 | 2024
pp. 359 –372

Research paper

Multi-objective optimization of construction management of expressway engineering based on improved particle swarm optimization algorithm

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Abstract: Engineering management is an extremely important aspect of construction engineering, and a better management approach can greatly enhance the production profits of enterprises. Traditional management optimization schemes cannot adapt to current technological needs due to their inability to effectively consider the impact of each factor. Therefore, a construction management optimization scheme combining improved particle algorithm and multi-objective optimization was proposed. The improved particle algorithm enhances its performance by introducing adaptive weight and multi-objective optimization ideas. These studies confirmed that the predicted direct cost savings for the project were around 1 million yuan. The total construction period of project was optimized to 380 days, saving 34 days. The optimization technology not only reduced construction costs, but also reflected the problems that could be improved during this construction process. This study contributes to achieving multi-objective balance in the construction management process, effectively improving project efficiency, reducing project costs and risks, and providing scientific support for construction decision-making.

Keywords: adaptive weight, construction management, highway, multi-objective optimization, particle swarm optimization

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1. Introduction

The level of the national economy and the advancement of urbanization have accelerated the construction of infrastructure such as houses, roads and bridges, and the environment for engineering and construction is favorable. Excellent engineering management can comprehensively coordinate various factors in project progress, avoid major errors in the project, and bring greater economic profits to the enterprise [1,2]. However, traditional management optimization schemes perform poorly in balancing various factors and fail to comprehensively consider all factors in the entire engineering project [3]. At the same time, the traditional management optimization program relies too much on industry experience, and the trade-off between resource allocation, schedule control, cost control and other aspects of the problem is more subjective [4,5]. At present, the development of computer information technology promotes the digitalization and automation transformation in the engineering field [6]. By collecting and analyzing data during the project process, computer algorithms can provide decision-making support to reasonably predict and formulate plans and resource allocation for the project [7]. Therefore, the study chose the Construction Management Multi objective Optimization Problem (CMMOP) based on Particle Swarm Optimization (PSO). The article aims to improve the management efficiency of construction projects and increase the profits of enterprises. There are two innovative aspects to the research. Firstly, the research uses algorithms to assign weights to various modules of management, resulting in higher quality optimized management. The second point is that IPSO can update management through continuous iteration, which allows managers to fine-tune decisions based on feedback from changes in project data while optimizing solutions. They make the entire optimization plan more realistic and flexible. The article mainly consists of four parts. The first is a literature review that integrates Improved PSO (IPSO) and CMMOP. The second part consists of two sections, first establishing the main structure and evaluation indicators of Multi-Objective Optimization Problem (MOP). Secondly, it combines adaptive weights with PSO for parameter calculation. The third part is the performance demonstration and application effect of integrating IPSO and MOP. Taking the construction of a certain highway project as an example, the performance and project data analysis ability of optimization technology are introduced. Finally, there are conclusion points, including analysis of data results and reflection on this study.

2. Related works

The management efficiency of engineering construction can affect the construction quality of the entire project. Improving management efficiency and enhancing the universality of management have always been widely concerned by scholars. Kasim N et al. used a literature review method to identify the driving factors and obstacles to implementing IR 4.0 (Industrial Revolution 4.0) in the construction industry's safety management while researching methods for implementing IR 4.0. Drivers for implementing IR 4.0 technologies include augmented reality, virtual reality, the Internet of Things as well as artificial intelligence, cloud computing technologies, etc., while barriers include setup details, user interface and data, calibration of cameras, and high cost issues. These studies confirmed that after analyzing obstacle factors, it reduced the difficulty of implementing IR 4.0 management methods and enhanced the feasibility and operability of this management [8]. Yap et al. used to identify the main causes of construction project delays and reveal potential factors when studying how to avoid construction delays through optimized management. The meta-analysis of 52 common causes of delays categorized 20 frequent causes as client, contractor, consultant, labor and equipment, materials, and other related causes. These studies confirmed that these findings contributed to critical reflection on the practice of building production planning and management [9]. Zhong et al. adopted a blockchain based approach to building quality information management framework when studying transparent construction management. These studies confirmed that blockchain could provide distributed, encrypted, and secure information records, and support automated compliance checks of construction quality, thereby promoting mutual trust in construction quality management [10].

