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Research paper

Multi-objective optimization of engineering project management based on mixed SFLA

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Abstract: To solve the problem of conflicting objectives in project management in the construction industry and comply with China's energy-saving and carbon reduction policies in the construction industry, this study introduces carbon emission conditions into a multi-objective model and designs an optimization model for project duration cost quality resources. On the basis of the mixed shuffled frog leaping algorithm, this study applies an improved encoding method, a target anchoring mixed initialization operator based on heuristic information, a design constraint handling operator, discrete jumping optimization rules, and local mining of individuals in external memory for mixing and optimization, to obtain the final multi-objective optimization solution method. The research results indicated that after the performance dimension was improved, the research method could still maintain stable and superior performance. The average fitness values of the f1 function and f2 function correspond to 1.81 · 101 and 1.81 · 101, respectively. In practical engineering project management applications, compared with the mainstream mixed frog leaping algorithm based on multi-population improved firefly algorithm, the research method obtained a total project duration that was 20 days less and a total cost that was $13125 less. Only the quality level and resource balance index were slightly inferior, with decibels of 0.93% and 49. The results indicate that the research method can quickly and effectively solve multiple solutions, enhance the competitiveness of enterprises in the construction industry, and promote the green development of the construction industry.

Keywords: mixed frog leaping algorithm, architectural engineering, project management, multi-objective optimization, constraint handling, heuristic information, green

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1. Introduction

As one of the pillar industries of China's national economy, the construction industry's market size continues to expand, and with the increase of urbanization rate and the continuous promotion of infrastructure construction, the total output value of the construction industry maintains a growth trend [1]. Construction engineering is a technically responsible production process that requires relevant personnel to creatively apply theories such as materials, mechanics, structure, and technology to continuously explain various difficulties that arise during actual construction, ensuring project quality and construction safety [2–4]. During the construction process of the project, it is necessary to organize personnel of different trades in an effective time and space for operation, and to integrate the operation of hundreds or thousands of materials and mechanical equipment [5, 6]. But currently, several management projects in construction engineering are usually interdependent yet contradictory, and any problem in any link can have a negative impact on the entire project. Achieving balanced optimization among conflicting multiple objectives and obtaining the most effective execution plan is currently the research focus. However, China has a large total construction volume and high energy consumption and carbon emission intensity, making it difficult to implement energy-saving and carbon reduction measures [7]. In response to the above issues, this study proposes a Duration Cost Quality Resource Optimization (DCQRO) model for engineering projects. Based on the Shuffled Frog Leaping Algorithm (SFLA), an improved encoding method, design constraint handling operators, and discrete jump optimization rules are used for mixing and optimization to obtain the Mixed SFLA algorithm (M-SFLA). The current research problem lies in the contradiction between building energy efficiency, lifecycle cost, and construction period. Based on the trend analysis of multi-objective optimization in building design, iterative optimization algorithms are the main challenge for deepening research, and computational efficiency needs to be improved. The research aims to provide project decision-makers with more balanced and optimized multi-objective solutions, enhance the competitiveness of enterprises, promote the low-carbon transformation of building energy consumption, and improve the level of building energy conservation and carbon reduction. The innovation of the research mainly lies in the following two points. The first point is the introduction of carbon emission conditions, based on which the DCQRO model is proposed to reduce the adverse impact of construction projects on the ecological environment. The second point is to design improved encoding methods, constraint handling operators, and discrete jump optimization rules to optimize the SFLA, to obtain project management solutions with better application effects.

2. Related work

The increasing number and continuous expansion of engineering construction projects in China have led to more and more enterprises entering the construction industry, and various problems continue to emerge, such as construction companies pursuing maximum economic benefits, slow low-carbon transformation of building energy consumption, and limited management systems. Numerous scholars have conducted in-depth analysis and exploration on the optimization of engineering project management. Ansari et al. proposed a multi-objective dynamic optimization method to determine time buffers in engineering and construction projects, addressing the complexity of random interference in project management. Numerical examples and case analysis verified the effectiveness of the research method, and the proposed adjustment method could generate more stable plans [8].