PSO has been applied in production and daily life due to its excellent performance in accuracy and computational efficiency. Gad et al. used PSO and system reviews in their research on simulating natural swarm intelligence, providing different perspectives on existing and ongoing research. These studies confirmed that the algorithm had excellent performance in accuracy and effectiveness [11]. Pawan et al. proposed a new PSO when studying IPSO methods, which utilized neural networks to predict the inertia weights of mobile groups to improve their performance. The results show significant performance gains of the new model compared to existing constant, stochastic and linear decreasing inertia weight particle swarm optimization models for cluster sizes of 50, 75 and 100 and dimensions of 10, 15 and 25 on five common benchmark functions [12]. Zeng et al. used a switching PSO based on dynamic neighborhood when designing a speed update mechanism. And adaptively select acceleration coefficients and update the velocity model according to the searching state of iteration to improve the searching ability of the model; Combine with differential evolutionary algorithm to solve the early convergence problem of the algorithm. These studies confirmed that the method had good convergence and better performance for complex multimodal optimization problems [13]. Pozna et al. used a hybrid algorithm that combines Particle Filter (PF) and PSO when studying IPSO. These studies confirmed that improved algorithm reduced the energy consumption of fuzzy control systems [14].

In summary, CM has high research value, and currently there are many scholars involved it. However, few scholars have adopted IPSO to address CMMOP. Therefore, this study proposes IPSO to provide a new solution for MOP.

3. Model construction by integrating IPSO and CMMOP

CM can enhance the production profits of enterprises and enhance the specialization of industries. At the same time, through the optimization algorithm to achieve construction management multi-objective optimization technology can improve the efficiency and quality of the construction project, reduce costs and risks, and achieve the maximization of the objectives.

3.1. The construction of MOP and the establishment of evaluation indicators

As the requirements for engineering management gradually increase, enterprises need to ensure the achievement of other indicators while pursuing benefits, and the demand for MOP solution also gradually increases. The study uses PSO for multi-objective solution to obtain multiple sets of solutions that meet the requirements, and then screens suitable solutions. In the management objectives of highway engineering, safety, quality, environment, cost, and efficiency are five main concerns. The research objective is to achieve cost minimization by coordinating five objectives while ensuring the balance of other objectives [15, 16]. Table 1 shows the specific target cost breakdown plan.

Table 1. Construction cost breakdown

Total cost target			
Progress cost	**Quality cost**	**Safety costs**	**Environmental costs**
Labor cost	Inspection test Inspection fee	Wastewater discharge fee	Security measures Protective equipment and facilities fee
Material cost	Engineering definition Bit retest fee	Waste discharge fee	Safety promotion Education expenses
Mechanist Expenses	Rework fee	Exhaust gas fee	Safety training Training fees
Freight and Miscellaneous expenses	To complete Process equipment protection fee	Guarantee Ring Other fees for the Environment use	Ensure safety All other fees use
Filling fee	Guarantee quality other fees for quantity use	–	–
Rainy season construction Additional labor costs	–	–	–
Nighttime application Labor costs	–	–	–
Expedition fee	–	–	–
Other phases customs fees	–	–	–

Safety, quality, environment, cost and efficiency in engineering are key indicators in project management, and the basis for target cost decomposition is based on four main principles. First, according to the project contract and relevant standards, to ensure that the project meets the requirements of the indicators; second, to take the risk factors into account through risk assessment and risk management; third, to determine the weight of each indicator according to the characteristics and importance of the project; and lastly, to determine and establish the corresponding decomposition rules and methods by taking into account the experience and professional knowledge of previous projects. Progress cost, as the main component of construction cost, has the characteristics of long-term and complexity [17]. Taking construction cost as an example, a progress control plan during construction is set up. To effectively reduce schedule costs, it is also necessary to consider the issue of schedule control during the CM process. Progress control mainly refers to the timely detection and correction of construction deviations by administrators, and the coordination of other costs to shorten the construction period. Taking the highway as an example, Fig. 1 shows the progress control chart.

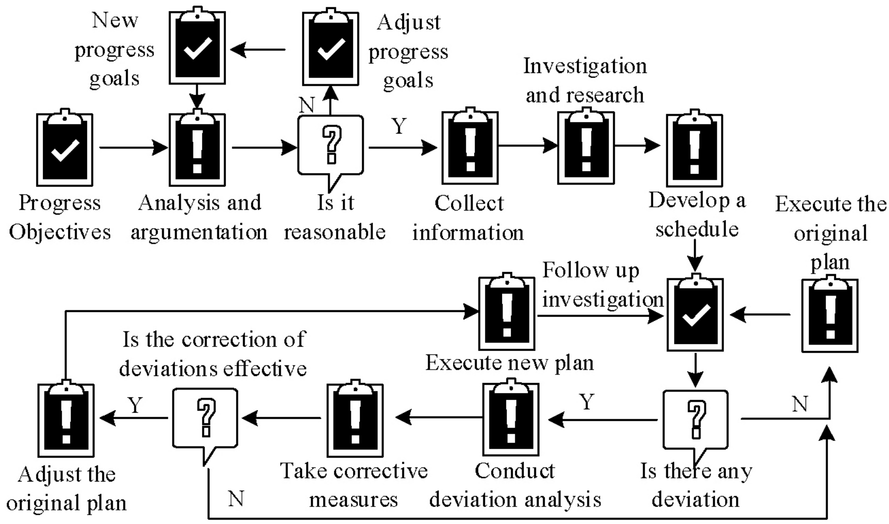

Fig. 1. Construction progress management flow chart

To ensure the high efficiency and quality of construction, this progress control plan can effectively respond to unexpected situations and make timely management adjustments to the construction plan, reducing the constraints on project quality and efficiency [18]. The safety control of highway engineering construction first needs to determine the safety pre control objectives based on objective needs. And it is necessary to conduct technical analysis on hazardous work nodes, and confirm the safety of each process when completing it. If the target should be corrected in a timely manner if it is not qualified, then Fig. 2 shows the specific safety control process.

In Fig. 2, for safety control during construction, research mainly focuses on two key nodes: safety inspection and whether construction operations violate regulations. And inspection steps are set up for two process nodes that are prone to danger, reducing process complexity while maximizing the safety of the entire construction. The environmental control of highway construction engineering, like other construction controls, requires supervision and inspection arrangements. Improper environmental control and management can have immeasurable impacts on the local ecological environment, resulting in serious economic losses. The key to

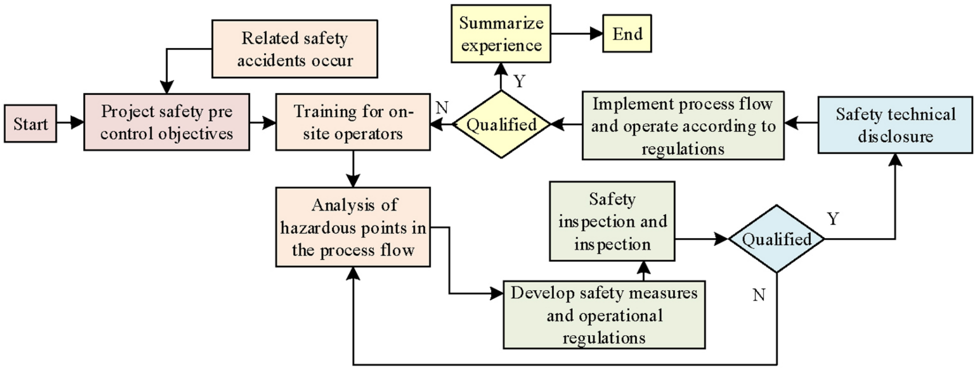

Fig. 2. Construction safety assurance program diagram

environmental control lies in the management of pollution, wastewater, and waste discharge during construction, which requires detailed arrangements and feasible reward and punishment regulations for the discharge process. In conventional construction, construction schedule control, construction safety control, and construction environment control are key factors that affect construction costs. The study adopts IPSO's MOP to reduce the economic costs of these three components while meeting the needs of schedule, safety, and environment. Figure 3 shows the specific MOP.