The SFLA algorithm is a new type of intelligent optimization method that has emerged in the field of intelligent optimization, which has the characteristics of simple structure, strong global optimization ability, and fast computing speed. Saidani et al. designed a channel equalization method that combined SFLA algorithm with directional search optimization to update the weights of neural networks. This method performed better than particle swarm optimization algorithm and directional search optimization algorithm in nonlinear channel equalization [9]. Zhang et al. used SFLA algorithm to solve the robot path planning problem in obstacle environments and optimized it using genetic algorithm. This method could effectively improve the minimum path optimization and robustness [10]. Karpagam et al. designed a heuristic novel SFLA algorithm clustering technique for workflow scheduling problems in cloud computing. This method has better performance in terms of completion time and resource utilization [11].

In summary, it can be concluded that the SFLA algorithm has demonstrated excellent performance in various scheduling and management problems, making it suitable for use in engineering project management optimization. However, this method still has the disadvantages of incomplete communication of local and global information, and the tendency to fall into local optima. Therefore, this study used improved encoding methods, discrete jump optimization rules, and local mining of individuals in external memory to optimize and construct the M-SFLA model.

3. Multi objective optimization of engineering project management based on mixed SFLA

The study proposes a DCQRO model for engineering projects and optimizes the SFLA algorithm to obtain the M-SFLA algorithm.

3.1. Construction of DCQRO model for engineering projects

In engineering project management, there are often issues of information asymmetry or delayed communication among multiple stakeholders, resulting in decision-making delays or execution deviations, and conflicting situations during the execution process. Multi objective optimization methods can balance the trade-off between multiple objectives, find a balanced set of solutions, and provide more choices and flexibility [12]. At present, relevant research focuses on the balance between construction period and cost. Therefore, the study comprehensively considers four optimization objectives: total construction period, quality level, total cost, and resource balance index. Meanwhile, the constraints include construction site carbon emissions and resource demand. Before implementation, managers need to determine the execution mode of each work activity, and are not allowed to modify or interrupt during the execution of each work. When constructing the DCQRO model, the first step is to select the execution mode x_{jc} for each task as the decision variable, as calculated in equation (3.1).

$$x_{jc} = \begin{cases} 1, & \text{When } j \text{ chooses to execute the job in } c \text{ mode} \\ 0, & \text{otherwise} \sum\limits_{c \in C_j} x_{jc} = 1 \end{cases} \tag{3.1}$$

In equation (3.1), if the work j is carried out according to the c method, x_{jc} is 1, otherwise it is taken as 0, the plan for the work activity is represented by a single code network plan chart, and combined with the associated path method, the objective function for calculating the total duration is shown in equation (3.2).

$$D = \max T_j \tag{3.2}$$

In equation (3.2), T_j is the end time corresponding to the j-th task. In the project cost section, it is to ensure the timely, high-quality, and cost-effective completion of the established goals within the approved budget. The construction of the cost management system is shown in Figure 1.