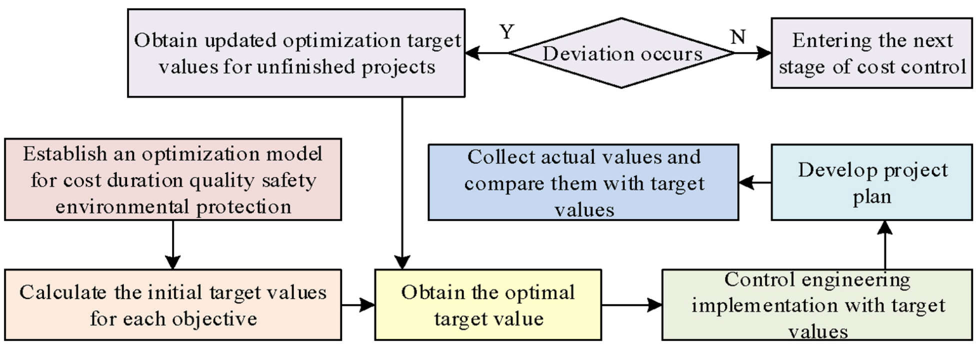

Fig. 3. MOP execution diagram

3.2. Parameter selection for combining adaptive weights with PSO

To increase the economic profits of construction enterprises, it is necessary to study the relationship between construction cost, construction time, and construction quality. By studying traditional building construction projects, the relationship between construction cost and construction period is closer to a curve. The direct cost will gradually decrease as the construction period increases. When the direct cost decreases to a certain value, the direct cost will also gradually increase if the construction period continues to be extended. According to the theory of marginal effects in economics, a mathematical model of this relationship can be easily obtained in Eq. (3.1).

$$C_i = C_{\text{in}} + r_i \times (T_i - T_{\text{in}})^2 \tag{3.1}$$

where: C_i – the actual expenditure cost of the i-th process, C_{in} – the expenses that need to be incurred under normal circumstances, r_i – the increasing coefficient between time and expenditure, T_i – the actual time spent on the i-th process, T_{in} – the time required under normal circumstances.

Afterwards, by transforming Eq. (3.1), the growth coefficient between the completion time of process and expenditure cost in Eq. (3.2) can be obtained.

$$r_i = \frac{C_i - C_{\text{in}}}{(T_i - T_{\text{in}})^2} \tag{3.2}$$

To increase the profits of construction projects, it is also necessary to study the construction cost and construction quality. Quality costs are mainly divided into two categories, namely prevention and identification costs and loss costs. The former is the cost investment required to ensure quality, while the latter is the subsequent compensation cost investment caused by quality failure to meet standards. With the continuous investment of prevention and identification costs, the loss cost gradually decreases. Relatively, if the investment in preventive identification costs is insufficient, the loss cost will also tend to infinity. By using the tangent function to describe this relative change, the relationship between the pre identification cost and the loss cost in Eq. (3.3) can be obtained.

$$C_q(i) = C_i \times \left\{\lambda_1 \left[\tan((\pi/4) \times Q_i\right]^{K_1} + \lambda_2 \left[\cot((\pi/4) \times (1 + Q_i))\right]^{K_2}\right\} \tag{3.3}$$

where: $C_q(i)$ – the total quality cost of the i-th process, Q_i – the overall quality level of the i-th process, λ_1 and λ_2 – the proportion of prevention appraisal cost and loss cost in the total cost of quality, respectively.

After analyzing the composition of profits in construction enterprises, it is necessary to construct algorithms to select appropriate management to control the stability of various costs and achieve maximum economic benefits. The study adopted a combination of IPSO and MOP to achieve this goal. PSO is an optimization algorithm based on group intelligence, inspired by the behavior of groups such as flocks of birds or schools of fish. The basic idea of PSO is to search for the optimal solution by simulating the position and velocity changes of each particle in the group. The rules of particle updating are adjusted according to the information of individual optimum and global optimum, i.e., each particle adjusts its velocity and position according to its own best position and the best position in the history of the whole population. The PSO algorithm is simple, effective, and easy to implement, and is suitable for all kinds of continuous and discrete optimization problems.

Equation (3.4) represents the particle update speed and position of PSO.

$$\begin{cases} v_{id}(t+1) = v_{id}(t) + c_1 r_1 (p_{id}(t) - x_{id}(t)) + c_2 r_2 (p_{gd}(t)) - x_{id}(t)) \\ x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \end{cases} \tag{3.4}$$

where: c – the acceleration constant during particle flight, t – the number of iterations.

After obtaining the update speed and real-time position of particles, the optimal position of particles can be obtained based on these two parameters. Eq. (3.5) is the optimal position.

$$p_i(t) = \begin{cases} p_i(t-1), f(x_i(t)) \geq f(p_i(t-1)) \\ x_i(t), f(x_i(t)) < f(p_i(t-1)) \end{cases} \tag{3.5}$$

In Eq. (3.5), the optimal position solution for a single particle is obtained, as in engineering CMMOP. Multiple variable factors need to be solved, so the optimal position of multiple particles can be expressed in Eq. (3.6).

$$p_g(t) = \arg\min \{f(p_0(t-1)), f(p_1(t)), \ldots, f(p_s(t))\} \tag{3.6}$$

To enhance the pertinence of PSO to the studied problems, improvements have been made to PSO. The improvements mainly include three aspects. Firstly, it is necessary to establish the global and individual guidance points for each particle. Secondly, it is necessary to fully store non-inferior solutions during continuous iteration. Finally, it is necessary to maintain the diversity of PSO to enhance the adaptability of the algorithm. In response to the above requirements, the study combines inertia weight PSO to balance the strength of local search and overall search through inertia weight, and then adds inertia weight in Eq. (3.7).

$$\begin{cases} v_{id}(t+1) = \omega v_{id}(t) + c_1 r_1(p_{id}(t) - x_{id}(t)) + c_2 r_2(p_{gd}(t)) - x_{id}(t)) \\ x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \end{cases} \tag{3.7}$$

In Eq. (3.7), the inertia weight will also cause particles to fall into individual guide priority during the search. Therefore, the algorithm also needs to perform linear decrement in Eq. (3.8).

$$\omega = \omega_{\max} - \frac{t \times [\omega_{\max} - \omega_{\min}]}{t_{\max}} \tag{3.8}$$

In Eq. (3.8), as the inertia weight changes, the performance of IPSO also changes accordingly. And appropriate solutions through continuous iteration and adjustment are obtained. Figure 4 shows IPSO.

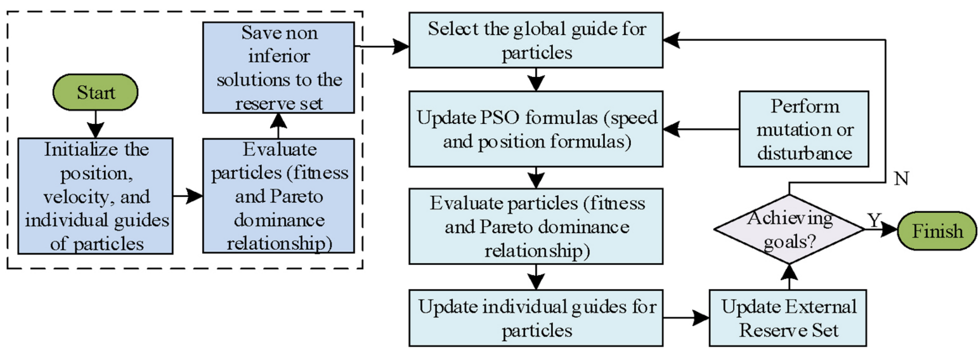

Fig. 4. Flow chart of IPSO

It is also necessary to solve the relevant parameters based on objective optimization techniques. C represents the expenditure cost of the process, and Eq. (3.9) is its evaluation model.

$$C = \sum_{i=1}^{N} \left[C_{\text{in}} + r_{\text{in}} \times (T_i - T_{\text{in}})^2\right] + \beta \times T + x \tag{3.9}$$

where: C_i – the actual expenditure cost of the i-th process, C_{in} – the expenses that need to be incurred under normal circumstances, T – the engineering consumption time.

Equation (3.10) is its evaluation model.

$$T = \sum_{i=1}^{N} T_i \tag{3.10}$$

where: T_i – the i-th process time, Q – the overall quality of project.

Equation (3.11) is its evaluation model.

$$Q = \sum_{i=1}^{N} \omega_i \ln(\alpha_i \times T_i + \beta_i) \geq Q_e \tag{3.11}$$

where: β_i – the indirect rate for the i-th process, S – the project safety.