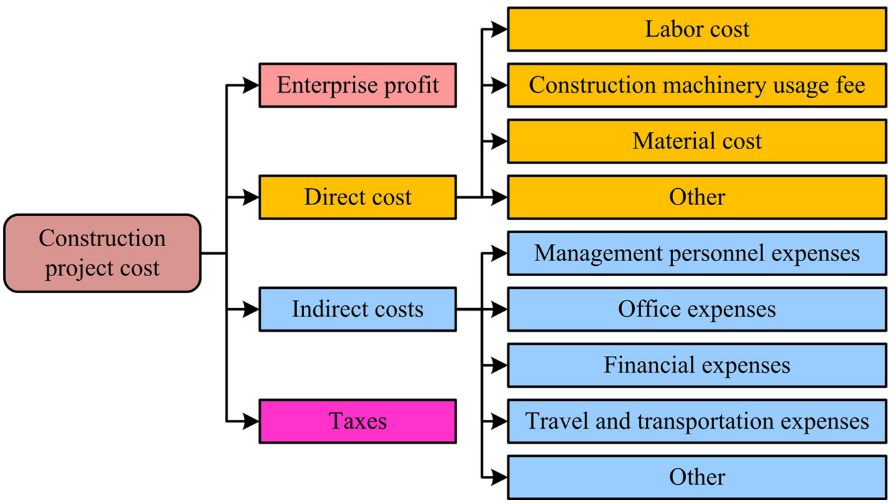


Fig. 1. Cost architecture for engineering project management

In Figure 1, costs are divided into four categories: direct costs, indirect costs, taxes, and corporate profits, and direct and indirect costs can be further subdivided into other specific costs. In the construction of the cost objective function, the total cost includes two parts: direct and indirect. Meanwhile, since the actual project may not be completed on time, a penalty function is also introduced in the study. The expression of the total cost objective function is shown in equation (3.3).

$$C_{\text{TOTAL}} = C_{\text{direct}} + \max f_j \cdot \text{cost}_{\text{ic}} + y \cdot \text{cost}_{\text{PF}} \cdot \left[\max f_j - G_p\right] \tag{3.3}$$

In equation (3.3), C_{direct} represents direct costs; cost_{ic} and cost_{PF} correspond to unit indirect costs and penalty functions for delays, respectively; G_p represents the agreed upon construction period; y represents a variable that is either 0 or 1. If the actual construction period exceeds the contracted period, the value is 1, otherwise it is 0. In terms of quality level, it is an optimization problem of discrete variables under multiple modes, so it is necessary to jointly execute the mode and the degree of influence on work quality, to complete the comprehensive quality level evaluation. The calculation is shown in equation (3.4).

$$QL = QL_{j,r}^{c} \tag{3.4}$$

In equation (3.4), $QL_{j,r}^{c}$ represents the quality standard that can be achieved for the j-th task in execution mode c in r. In the resource balance section, the variance is used to quantify the resource balance of the engineering project, and the expression is calculated as equation (3.5).

$$RL = \sum_{m=1}^{M} \sum_{t=1}^{T_D} \left[r_m^t - \overline{r}_m\right]^2 \tag{3.5}$$

In equation (3.5), T_D represents the total construction period; r_m^t is the time point t corresponds to the usage of the m-th resource; $\overline{r}_m$ represents the average usage of the resource. In the constraint section, the execution of engineering projects will be limited by factors such as labor, schedule, and cost. Therefore, the corresponding constraint expression is obtained as equation (3.6).

$$\sum_{j \in Z_t} \sum_{c \in C_j} \left(x_{jc} \cdot r_{jcm}\right) \leq R_c, \quad m = 1, 2, \ldots, M \tag{3.6}$$

In equation (3.6), Z_t represents all the work at time t; R_c is the maximum supply; r_{jcm} is the demand of j for any m under c. A large amount of carbon dioxide will be emitted at the construction site of engineering projects, which will have a huge adverse impact on the ecological environment. Meanwhile, the construction sector is one of the main areas of energy consumption and carbon emissions in China. In recent years, China has focused on improving the energy-saving and carbon reduction level of new buildings, providing important guidance for promoting energy-saving and carbon reduction work in the construction industry. Therefore, controlling carbon emissions at project construction sites has extremely important value for ecological environment and industry development. Building carbon footprint refers to the total amount of greenhouse gases, especially carbon dioxide, emitted during the lifecycle of a construction project, covering emissions from various stages such as material extraction, manufacturing, transportation, construction, maintenance, and demolition. The carbon emissions in this study are mainly concentrated in the construction phase, so the carbon emission factor method is used to calculate and limit the carbon emissions brought by each work part. The constraint condition calculation is shown in equation (3.7).

$$\frac{\sum_{i=1}^{n} E_{jc} EF_i}{A} \leq E \tag{3.7}$$

In equation (3.7), E_{jc} and E correspond to the carbon emissions and maximum carbon emissions of work j under operation mode c, respectively; EF_i represents the coefficient corresponding to Class i energy and carbon dioxide emissions, used to quantify the carbon emissions of buildings during various stages of related activities; A represents the building area. The calculation of carbon emissions in the study is based on the "Calculation Standards for Building Carbon Emissions" (GB/T53166-2019) approved by the Ministry of Housing and Urban Rural Development. This standard specifies the calculation standards for buildings at various stages of construction, and clarifies the definition, calculation boundaries, and emission factors of building emissions. By constructing the objective functions of equations (3.2) to (3.4) and designing the constraints of equations (3.5) to (3.7), the complete mathematical expression of the DCQRO model can be obtained.

3.2. Design of multi objective optimization method based on M-SFLA

Among the numerous multi-objective optimization methods for solving the optimization problems of the above-mentioned engineering projects, the SFLA algorithm can combine the frog leaping algorithm with other algorithms, comprehensively utilize the advantages of different algorithms to improve optimization performance, and can search for the global optimal solution in a relatively short time. It has fewer variable factors, making it one of the hot algorithms for solving multi-objective optimization problems. In addition, the algorithm is simple to operate, has fewer parameters, and can generate better offspring through local search and other processes, achieving information exchange between populations. Therefore, the SFLA algorithm is chosen as the basic method for research. However, this algorithm has disadvantages such as being easily affected by the initial population, slow convergence speed, and incomplete global information exchange. In response to the above issues, the M-SFLA algorithm is obtained by mixing and optimizing the basic SFLA algorithm from five aspects: improving the encoding method (F1), target anchoring hybrid initialization operator based on heuristic information (F2), designing constraint handling operator (F3), discrete jump optimization rule (F4), and locally mining individuals in external memory (F5). The specific process is shown in Figure 2.

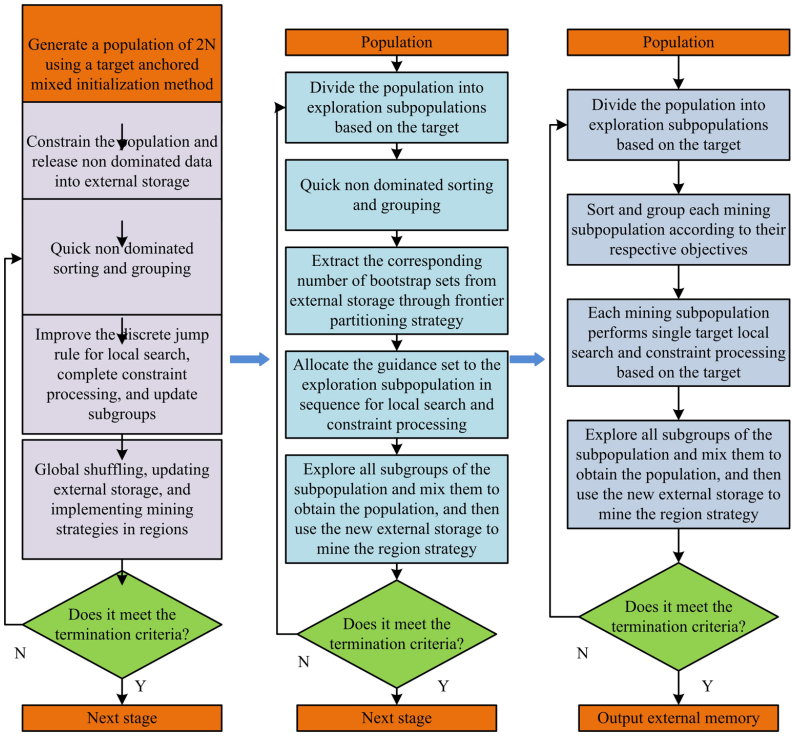


Fig. 2. The process of M-SFLA

In Figure 2, first in section F1, the integer double-layer encoding form is utilized to encode individuals. The data is divided into two levels: work activity coding and execution mode coding, and the structures of the two parts correspond one-to-one. In section F4, the individual update method of the basic SFLA algorithm needs to be used instead of the discrete jump rule, as shown in Figure 3.