Equation (3.12) is its evaluation model.

$$S = \left[1 - \sum_{j=1}^{\omega} \left(\omega_{nj}\left(1 - S_{nj}^{ij}\right)\right)/m\right] \times S_n \geq S_e \tag{3.12}$$

where: S_{nj}^{ij} – the safety level of the i-th process, G – the engineering environment.

Equation (3.13) is its evaluation model.

$$G = \sum_{i=1}^{N} \left(\frac{T_i}{T_s} \times e_i \times 1 \times s\right) \geq G_e \tag{3.13}$$

where: e_i – the environmental parameter of the i-th process.

At this point, the relevant evaluation parameters of the multi-objective management model for construction engineering have been established.

4. Performance demonstration and application effect of integrating IPSO and MOP

Nanjing Pu Yi highway construction process as an example, the highway for the pilot section of the Ningyan high-speed, starting from Nanjing Pukou Yangtze River Bridge under the North Fort, terminated in Yizheng territory docking Ningtong Expressway, completed in 2020, the study divided the construction process into 10 processes. In this construction project, the total mileage was 40km, the cost target was limited to 28.5 million yuan, and the construction period was 418 days. The minimum quality target score for the project was set to 0.86, the minimum safety protection score for the project was set to 0.92, and the minimum environmental protection target for the project was set to 0.78. After sorting various processes using optimization techniques, the obtained construction process arrangements include construction preparation, roadbed earthwork excavation, retaining wall foundation excavation, culvert construction, roadbed filling, retaining wall construction, culvert ancillary works, roadbed slope protection, roadbed and pavement layers. When evaluating construction quality and other issues, research mainly used expert scoring to evaluate various indicators of the project. After adopting the engineering construction MOP that integrated IPSO, Fig. 5 showed the engineering safety score and the importance ratio of various safety indicators.

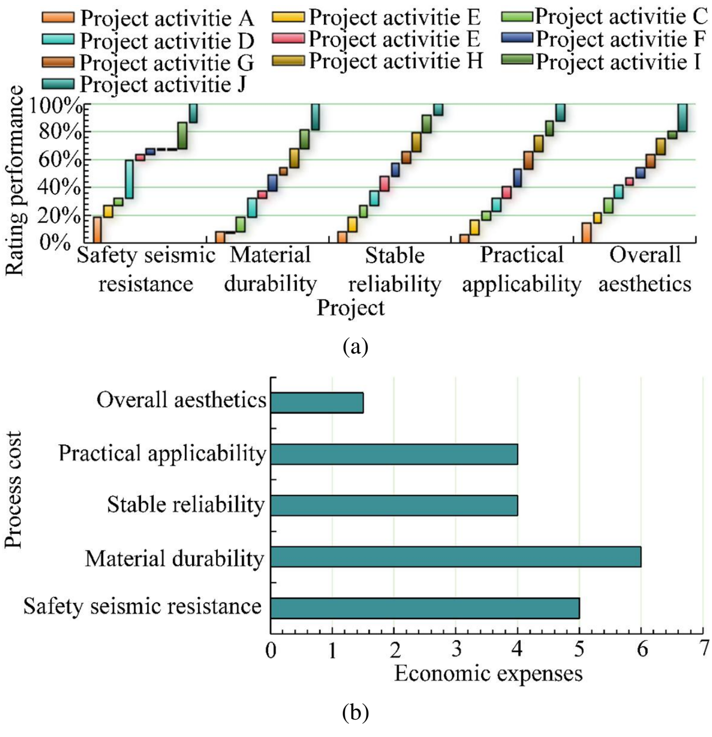

Fig. 5. Quality indicators and importance of each process; (a) Project rating, (b) Weights of various safety indicaters

In Fig. 5, based on the analysis of engineering safety in the figure, the importance of material durability reached over 30%, and the safety cost consumption of Project J, which was the most critical, reached 18%. The importance of safety seismic performance reached 25%, ranking second in the importance of safety projects. The investment cost of process D in terms of safety seismic resistance has also reached over 20% of the investment cost. The project management personnel could adjust the system and regulations of engineering quality control through intuitive data representation. And the analysis of environmental factors in the article still adopted the expert scoring system for evaluation, and the environmental impact coefficient of project was obtained. Figure 6 showed the proportion of environmental pollution and the proportion of environmental impact coefficient e for each process.