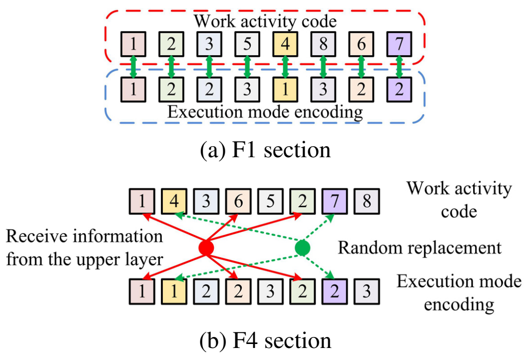


Fig. 3. Specific examples of F1 (a) and F4 sections (b)

Figure 3(a) and Figure 3(b) show the improvement strategies for F1 and F4, respectively, where the upper layer corresponds to the needs of the work activity and the lower layer corresponds to the execution mode of the corresponding work activity. In addition, for the F4 part, the work activity code needs to be placed in the candidate pool, and then some gene loci are randomly selected, and the optimal solution is transmitted to the inferior solution, so that the inferior solution can obtain more valuable information from the excellent individual. Then, the gene loci in the remaining candidate pool are replaced through replacement probability. In the F2 section, the optimization objective needs to be combined to obtain two approximate extreme solutions and insert them into the initial population, one of which selects a low-cost work activity to complete the entire project, and the other selects a shorter duration work activity to complete the overall project, while the other solutions of the initial population can be generated through random methods. In section F3, the encoding string corresponding to the infeasible solution is partially adjusted to retain a large amount of information while still satisfying the constraint conditions. The maximum number of tasks that can be executed by job j is calculated using equation (3.8).

$$n_{\max} = \begin{cases} g \cdot \beta + \left\lfloor \frac{h \cdot \beta}{\chi} \right\rfloor, & g \cdot \chi \geq h \cdot \beta \\ g \cdot \beta + h, & g \cdot \chi < h \cdot \beta \text{ and } g = 1 \\ g \cdot \beta + h + 1, & g \cdot \chi < h \cdot \beta \text{ and } g \geq 2 \end{cases} \tag{3.8}$$

In equation (3.8), β is the maximum number of tasks per job; χ represents the number of jobs executed per mode; g and h correspond to the quotient and remainder of $A\dfrac{Z_t}{\beta}$, respectively. If the number of tasks required for the execution mode is met, the constraint handling operator can repair the infeasible solution. Otherwise, the execution task cannot be completed by sufficient work activities, so there is no feasible solution for the model established in the study. Finally, in the F5 section, research is conducted on the mining strategy of providing regions through external storage to reduce the optimization process. Due to the long-term non updating of the global optimal solution in the current iteration, there is a serious phenomenon of population assimilation, ultimately leading to premature convergence. The specific example of a two-dimensional decision space is shown in Figure 4.

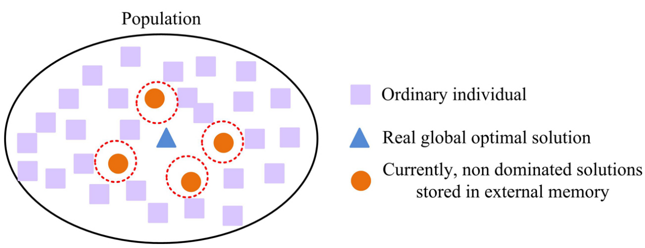


Fig. 4. F5 Partial example for M-SFLA

In Figure 4, the non dominated solution stored in the external memory is closer to the true global optimal solution, while the individual encoding consists of two levels. Therefore, by locally perturbing any part, the search for the current non dominated neighborhood can be completed.

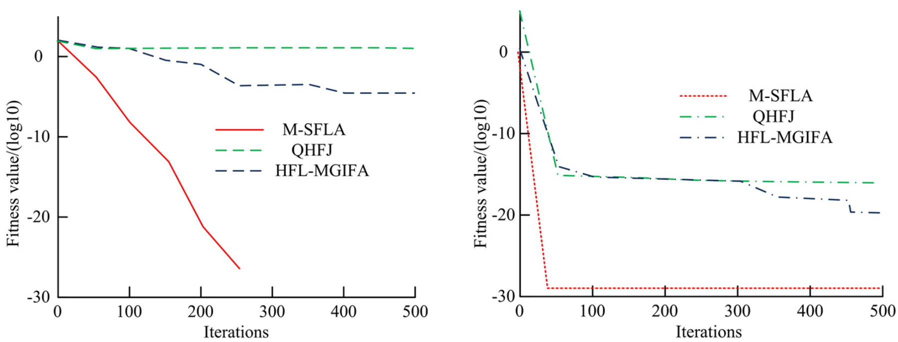
This can not only increase the richness of external storage, but also potentially mine more valuable non dominated solutions or true global optimal solutions. Based on the above basic frog leaping algorithm and various mixed strategies, the design of M-SFLA algorithm can be completed.

4. Multi objective optimization results for engineering project management based on M-SFLA

To evaluate the effectiveness and feasibility of the research method, this study first analyzed its performance, and then explored its application effect in actual construction projects.

4.1. Performance analysis of multi-objective optimization in engineering project management based on M-SFLA

To test the performance of the research method, experiments were conducted using the following f1 and f2 benchmark test functions. Among them, f1 belonged to a non convex function, which was represented by a narrow parabolic valley on the graph. It was very difficult for this function to converge to the minimum value; And f2 was a typical multimodal function with only one minimum value, which had characteristics such as nonlinearity, symmetry, and inseparability, and there were many local minima in the top sentence. The experimental platform was Matlab software, the computer processor was AMD Ryzen 5 4600U, and the running memory was 16 GB. To more scientifically validate the performance of research methods, this study conducted comparative experiments using current mainstream algorithms, namely Quantum Hybrid Frog Jump (QHFJ) and Hybrid Frog Leaping Based on Multi Group Improved Firefly Algorithm (HFL-MGIFA). In addition, the study set three dimensions of 10 and 20 dimensions for testing. The experimental parameters were set as follows: the number of frog individuals and subgroups were 100 and 10, respectively. The number of global iterations for individuals and within group iterations were set to 500 and 50, respectively. Each test function was independently run 40 times to obtain the optimal and average values. From this, the convergence curves of various algorithms based on the f1 and f2 functions in 10 and 20 dimensions can be obtained, as shown in Figure 5.



(a) (b)

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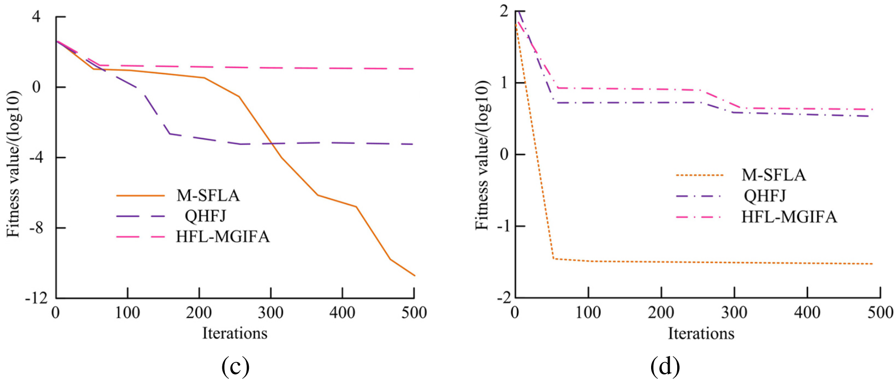