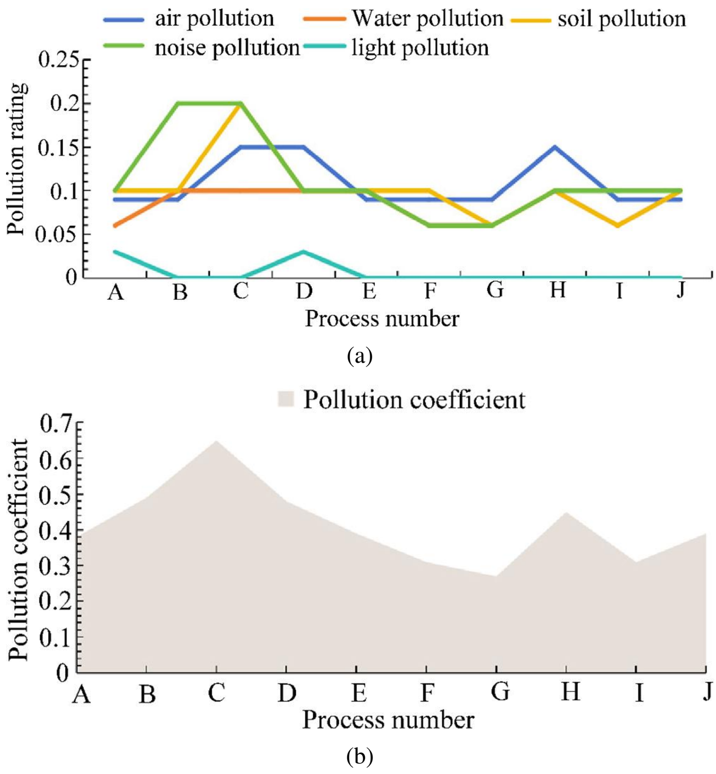

Fig. 6. Construction pollution and proportion of pollution in each process; (a) Pollution ratings for each process, (b) Various pollution coefficients of each process

In Fig. 6, according to the local policy requirements of the project, the study divided five environmental pollution types into three levels: mild, moderate, and severe. Among them, a score of less than 10% indicated mild, 10–20% indicated moderate, and over 20% indicated severe. According to these data, the pollution caused by light pollution was the lightest and the noise pollution was the most severe during this road construction. Among the 10 construction processes, Project C had the highest contribution of pollution by about 20%, while Project G had the lowest contribution of pollution by 7%. After obtaining the quality cost and environmental cost of project by combining PSO's MOP, the project management could be re-planned. Among them, under the premise of meeting the quality and cost requirements, Fig. 7 showed the schedule arrangement of the research output.

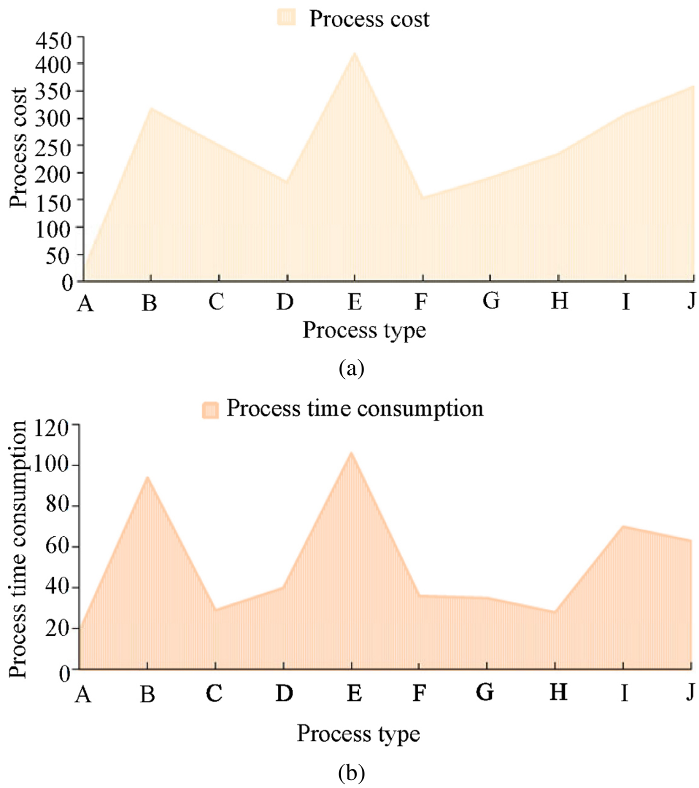

Fig. 7. Duration consumption and proportion of each process

In Fig. 7, the total construction period of project had been optimized to 380 days, meeting the required construction period of 418 days. The construction time for processes E and B was the longest, with 106 and 93 days respectively. The total time of these two processes accounts for over 35%, with process E accounting for 24%. The optimization plan significantly reduced the construction time and provided the main direction for future project optimization. Subsequently, the study analyzed and optimized the direct costs of each process. The cost proportion of processes B, C, E, I, and J all reached over 2.5 million yuan. The direct cost of these five processes accounted for about 70%. And the total cost of 10 processes was 24 million yuan, which saved about 1 million yuan compared to the predicted direct cost of the project, reflecting the good practicality of optimization technology. Finally, the study analyzed and predicted the various indicators of the entire engineering project, and pointed out the indicators and processes that needed the most attention in Fig. 8.

In Fig. 8, the quality rating, safety rating, and environmental rating of the project remained above 0.75. After optimization analysis, all indicators of the entire highway construction project met the contract requirements. And the quality rating and environmental rating of the project were insufficient through the radar map. When evaluating construction process I, there had been a significant decrease in both engineering quality and environmental quality.

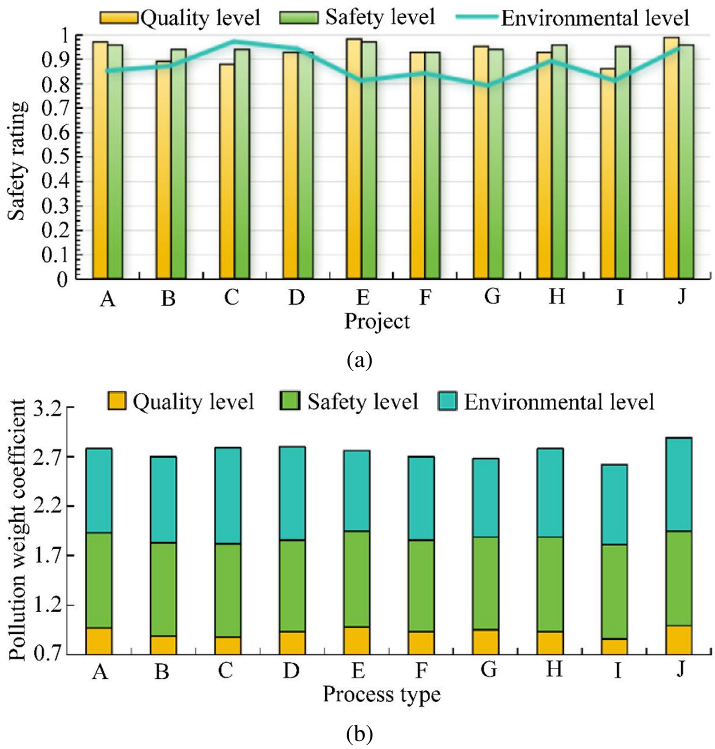

Fig. 8. Safety, quality, and environmental scores for each process; (a) All safety performance of the project, (b) Pollution weight coefficient of each process

5. Conclusions

Due to the professional development of the civil engineering industry, the demand for industry management optimization is gradually increasing. The study proposed a MOP engineering management technology that combined adaptive weights with IPSO. These studies confirmed that the total cost of 10 processes was 24 million yuan, which saved about 1 million yuan compared to the predicted direct cost 25.36 million dollars. The total construction period of the project had been optimized to 380 days, meeting the required 418 days. The quality rating, safety rating, and environmental rating of the project had all remained above 0.75. Optimization technology had good performance, not only could reduce enterprise costs according to engineering needs, but also could clearly output various problems of engineering projects. This provided support for the next optimization iteration or data reference for future engineering management development. However, due to objective factors, the study is unable to conduct a larger number of experiments to comprehensively reflect the performance of management optimization techniques. And it cannot help to arrange for the next project, which can serve as a direction for future research.

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Received: 2023-12-13, Revised: 2024-01-23