Fig. 5. Convergence curves of various algorithms based on f1 and f2 functions in 10 and 20 dimensions: (a) The result of f1 function in 10 dimensions; (b) The result of f2 function in 10 dimensions; c) The result of f1 function in 30 dimensions; (d) The result of f2 function in 30 dimensions

Figures 5(a) and 5(b) correspond to the convergence curves of different algorithms in 10 dimensions under the f1 and f2 functions, respectively. Under the f1 function, the M-SFLA algorithm only needed 199 iterations, and the average fitness value could reach $5.97 \cdot 10^{-30}$; After 50 iterations of the QHFJ algorithm, the average fitness value stabilized at 9.528101; The HFL-MGIFA stabilized its curve after 327 iterations, with an average fitness value of $7.53 \cdot 10^{-5}$. In the results of the f2 test function, the M-SFLA performed the best. Although the F1 function had a complex style, the research method could still obtain the global optimal value in a 10 dimensional search space, and could still performed well in multiple peaks and valleys of the F2 function. Figures 5(c) and 5(d) correspond to the convergence curves of different algorithms in 10 dimensions under the f1 and f2 functions, respectively. Compared with other methods, the M-SFLA still had the best average fitness values for the f1 and f2 functions, which were $5.63 \cdot 10^{-4}$ and $1.13 \cdot 10^{-1}$, respectively. The above results indicated that although the dimension of the search space had been increased, the research method had not fallen into local optima, and the convergence speed was faster than other mainstream algorithms. Moreover, it could still converge quickly in the F1 test function. In summary, the research method had excellent performance, and the optimization of the worst frog individual had been improved. The overall optimization ability of the population had also been greatly enhanced.

4.2. Application analysis of multi-objective optimization in engineering project management based on M-SFLA

To better evaluate the effectiveness of research methods in actual construction projects, this study focused on Project G, which included 18 work activities. The specific logical relationship diagram was shown in Figure 6.

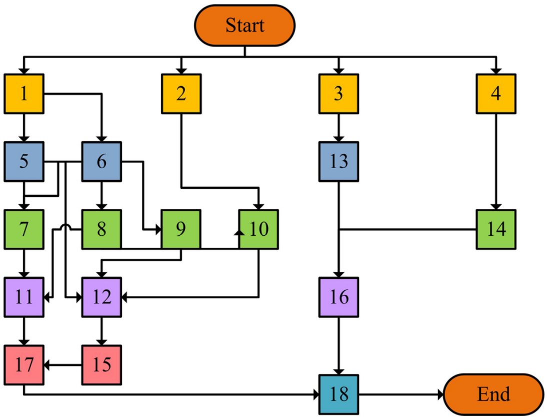

Fig. 6. Logical relationship diagram of the research object

Before the construction of the project, decision-makers needed to determine the execution mode of each task, and it was not allowed to change or interrupt the work midway. Meanwhile, the HFL-MGIFA with better performance among mainstream algorithms was studied for application effect comparison. This study used the Pareto solution set for evaluation, and set the external set to update and save the generated Pareto solution at any time during the calculation process. From this, the final results of different methods' Pareto solution sets can be obtained, as shown in Figure 7.

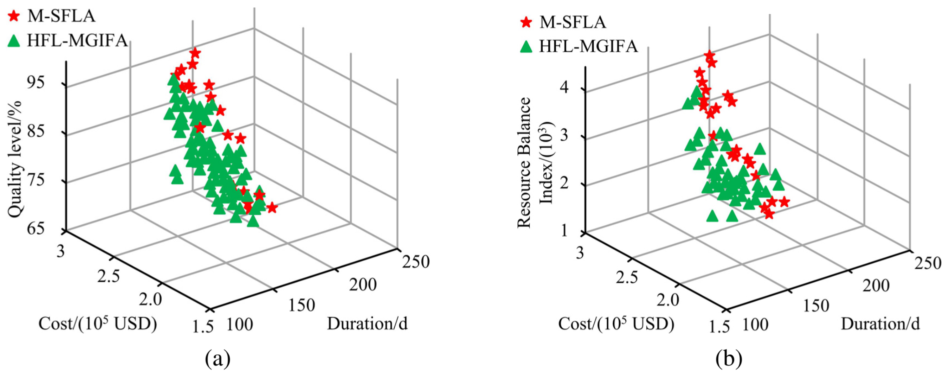

Fig. 7. The final results of pareto solution sets using different methods: (a) Quality level; (b) Resource balance index

Figures 7(a) and 7(b) show the Pareto solution sets of different algorithms at the quality level and resource balance index, respectively. The Pareto solutions of M-SFLA and HFL-MGIFA were 135 and 27, respectively, and the former was closer to the optimal position. Finally, from an overall perspective, the performance of different methods in terms of total duration, total cost, quality level, and resource balance index in practical applications could be analyzed, as shown in Figure 8.

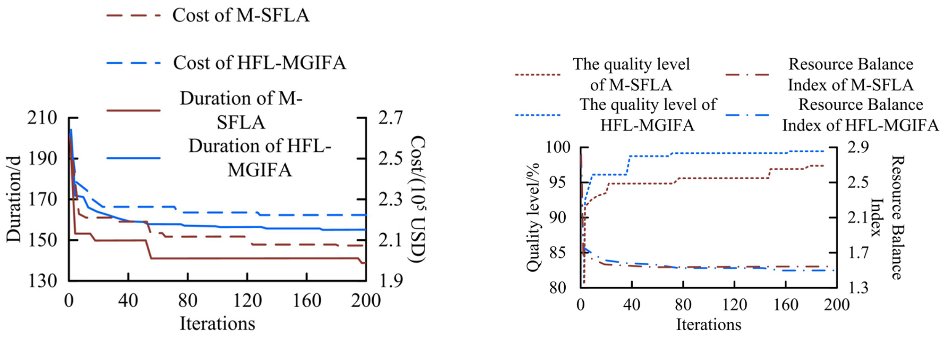

Fig. 8. The performance effects of different methods on various indicators in the project: (a) Total duration and total cost; (b) Quality level and resource balance index

Figures 8(a) and 8(b) corresponded to the optimal results of total duration and total cost, quality level and resource balance index under different methods, respectively. Compared with the HFL-MGIFA, the M-SFLA had a total project duration that was 20 days shorter and a total cost that was \$13125 lower. However, the quality level was 0.93% lower and the resource balance index was 49 lower, which could be considered as a small difference within the same level range. Overall, the research method could obtain more and better Pareto solutions in a shorter period of time, thus its application performance was also more excellent.

5. Conclusions

The rapid promotion and development of the construction industry has formed the magnificent construction industry today, which not only drives employment for countless people, but also effectively promotes the development of the national economy. But this has also brought about increasingly fierce competition, where project management is closely linked to the competitiveness of enterprises, and resolving numerous conflicts in projects is a huge challenge. In response to the above issues, a DCQRO model for construction project management is developed, and an M-SFLA that combines multiple improvement strategies is designed to solve multi-objective problems. The experimental results showed that in the F1 test function results under 10 dimensions, the average fitness value of the research method was the smallest at $5.97 \cdot 10^{-30}$, while the average fitness values of QHFJ algorithm and HFL-MGIFA were larger, corresponding to 9.528101 and $7.53 \cdot 10^{-5}$, respectively. In terms of application effectiveness, the research method could quickly obtain 135 Pareto solutions, and compared with the HFL-MGIFA, the total construction period and total cost were reduced by 20 days and \$13125, respectively. The quality level and resource balance index were only reduced by 0.93% and 49, respectively. In summary, research methods can balance numerous conflicting goals as a whole and propose multiple practical and effective response plans. Decision makers can choose the best solution based on actual needs, which is beneficial for the sustainable development of the construction industry. However, there are still certain limitations in the research, and the improvement strategies are currently in the early stages. In future research more refined and advanced processing techniques can be introduced to more accurately enhance the performance of methods for handling multi-objective optimization problems in engineering projects.

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